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Assessing the spatiotemporal changes, associated carbon stock, and potential emissions of mangroves in Bahrain using GIS and remote sensing data

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ABSTRACT

The gray mangrove (*Avicennia marina* (Forssk) Vierh) constructs one of Bahrain's most critical ecosystem, severly deteriorating, which has been severely deteriorated by increasing anthropogenic pressures. This study aimed to assess the spatiotemporal changes in the mangrove habitat around Tubli Bay, Kingdom of Bahrain, over the last 50 years through achieving the following: (1) detect the progressive reduction in the mangrove cover using Geographic Information Science and Systems (GISs) techniques and remote sensing data, (2) estimate the changes of above–below ground (AGB-BGB) carbon sequestered in the mangroves using a GIS-based spatial analysis approach, and (3) estimate the potential carbon emission changes from the loss of original mangrove habitats. Various GIS and remotely sensed data were employed in the study, including high-resolution satellite images from Worldview-3, Worldview-2, IKONOS, and QuickBird, coupled with true-color orthorectified aerial photographs. Additional data was acquired from fieldwork and the ancillary GIS maps. Image processing of the satellite data was conducted using ENVI 5.5 Software. ArcGIS 10.8 was used for digitizing the mangrove areas in all satellite imagery. The final maps were used to calculate mangrove area changes and carbon loss due to land reclamation activities. Our results indicated that Bahrain lost more than 95% of the natural mangrove cover from 1967 to 2020. The mangrove extent area's net loss reached 280 ha during 1967–2020, as it declined from 328 ha in 1967 to 48 ha in 2020. The primary cause of the decline was land reclamation associated with urban development. The rates and causes of the loss varied both spatially and temporally. Due to land clearing, the total carbon stored in the mangrove habitats declined from 34,932.2 Mg C ha^{-1} in 1967 to 5112 Mg C ha^{-1} in 2020. Consequently, the potential carbon Sequestration decreased from 128,200.44 Mg CO_2e ha^{-1} in 1967 to 18,761.04 Mg CO_2e ha^{-1} in 2020. Our study urges for more efficient conservation of the remaining mangroves in Bahrain to sustain their valuable ecosystem services particularly carbon sequestration.

1. Introduction

1.1. Mangrove, climate change, and carbon sequestration

Coastal environments are considered one of the most ecologically and economically valuable expanses on planet Earth (Kirwan et al., 2008). Coastal wetlands assist in regulating local, regional, and global climates, and ecosystems (Nemani and Running, 1996). They sequester considerable amounts of carbon

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(Ellison, 1994). Taillardat et al. (2018) defined carbon sequestration as an ecosystem's ability to absorb and store more carbon in biomass, sediments, or water than is released to the atmosphere through respiration . The carbon sequestered by non-terrestrial sources of vegetation such as seagrass beds and mangrove forests is called blue carbon (Mcleod et al., 2011; Pendleton et al., 2012; Alongi, 2012). At the same time carbon sequestration refers most often to the ability of the ecosystems to reduce the impact of increasing CO_2 concentrations in the atmosphere (Alongi, 2014; Rogers et al., 2019). Unlike terrestrial vegetation or green carbon, blue carbon is stored for thousands of years in ocean sediments (Brevik and Homburg, 2004). However, these ecosystems quickly deteriorare in developing countries, reducing their carbon sequestration capacity and potentially converting them into carbon dioxide sources (Rani et al., 2021; Rovai et al., 2021). Mangrove constructs highly productive ecosystems that store substantial amounts of carbon for long periods, and their preservation helps to mitigate climate change by reducing greenhouse gas emissions (Jennerjahn and Ittekkot, 2002; Gilman et al., 2008; Kristensen et al., 2008; Alongi, 2014; Adame et al., 2018, 2021). The blue carbon stored in the ocean's sediments by mangroves, seagrass, and marine algae will be affected by the degradation of these habitats (Brevik and Homburg, 2004; Nellemann et al., 2008). Climate change is expected to have two significant effects on wetlands: First, a declining number and functional capacity of wetlands, and second, a shift of geographic regions of some wetlands (Erwin, 2009). Climate change will have harmful consequences on wetlands due to the rhythm and magnitude of the changes in sea level, flooding, erosion and sedimentation, fluctuating precipitation and temperature regimes, and storms and cyclones (McLeod and Salm, 2006; Gilman et al., 2008; IPCC, 2013). Mangroves are critical ecosystems of high levels of diversity of terrestrial and marine plants and animals (Moberg and Ronnback, 2003; Nagelkerken et al., 2008). These ecosystems are of high levels of diversity and productivity (Kristensen et al., 2008; Howari et al., 2009). For instance, they provide feeding and roosting grounds for several residents and migrant birds (Ellison, 2008). Furthermore, mangroves provide vital ecosystem services, including coastal stabilization, erosion control, climate change mitigation and adaptation, and carbon sinks in the context of global warming; (Alongi, 2020; Dinilhuda et al., 2020; Lovelock and Duarte, 2019; Simard et al., 2019; Wang et al., 2018; Salem and Mercer, 2012; Koch et al., 2009). Cusack et al. (2018) reported that mangrove habitats were the most efficient organic carbon sequesters and storage with the highest carbon burial rate than the ecosystems of seagrass and saltmarshes over the past century on the western coast of the Arabian Gulf. Blue Carbon's contribution to climate change mitigation and adaptation is now well-known on a global scale (Macreadie et al., 2019). Natural-based climate solutions can potentially mitigate climate change (Crusius, 2020; Zeng et al., 2021). Taillardat et al. (2018) contend that mangrove blue carbon, in conjunction with other blue carbon ecosystems, may contribute to climate change mitigation at the national scale. However, mangroves are globally subjected to increasing pressures from overexploitation, coastal development, and pollution (Chong, 2006). The significance of assessing the capacity for carbon storage in mangrove vegetation to mitigate global warming raises a signal that we should preserve the mangrove ecosystem (Chow, 2018).

There are three commonly used methods for estimation of aboveground biomass (AGB) and carbon stocks stored in the forest ecosystems (Gibbs et al., 2007), these are 1) the destructive method, 2) the average tree method, and 3) the allometric method. The destructive method is the most direct one. It involves cutting all trees into sections and components, drying them, and weighing them. The average tree method is usually be applied only in forests with a homogeneous size distribution in the trees, as in the case of the plantations (Komiyama et al., 2008). The allometric method uses measurable dimensions such as the diameter and tree height to estimate a tree's partial or total weight. Allometric equations are available and applicable for all structural forms of mangroves (Clough et al., 1997; Ross et al., 2001; Dahdouh-Guebas et al., 2005; Komiyama et al., 2008). Saenger and Snedaker (1993) had reviewed 43 AGB equations of mangroves worldwide, to derive a single, global height–biomass and height–productivity equation. Also, Komiyama et al. (2008) had described the current state of knowledge on mangrove biomass and productivity equations based on 72 published studies in detail, while Soares and Schaeffer-Novelli (2005), and Comley and McGuiness (2005) described the mangroves species and related site-specific equations comprehensively. Chave et al. (2005) and Komiyama et al. (2005) proposed the use of equations that are not dependent on neither site nor species. Several common allometric equations were developed for *A. marina* trees (Chave et al., 2005; Komiyama et al., 2008). The AGB content of mangrove species has been widely used as an indicator of carbon storage capacity by applying common allometric equations (Komiyama et al., 2005, 2008; Prasanna et al., 2017). Detailed estimates of biomass are essential in describing the status of mangroves, evaluating the yield of commercial woody products, developing sound cultural practices, modeling potential impacts of climate change, and as an essential component of carbon sequestration estimation (Earmus et al., 2000; Comley and McGuiness, 2005; Soares and Schaeffer-Novelli, 2005). Fatoyinbo et al. (2008) established a generic biomass equation for Kenyan mangroves that has the potential for broad application. This equation can be used to estimate the AGB of new trees where there is no pre-existing knowledge of the specific species–site allometric relationship.

1.2. Bahrain mangrove

Gray mangrove grows naturally in the hot and dry intertidal zones of the Arabian Gulf (Sheppard et al., 1992; Dodd et al., 1999; Katheiresan and Najendran, 2005). The habitat constructed by the mangroves supports a variety of marine flora and fauna and significantly contributes to coastal biota diversity and productivity in the region (Al-Maslamani et al., 2013). In the Kingdom of Bahrain, the mangroves grow naturally only on Tubli Bay coatlines. However, the mangrove distribution has been expanded by introducing programs that transplanted mangroves to new locations. Recognizing the mangrove ecosystem's valuable goods and services, Bahrain declared the mangroves area at Ras Sanad of Tubli Bay protected. Latter, the Bay was declared a wetland of international importance for birds in 1997 (Naser, 2016). Moneywise, the national economic value of Bahrain mangroves was estimated at $\$803/ha^{-1}/yr^{-1}$ (World Bank, 2015).

Mangrove of Tubli Bay was declared critically endangered in Bahrain (ARCWH, 2017). However, due to inadequate management (Al-Sayed et al., 2008), Tubli Bay and its associated mangrove stands are still under severe threat. The mangroves have been dramatically impacted by reclamation, dredging, oil pollution, domestic and industrial effluents, solid waste dumping, and physical destruction leading to significant shrink in their spatial cover (Abido et al., 2011). Several studies highlighted the substantial shrink in the mangrove cover due to land reclamation associated with urban development (Vousden, 1988; Spalding et al., 1997; Abbas, 2002; Abido and Saeed, 2002; AlZayani and Loughland, 2009; Abido et al., 2011; Zainal et al., 2012; Naser, 2014). However, different estimations were proposed for the loss of mangrove cover and the total area remained of Tubli Bay. For instance, the original cover of the mangroves along the coastlines

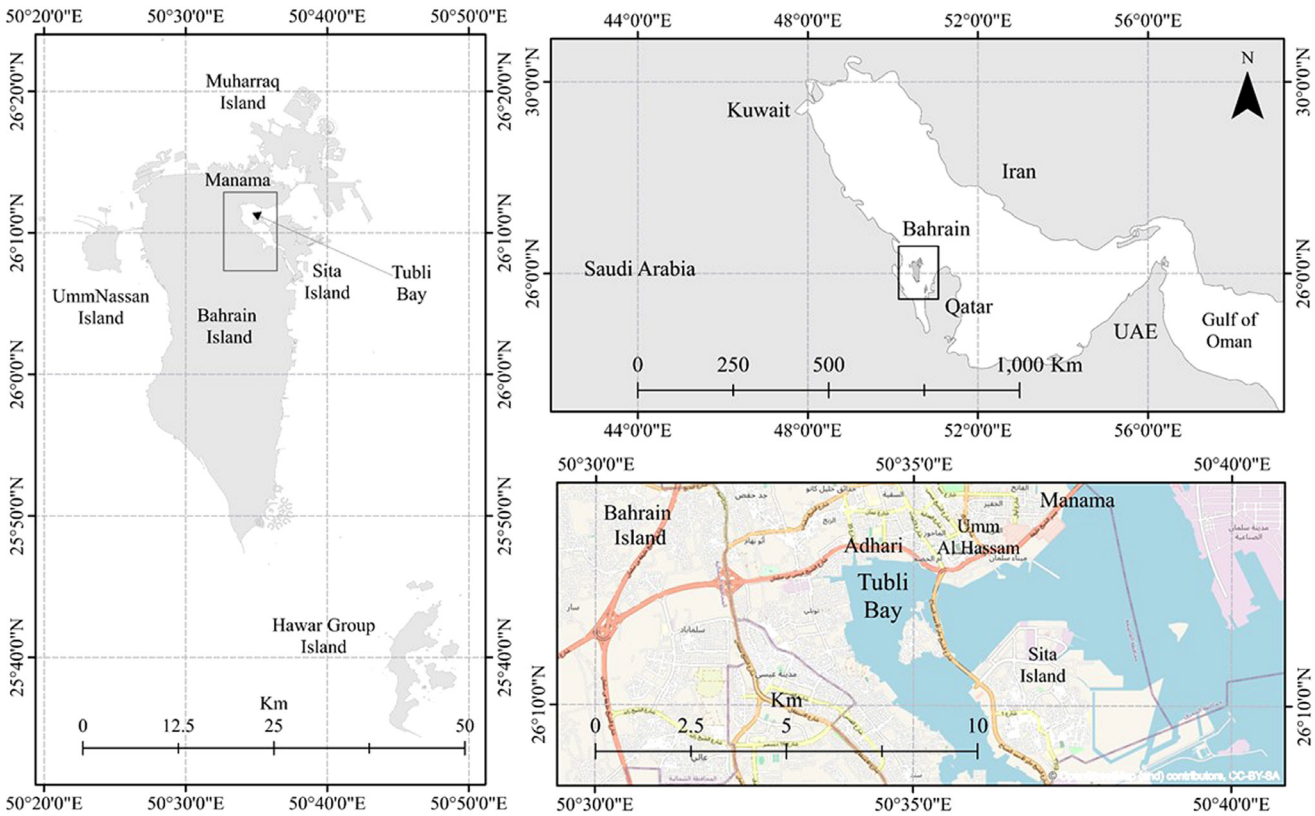

Fig. 1. Study area, Bahrain Islands and Tubli Bay location, 2020.

of Tubli Bay was projected to range from 100 hectares (Vousden, 1988) to 300 hectares (Spalding et al., 1997). Abou Seedo et al. (2017) estimated the AGB and belowground biomass (BGB) using the allometric equation of mangrove species provided by Comley and McGuiness (2005) and Brown (1997). These equations were highly species-specific and believed to be less site-specific (Komiyama et al., 2008). The AGB was estimated as $AGB\ (Kg) = 0.308 \times DBH^{2.11}$($r^2 = 0.97$, $n = 22$, $D_{max} = 35$ cm). The BGB was estimated as $BGB\ (Kg) = 1.28 \times DBH^{1.17}$($r^2 = 0.80$, $n = 14$, $D_{max} = 35$ cm). The estimation of AGB and BGB carbon stock was calculated according to the formula of Sridang (2008) as *Aboveground C stock* (Mg ha^{-1}) = $OC\% \times AGB$; and *belowground C stock* (Mg ha^{-1}) = $OC\% \times BGB$. The mean carbon stock in mangrove sediment was calculated as 55.2 Mg C ha^{-1}, and the average CO_2 stored in mangrove sediments in Tubli Bay was approximated at 204.24 Mg CO_2 ha^{-1}. The mean carbon stock (AGB and BGB) in Tubli Bay mangrove trees was 34.0 and 22.0 Mg ha^{-1}, respectively. The carbon stock of mangrove trees in Tubli Bay was estimated as 51.3Mg C ha^{-1}, which is equivalent to 189.8 Mg CO_2 ha^{-1}. The total carbon of Tubli Bay sediments and trees was approximated at 106.5 Mg C ha^{-1}, and 394.03 equivalent of CO_2 (Abou Seedo et al., 2017). Mangrove ecosystems are essential and effective long-term carbon sinks (Howard et al., 2017). Therefore, the role of mangroves in climate change is being increasingly included in national reports to the United Nations Framework Convention on Climate Change (UNFCCC). Characterizing the past and current spatial and temporal statuses of mangroves in Bahrain is vital for effectively protecting of the critically endangered local ecosystems. Additionally, quantifying the potential carbon sequestration by mangroves is considered a national and regional priority to mitigate the impacts of climate change (Vermeulen et al., 2019). Many studies have documented the extent of mangroves surrounding the Bay, but no specific assessment was conducted on the spatio-temporal changes of the species. This study was directed mainly to quantify the historical and current extent of Tubli Bay mangroves within the historical setting of the Bay since 1930s. The produced spatial data could be added to the previous spatial data to decide future rehabilitation, restoration, conservation, and development guidelines. The main objectives of this study were to 1) detect the decline of mangrove area along the coasts of Tubli Bay over the last 50 years using GIS and remote sensing ata, 2) estimate the changes of above-below ground (AGB-BGB) carbon sequestered in mangroves using a GIS-based spatial analysis approach, and 3) estimate the potential carbon emission changes from the loss of original mangrove habitats since the 1960s.

2. Material and methods

2.1. Study area

Bahrain is composed of 36 low-lying islands with a total area of 782 km^2. The coastal length is more than 537 km, while the marine area embraces more than 9200 km^2. The country is situated in the southern part of the Arabian Gulf, between longitudes 50°16′ and 51°00′ easting, and latitudes 25°33′ and 27°12′ northing (Fig. 1). Tubli Bay is a sheltered and shallow bay with extensive intertidal mudflats on the northeast coast of the Bahrain main island. The Bay hosts several aggregations of natural mangroves in the intertidal mudflats, banks of tidal channels, inside drainage channels of the surrounding farms, and enclosed coastal areas. Only three fragmented mangrove stands surrounding Tubli Bay existed in 2020 (see Fig. 2: A, B, and C). Mangrove was more extensive in the past in the area, but has been lost to landfills and other coastal activities (GoB, UNDP, 2007). However, mangroves are currently restricted to the sheltered southern area of the Bay. A substantial portion of Tubli Bay has been subjected to physical alternation and pollution

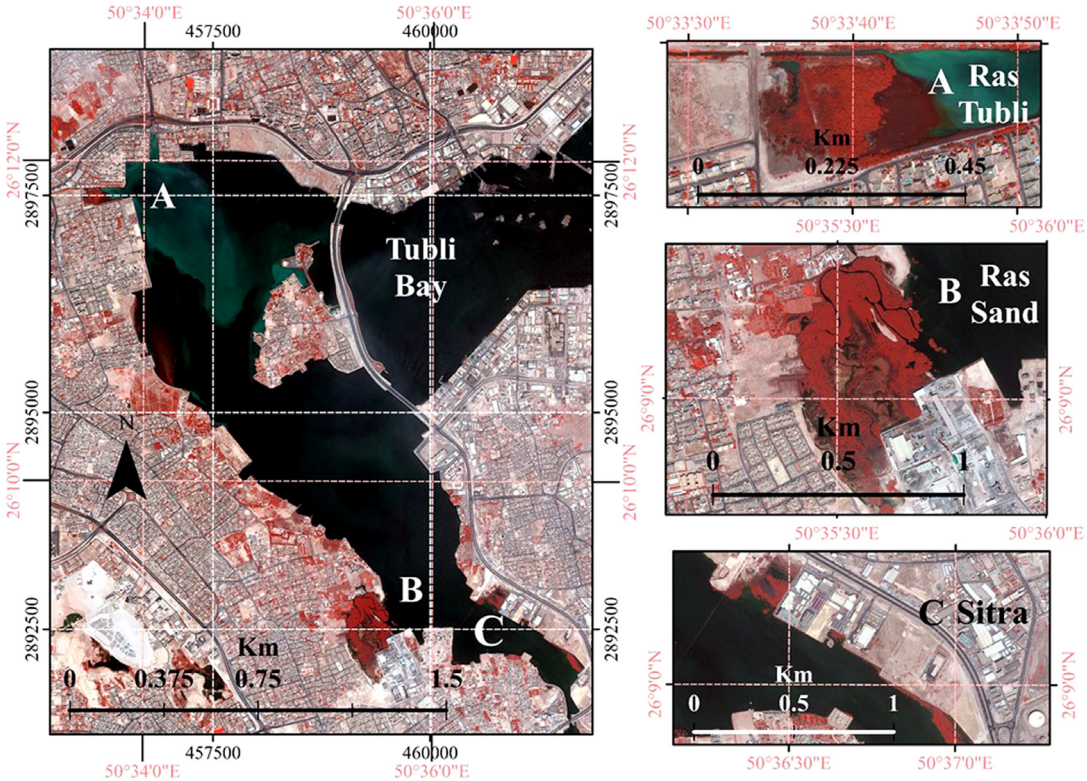

Fig. 2. Mangrove coverage sites A, B, and C surrounding Tubli Bay, 2020.

that contributed substantially in the deterioration of mangrove ecosystems. Most of the mangrove habitats had been lost by 1960s (Al-Eisawi, 2001). Doornkamp et al. (1980), revealed that large areas of the former intertidal zone along both sides of the Bay inlet have been reclaimed with constructions of walls and banks, and have been converted into date farms. Other areas have been built and covered with earthfill for construction sites. Several anthropogenic activities are continuously damaging the health of the mangrove ecosystems, including sewage discharges and solid wastes disposals (Naser, 2011, 2014; Abahussain and Al-Sabbaq, 2011). Presently, mangroves of Ras Sanad are restricted to an area of about 40 ha. The other significant stand of mangrove (less than 10 ha) is near Tubli Water Pollution Control Center.

2.2. Data sets

This study mapped and analyzed the historical sites of mangroves along the shorelines of Tubli Bay. The coverage of mangroves in the 1960s was discerned from interviews with older adults, literature, historical maps, aerial photographs, and data collected from satellite images. Different types of data were collected, including orthorectified, multi-resolution, and seamless image database from Aerial Photograph (1967), Orthophoto, MR-SID (1998, 2003), high-resolution satellite images from IKONOS (2005, 2007, 2009), GeoEye1 (2004, 2008, 2011, 2013), and Worldview-2 and 3 (2014, 2015, 2017, 2019, 2020) (Table 1). The resolution of the spatial data ranges between 0.5 m × 0.5 m, 2.0 × 2.0 m to 4.0 × 4.0 m. In addition, Bahrain topographic maps in digital format, from 1937 to *2020*, were used for referencing from 1937 t0 2020. For the analysis, we used a combination of historic Black & White (B&W) digital photographs, true color (RGB), color infrared (NIR, 3, 2), and true-color images from 1967 through *2020*. The baseline of Tubli Bay and mangrove presence were determined from the historic Black & White (B&W) Photograph Digital Image (1967), acquired from USGS earthexplorer. Image analysis was done in ArcGIS 10.8 (ESRI, Inc.), whereas statistical analysis was done in Excel (Microsoft™).

2.3. Methods

Systematic steps were followed to collect and estimate the total area of mangroves in Tubli Bay since 1967. The first step started with to collecting, analyzing, and synthesing the previous literature on Tubli Bay mangrove to estimate the historical area since 1960s. The second step concentrated on building a geodatabase and producing a map of mangrove areas. The third step was to investigate Ras Sanad mangrove area using remote sensing technology. The final step was to assess the spatiotemporal changes of the mangrove area, the carbon stock in trees, the total potential emission, the carbon stock of mangrove sediment, and total carbon stored in the mangrove habitat and potential emission CO_2^{-1} of the last 50 years.

2.3.1. Spatial data processing

Our estimation of mangrove areas, potential carbon stock of trees, and other related parameters, were based on a collection of datasets, that include vector-GIS mangrove polygon shapefiles, and Tubli Bay boundaries from 1967 to 2020. GIS processing techniques and spatial analysis approaches were used to map the mangrove area and the Bay boundary. Mangrove is the only vegetation that found along the coastline in the study area. Thus, the classification is limited to the presence/absence of mangrove. Hence, we adapted a GIS vector-based as the primary layer to detect the changes in mangrove areas. Several steps were used to ensure that all data used in this study were georeferenced and stored with all the descriptive information to achieve the consequent change detection model. All undefined aerial photos, Orthophoto, and satellite image files were georeferenced to Universal Transverse Mercator (UTM) coordinate system Zone 39 with the World Geodetic System 1984 (WGS84) datum.

Table 1
Historical aerial photographs and remotely sensed data (1967–2020) used in the digitization process to estimate the mangrove area.

Year	Data type	Resolution (m^2)	Description	Source
1967	Photograph Digital Image	0.7 m	Black & White	USG
1998	Orthophoto: MRSID	1.0 m	Black & White, Color	SLRB
2003	Orthophoto: MRSID	1.0 m	Black & White, Color	SLRB
2004	GeoEye-1	0.46 m, 1.84 m	4 Bands	NCRS/KSA
2005	IKONOS	0.82 m, 3.2 m	4 Bands	SLRB
2007	IKONOS	0.82 m, 3.2 m	4 Bands	SLRB
2008	GeoEye-1	0.46 m, 1.84 m	3 Bands	SLRB
2009	IKONOS	0.82 m, 3.2 m	3 Bands	SLRB
2011	GeoEye-1	0.46 m, 1.84 m	3 Bands	NCRS/KSA
2013	GeoEye-1	0.46 m, 1.84 m	4 Bands	NCRS/KSA
2014	Worldview-3	0.31 m, 1.24 m	8 Bands	AGU
2015	Worldview-2	0.46 m, 1.85 m	8 Bands	UNCW
2017	Worldview-2	0.46 m, 1.85 m	8 Bands	NCRS/KSA
2019	Worldview-3	0.31 m, 1.24 m	8 Bands	AGU
2020	Worldview-3	0.31 m, 1.24 m	8 Bands	AGU

SLRB: Survey & Land Registration Bureau, Kingdom of Bahrain; NCRS/KSA: The National Center for Remote Sensing; AGU: Arabian Gulf University; UNCW: University of North Carolina, Wilmington.

2.3.2. Calculating the area of mangroves

We interpreted and mapped the three discrete patches of mangroves directly into several GIS features polygons for the data captured. We used manual digitizing to delineate the area by tracing the outline of each site based on the tone and texture of the aerial photograph and orthorectified images. The tone was classified into light, medium, and dark. On the other hand, the texture, was categorized into coarse, medium, and fine. Later, mangrove was delineated, based on the combination of characteristic photo tone and texture, digitized and converted into a suitable format utilizing an up-desktop digitizing process for each period (ESRI, 2020). We created a subset of the aerial photographs and imagery datasets by a defined area polygon surrounding the defined Tubli Bay area from the previous studies, and the SLBR maps since 1930, followed by an on-screen digitizing to detect the Bay boundary and mangrove area (Jensen, 1996). We outlined the mangrove area for all the spatial data collected between 1967 and 2020. We digitized two additional classes to categorize the full extent of each study area polygon; non-mangrove and seawater classes The vector representations of mangrove and other cover class regions were digitized at a 1:1000 scale for all features, where the spatial data resolution ranged from <0.46 m to 3.2 m. Checking the dominance of mangrove and sea area was done using topographic maps from Survey and Land Registration Bureau (SLRB), Bahrain, 1:50,000 and 1:10,000. Besides, Bahrain maps, for the period from 1937 to 2016 were used to enhance the depiction results for identificating and digitizing aerial and satellite images. Then, systematic steps were followed to delineate the extent of mangrove areas. First, we identified the study area for each collected spatial data time. Then, the main classes in the study area (mangrove, non-mangrove, and sea) were categorized, followed by digitizing the study area boundary and the different classes, at a fixed mapping scale of 1:2.5 m for all the layers. Tubli Bay area coastline was modeled using the topological structural model rules, which established the segregation of coastal areas from the sea. Additional manipulations using ArcGIS 10.8 and ENVI 5.5 were undertaken to establish the main classes in the study area. A geodatabase for mangrove extent was generated using the digitizing process (Tang et al., 2018). The accuracy of the exact location of the resulting digitized map was maintained using the scanned, georeferenced map of the same period, which was superimposed over the editing base map after the digitization process. The final output files of the above steps consisted of 30 GIS-vector maps. The fifteen boundaries were used to assess the degradation of mangroves since the 1967 (see Table 2). Raster Calculatorin ArcGIS Spatial Analyst was used to calculate the differences between these maps. The final maps of mangrove areas were used to assess and calculate the changes for all years. Spatiotemporally process was applied to calculate the carbon values and estimate the amount of carbon lost due to reclamation activities.

2.3.3. Estimated total carbon stock and potential emission of mangrove habitats (1967–2020)

The estimation of the total carbon present in the mangroves of Tubli Bay was performed using the data obtained from previous studies (Abou Seedo et al., 2017). The average heights and diameter at breast height (DHB) of Ras Sanad's 30 mangrove plots averaged 3.48 m and 35 cm, respectively, by fieldwork. The AGB and BGB were estimated using allometric equations produced by Comley and McGuiness (2005) and Brown (1997). The AGB was estimated as $AGB\ (Kg) = 0.308 \times DBH^{2.11}$($r^2 = 0.97$, $n = 22$, $D_{max} = 35$ cm). The BGB was estimated as $BGB\ (Kg) = 1.28 \times DBH^{1.17}$($r^2 = 0.80$, $n = 14$, $D_{max} = 35$ cm). The AGB and BGB carbon stock was calculated according to Sridang (2008):

$$Aboveground\ C\ stock\ (\text{Mg ha}^{-1}) = OC\% \times AGB$$
$$Belowground\ C\ stock\ (\text{Mg ha}^{-1}) = OC\% \times BGB.$$

The AGB and BGB carbon stock stored in Tubli Bay mangroves were assessed based on GIS and statistical approach for the three delineated sites. Total carbon (unit: Mg) was calculated as mean carbon (unit: ha) * Area. According to Appendix I of the IPCC's special report on land use, land-use change, and forestry, one megagram (Mg) is equal to one tonne (t), and one tonne of Carbon (t C) is equal to 3.67 tonnes of carbon dioxide (t CO_2). The Mg/C was converted into carbon dioxide (CO_2) equivalent using this data. The CO_2 equivalent was calculated from 1967, when the area of mangroves was the highest, to the lowest mangrove area in 2018. The CO_2 emission has been expressed as carbon loss, assuming that CO_2 is emitted when mangrove habitat is reclaimed. The metric tons of carbon units were converted to CO_2 by multiplying the ratio of the molecular weight of carbon dioxide to that of carbon (44/12 = 3.67) (Eggleston et al., 2006). Net emission, as resulted from reclamation of mangroves, can be estimated based on the stock-difference method (Eggleston et al., 2006).

$$\Delta C = \frac{(Ct1 - Ct2)}{(t2 - t1)} \quad \text{(IPCC, 2006)}$$

Table 2
Mangrove area estimation changes over time using different data and methodologies.

Year	Area (ha)	Source	Quantitative			Source/Evidence
			Survey	GIS's Map	Aerial photos/Satellite images	
1967	328	This study		•	•	Photograph Digital Image
1980	150	FAO (2005a)	The method is not specified			
1985 1988	100		•	•	•	Remote Sensing, Landsat 5, 1985
1998	57	This study		•	•	Photograph Digital Image
1991	40	Vreeland (1991).	The method is not specified			Personal communication There is no reference on the date or methods used Cited in: Fisher, P and Spalding, M.D., 1993. Protected areas with mangrove habitat. Draft Report World Conservation Centre, Cambridge, UK. 60pp. There is no reference on the date or methods used. Cited (FAO, 2003)
1992	100	Sheppard, C., Pric Roberts, C. 1992. Sheppard, C., Pric Roberts, C. 1992. Marine Ecology of the Arabian Region: Patterns and Processes in the Extreme Tropical Environment. Academic Press, London UK 359 pp.	The method is not specified			Cited in: Spalding, M.D., Blasco, F. and Field, C.D., eds. 1997. World Mangrove Atlas. The International Society for Mangrove Ecosystems, Okinawa, Japan. 178 pp. Cited (FAO, 2003).
1995	300	Spalding, M.D., Blasco, F. and Field, C.D., eds. 1997. World Mangrove Atlas. The International Society for Mangrove Ecosystems, Okinawa, Japan. 178 pp.		•		Cited (FAO, 2003). Map analysis. Mangrove data are taken from Abbott, 1995, Coral Reefs of Bahrain (Arabian Gulf), an unpublished report, prepared for Reef Base and the World Conservation Monitoring Centre, including sketch-map showing mangroves at 1:350 000. According to the authors, the estimate by (Sheppard et al., 1992) (see above) is likely to be more accurate.
1997	300	Spalding, M.D., Blasco, F. and Field, C.D., eds. 1997.		•		
2000	90	(Sources: (FAO, 2005b): based on the qualitative information)	The method is not specified			
2001	<12	FAO, 2001	The method is not specified			
2002	<12	Abbas (2002)	The method is not specified			
2002		Abido and Saeed	The method is not specified			
2003	50	This study		•	•	Orthophoto: MRSID
2005	90	(Sources: (FAO, 2005b): based on the qualitative information)	The method is not specified			
2005	53	This study		•	•	GeoEye-1
2006	49	MARGIS II., 2006		•	•	
2007	42.04	This study		•	•	IKONOS
2008	46.27	This study		•	•	IKONOS
2009	85	Loughland and Zainal (2009)				
2009	50	SoE_KB, 2009	Method is not specified			
2009	–	Adel AlZayani (2009)				
2009	54	This study		•	•	IKONOS
2009	54	This study		•	•	GeoEye-1
2011		Abido et al. (2011)	•	•	•	
2011	–	Asma and Maha (2011)		•	•	The study concentrated on Tubli Bay only and did not estimate the mangrove area
2011	50	This study		•	•	GeoEye-1

(*continued on next page*)

Table 2 (*continued*).

Year	Area (ha)	Source	Quantitative			Source/Evidence
			Survey	GIS's Map	Aerial photos/Satellite images	
2012	–	Zainal et al. (2012)	–	•	•	
2013	50	This study		•	•	GeoEye-1
2014	–	Naser (2014)	The method is not specified			
2014	50	This study		•	•	Worldview-3
2015	50	This study		•	•	Worldview-2
2016	–	Naser (2016)	The method is not specified			Mangrove at Ras Sanad site
2017	–	Abou Seedo (2017)	•			Mangrove area at Ras Sanad site did not included
2017	48	This study	•	•	•	Worldview-2
2019	48	This study	•	•	•	Worldview-3
2020	48	This study	•	•	•	Worldview-3

Where
ΔC = changes in carbon stock (Mg C yr-1),
Ct1 = carbon stock at time t1 (Mg C)
Ct2 = carbon stock at time (Mg C)
t1 = initial time
t2 = later time

To estimate the change in mangrove coverage, we used the on-screen digitized areal extent of mangroves coverage for each set of images from 1967 to 2020. Additionally, we defined and digitized polygons to represent the remaining Non-mangrove and Sea Water classes within the study area boundaries, (see Table 3). We combined the total coverage of the three sites in hectare squares as an approximation between 1967 and 2020 (see Table 4). We used the area values of those polygon layers of mangroves for the periods (1967–1988, 1988–1998, 1998–2003, and 1967–2020), where there is an evident decline in mangroves extent (see Table 5).

3. Results and discussion

3.1. Mangroves extent: Historical perspective

Table 2 illustrates mangrove extent estimation based on assessment of studies conducted since 1967s. A critical examination of more than 20 studies considered indicated that most of them lack actual data and are primarily based on citation of preceding studies and reports. Hence, changes in mangrove areas were not consistent in consecutive years. Due to Bahrain's limited land availability, government policy has encouraged land reclamation to accommodate development. From of 1967 to 2020, land area increased by almost 116 km^2, from 666 km^2 to 782 km^2, about 18% (SLRB, 2020). Most of the reclaimed land is on the northern built-up portion of Bahrain's main island (Zainal et al., 2009). Hence, Tubli Bay marine area and its mangroves have been reduced since the 1960s due to intensive dredging and reclamation activities (Naser, 2013, 2016). Vousden (1995) projected the mangrove areas in Tubli Bay to be deteriorated due to infill and other perturbations. The author estimated the mangrove areas at 100 ha. Vreeland (1991) estimated the total area of mangrove as 40 ha. In comparision, Sheppard et al. (1992) put it at 100 ha. In the meantime, Spalding et al. (1997) estimated the area as 300 ha. The Environmental Affairs (1996) stated that the Bay area was decreased from 23.5 km^2 in 1956 to 16.1 km^2 in 1996. Hence, the mangrove stands have progressively reduced over the years in around the Bay. AlZayani (1999) reported a steady decline of mangroves since 1975 as 300 ha of mangrove habitats was lost to land reclamation. Several authors reported different figures for mangrove extent reduction in Bahrain. Some reported a loss of 25 ha to less than 1200 ha since the 1970s (Abbas, 2002). Abido and Saeed (2002) affirmed that the mangrove area reduced from 2400 ha in 1956 to less than 1000 ha in 2000, i.e., 58% less. In 2006, mangrove area was estimated to be 0.49 km^2 (49 ha) (MARGIS II, 2006). According to Loughland and Zainal (2009), around 3 km^2 (300 ha) of mangroves between the Adhari and Umm AI Hassam areas were reclaimed in 1975. The authors of the current work estimated the area of mangroves to be around 85 ha; 50 ha was in in the Ras Sanad. In addition, the Bahrain Public Commission for the Protection of Marine Resources, Environment, and Wildlife, confirmed that the total area of mangroves was estimated at 50 ha in 2009 (SoEKB, 2009). Abido et al. (2011) estimated the mangrove plant communities in Tubli Bay during the period of 2005–2010 at 31 ha. Abido et al. (2011) investigated mangrove's stand characteristic; reported mangrove coverage and density at Ras Sanad site at 70% and 1245 tree ha^{-1}, (124,500 tree km^{-2}), whereas the same parameters for the mangroves at the Sitra sites were 63.3% and 1300 tree ha^{-1} (130,000 tree km^{-2}), consecutively, 45% and 959 tree ha^{-1} (95,900 tree km^{-2}), respectively (Abido et al., 2011). Recently, Abou Seedo et al. (2017) indicated that the mean density and basal area of mangrove trees of the Bay were 4576.8 tree ha^{-1} (457680 tree km^{-2}) and 11.4 m^2 ha^{-1} (1140 m^2 km^{-2}), respectively. Abahussain and Al-Sabbaq (2011) revealed that the area of Tubli Bay was decreased from 12.47 ha in 1990 to 1057 ha in 2006. The authors recommended restoring degraded environments and encouraging eco-tourism activities in the Bay. Fig. 3 illustrates the total area of Tubli bay in 1967. The surface geology characteristics of the Bay surrounding area played a significant role in draining water from the palm tree farms to the Bay. The minimal motion of the water represents these characteristics, the muddy nature of the sediment, and input of low salinity water from nearby farms and underground springs, which used to be abundant within and around the area. The springs played a vital role in the stabilization of coastlines by promoting sedimentation (Al Khuzai et al., 2009).

3.2. Tubli Bay shoreline and mangrove habitat area changes

Table 3 defines the main classes used to classify the study area. Table 4 shows the result of the total area for each class across years (in ha) which was used to detect the changes in mangrove coverage class area in the study area.

Tubli Bay was subjected to heavy anthropogenic activities since the 1960s. The bay area was estimated at 2000 ha in 1937. In 1967, the bay area was reduced by about 500 ha. In 2020, almost 50% of the bay was reclaimed, reducing its area to 1044 ha (Table 4). Along with that, we observed significant mangrove loss across all the sites between 1967 and 2020. The primary site (B:

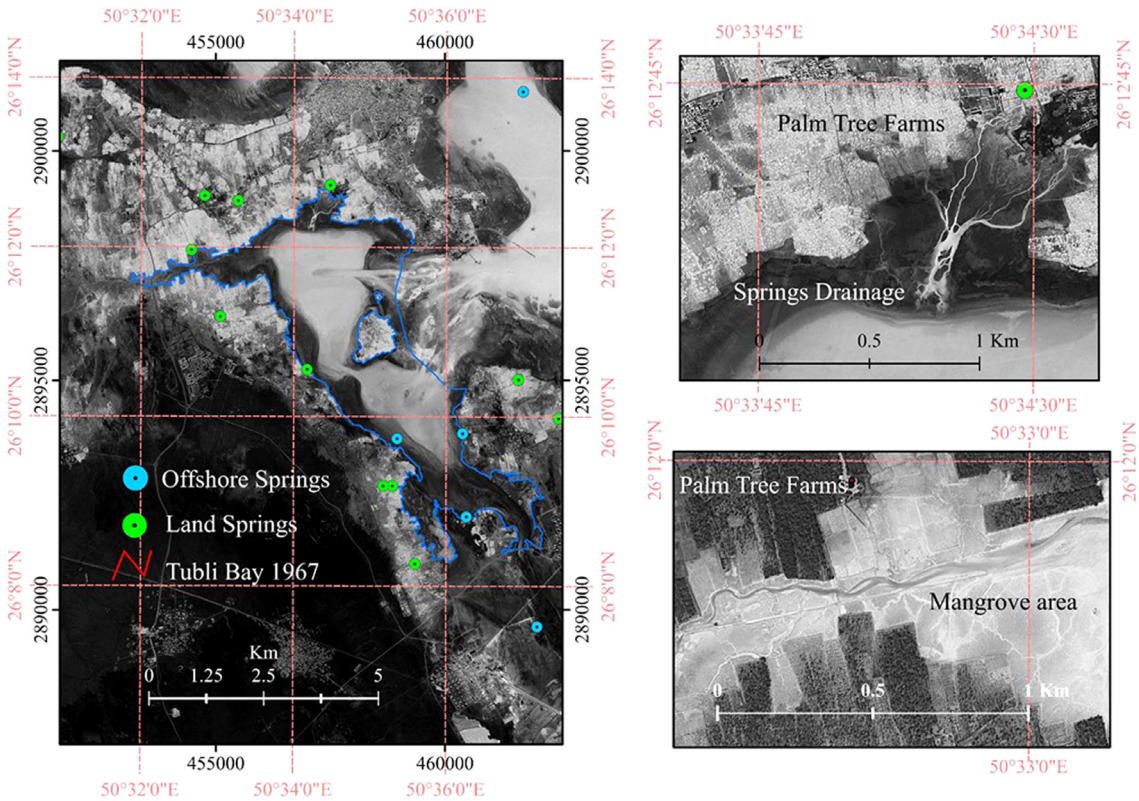

Fig. 3. Tubli Bay location in 1967 surrounded by palm trees farms and lands and offshore springs.

Table 3
Class definition of the study area.

Classes	Definition
Mangrove	Areas covered by open mangrove
Non-mangrove areas	Areas covered by other land use
Seawater	Open water

Table 4
Total area of different classes in the study area derived from aerial photographs and imagery, 1967 2020.

	Total area extent (ha)					
	1967	1998	2005	2009	2017	2020
Mangrove	328	57	53	54	48	48
Non-mangrove	8477	9116	9157	9191	9230	9230
Water body (Bay)	1515	1150	1110	1075	1044	1044
Total study area	10320					
Mangroves % total area	3.2%	0.6%%	0.5%	0.5%	0.48%	

Ras Sanad) maintained half of its mangrove in 2020. Mangrove coverage decreased at all other sites for the entire period which was reviewed (see Fig. 4).

Mangroves area dwidled over the years due to constructing bridges between Manama, the capital, and Sitra Island, to almost 50 ha in size. In 2017, the decrease reached 48 ha. Ras Sanad mangrove coverage decreased by 60% from 1967 to 1998, 96.52 and 38.61 ha, respectively. However the site preserved 40% of the total area of mangrove coverage for 30 years. In 2020, the area decreased to little more than 30 ha. Declaring the site as a protected mangrove was mainly why the site has preserved a distinct mangrove coverage. Sitra island mangrove coverage decreased by nearly 84% between 1967 to 2020 (60.47 and 9.93 ha, respectively). In 2003, the area decreased to less than 7 ha. The mangrove area coverage in Sitra island fluctuated in size over the years and became almost 10 ha in 2020 (Table 5). Mangroves

Table 5
Extent of mangroves (ha) derived from aerial photographs and imagery, 1967 2020, for Tubli Bay, Bahrain.

Study site	Area extent (ha)				
	1967	1998	2003	2017	2020
A: Ras Tubli	170.78	8.96	7.10	4.17	4.17
B: Ras Sanad	96.75	38.91	36.30	33.90	33.90
C: Sitra	60.47	9.12	6.61	9.93	9.93
Total	328	57	50	48	48

coverage decreased at the three sites from 1967 to 2020. Losses ranged from approximately 84% at the C site (≈ -50.54 ha) to 40% at B site, Ras Sanad area (-57.91 ha). Over the last five decades, the total mangroves area declined by 95%, from 328 ha to 48 (see Fig. 5). The remaining mangrove extent is at risk from the ongoing anthropogenic activities. These activities include the continuous land reclamation process and the released residue of sand washing plants, and the continued discharge of secondary treated wastewater into the Bay.

3.3. Potential carbon emission and sequestration (1967–2020)

Table 6 shows the changes for carbon that could be sequestered based on the calculated results. Accordingly, total carbon stored in the mangrove habitat decreased by 85% from 34,932 Mg C ha^{-1} in 1967 to 5,112 Mg C ha^{-1} in 2020 due to mangrove clearance. Therefore, the potential carbon sequestration from 128,200.44 Mg CO_2e ha^{-1} in 1967 to 18,761.04 Mg CO_2e ha^{-1} in 2020, with an average of about 9874.62 Mg CO_2e yr^{-1}, for the last fifty-three years (see Fig. 6). Thus, around 109 Gg CO_2e are estimated to be released due to mangrove loss, equating to 0.3% of Bahrain's total CO_2 emissions in 2015 (Supreme Council for Environment, 2020). Although the amount of emission may seem negligible, the degradation and loss of mangroves in Tubli Bay turned a carbon

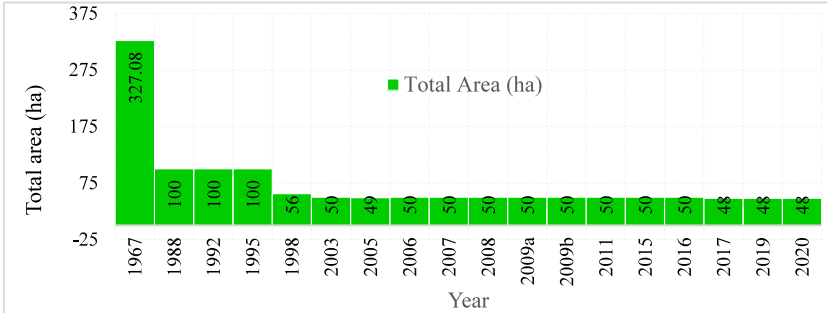

Fig. 4. Decrease in the mangroves area over the last five decades (1967–2020).

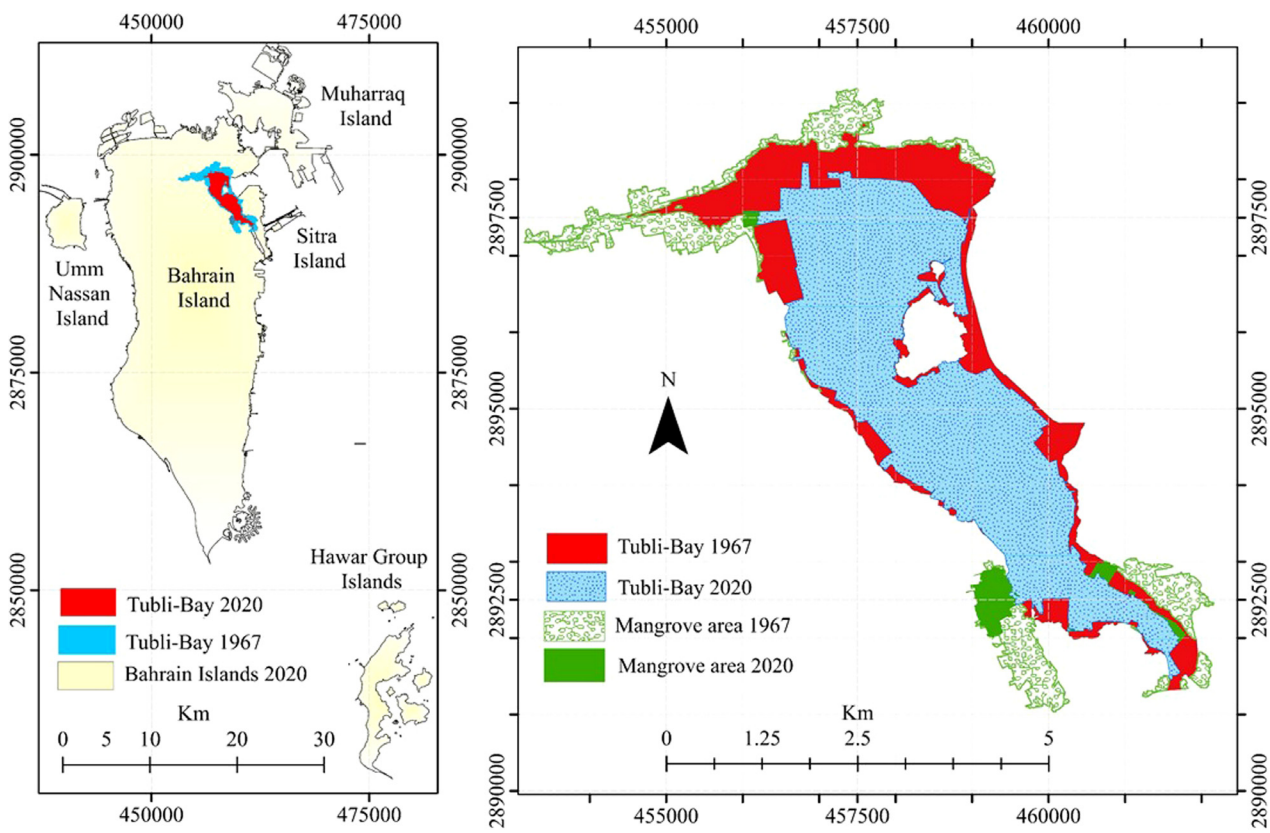

Fig. 5. Tubli Bay and mangrove area changes from 1967 to 2020.

sink into a source of CO_2e. Table 7 summarizes the impact of the mangrove loss in terms of CO_2e by period. These figures are indications of GHGs emissions from mangrove wetland in Bahrain and could lead to further studies and investigation, especially with relations to GHGs emissions and climate change. Undoubtedly, this potential loss limits Bahrain's capacity to cope with its set mitigation measures. In similar conditions, Chatting et al. (2020) estimated total carbon stocks in Qatar mangroves at 45.7 Mg C ha^{-1}, far less than the value (106.5 Mg C ha^{-1} obtained in Bahrain and used in this study. In this respect, the carbon stock of mangroves ecosystems is site-specific. It depends on the method used, latitudes, and site characteristics that influence mangroves' community composition and productivity (Pérez et al., 2018; Atwood et al., 2017; Senger et al., 2021). For instance, the results obtained from Al-Qurm Nature Reserve in Oman (Al-Nadabi and Sulaiman, 2018), coastal Red sea of Saudi Arabia (Almahasheer et al., 2017), and Khor Kalba in UAE (Crooks et al., 2019) of carbon sequestration by mangroves explain the enormous differences obtained and the shortcoming of absolute use of these values. Thus, a comparison of the findings is not possible. However, the total carbon stock of mangrove in Tubli Bay (i.e., 106.5 Mg C ha^{-1}) is within the range reported in other regions (e.g., 45 Mg C ha^{-1} in north-west Australia (Hickey et al., 2018), 60-140 Mg C ha^{-1} in Bonaire, Dutch Caribbean (Senger et al., 2021).

4. Conclusion

The mangrove cover in the Tubli Bay area were reduced substantially over the last fifty years due to reclamation activities. Along with that, the reduction was substantially at the expense of mangrove habitats. Over 95% of mangroves were lost since 1967, equivalent to 29709.6 ton carbon stock, implying that 109,034.23 of potential CO_2 emissions stored has been released since 1967. Mangroves are essential components of the ecological systems of the Bahrain wetland coastal ecosystems. Promoting mangrove ecosystem-based adaptation ensures conservation and management of mangrove biodiversity, contributing to climate change

Table 6
Potential carbon emission and sequestration based on mangrove sediments and tree area (1967–2020).

Year	Total area (ha)	Carbon stock of mangrove trees = Area* (Mg C ha^{-1})	Carbon stock in mangrove's sediments = Area* (Mg C ha^{-1})	Total stock carbon of mangrove's habitat (Mg C)	Potential carbon emission (Mg C) (Total stock carbon of mangrove's habitat *3.67)
1967	328	16,826.40	18,105.60	34,932	128,200.44
1988*	100	5130	5520	10,650	39,085.5
1992	100	5130	5520	10,650	39,085.5
1995	100	5130	5520	10,650	39,085.5
1998	57	2924.1	3146.4	6,070.5	22,278.735
2003	50	2565	2760	5,325	19,542.75
2005	53	2718.9	2925.6	5,644.5	20,715.315
2006	50	2565	2760	5,325	19,542.75
2007	50	2565	2760	5,325	19,542.75
2008	50	2565	2760	5,325	19,542.75
2009a	53	2718.9	2925.6	5,644.5	20,715.315
2009b	54	2770.2	2980.8	5,751	21,106.17
2011	50	2565	2760	5,325	19,542.75
2015	50	2565	2760	5,325	19,542.75
2016	50	2565	2760	5,325	19,542.75
2017	48	2462.4	2760	5,112	18,761.04
2019	48	2462.4	2760	5,112	18,761.04
2020	48	2462.4	2760	5,112	18,761.04

* Vousden, D. (1988). The Bahrain Marine Habitat Survey. Vol. 1. The Technical Report ROPME. Pp 103.

Table 7
Mangrove area, carbon loss, CO_2 emissions, and emission rates (1967–2020).

Year	Area (ha)	Mangrove area loss (ha)	Carbon loss (Mg C)	CO_2 emission (Mg CO_2 yr^{-1})	Rate of CO_2 emission (Mg CO_2 yr^{-1})
1967	328				
1988*	100	228	24282.00	89114.94	4243.57
1998	57	43	4579.50	16806.77	1680.68
2003	50	7	745.50	2735.99	547.20
2017	48	2	102.6	376.542	26.90
2020	48	–	–	–	–
Total		**280**	**29709.60**	**109034.23**	**6498.34**

* Vousden, D. (1988). The Bahrain Marine Habitat Survey. Vol. 1. The Technical Report ROPME. Pp 103.

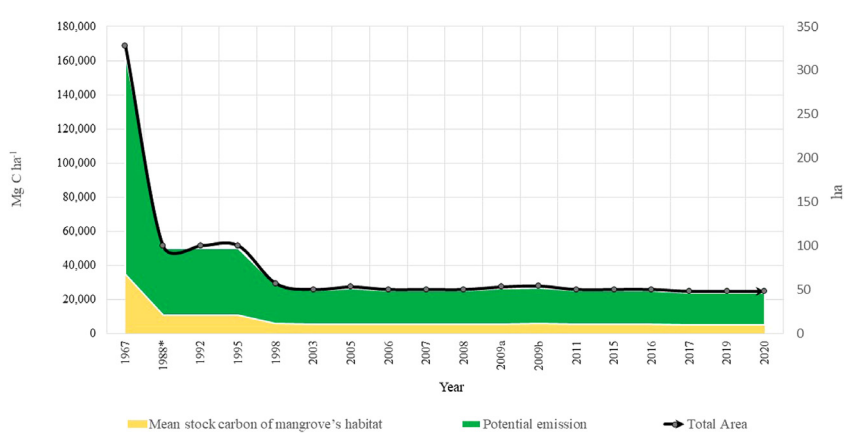

Fig. 6. Mangrove Loss Impacts on Potential Carbon Emission and Sequestration (1967–2020).

adaptation with mitigation co-benefits. In this regard, afforestation and restoration of degraded mangrove areas may improve the role of mangroves in protecting biodiversity and enhance combating the effect of climate change and sea level rise in particular.This study's use of GIS, RS, and allometric equations proved suitable and resonated with conclusions drawn from previous studies. The integration of different methods allowed for identifying the total mangrove area in Tubli Bay and its carbon stock through deskwork, especially where access to mangrove areas is difficult or restricted. The integration of methods also provided a

historical trend of the mangrove area and carbon stock in Tubli Bay. This approach can be applied in other places to calculate the carbon stock and potential emissions released as part of the national CO_2 emissions inventory and mitigation. Furthermore, the current detailed maps of the remnant mangrove areas will help further studies shed light on mangrove ecosystems' contribution to climate change. Moreover, our study emphasizes the need for further attention to the effects of anthropogenic and natural stressors on mangroves in Bahrain. Additional efforts are needed to manage human activities within Tubli Bay to preserve and sustain the remaining mangroves in Ras Sanad.

CRediT authorship contribution statement

Sabah Aljenaid: Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Writing – original draft, Writing – review & editing. **Mohammad Abido:** Conception and design of study, Analysis and/or interpretation of data, Writing – original draft, Writing – review & editing. **Ghadeer Khadeem Redha:** Acquisition of data, Analysis and/or interpretation of data, Writing – original draft. **Manaf AlKhuzaei:** Writing – original draft. **Yvonne Marsan:** Writing – review & editing. **Abdel Qader Khamis:** Writing – review & editing. **Humood Naser:** Writing – original draft. **Mohammad AlRumaidh:** Writing – review & editing. **Maha Alsabbagh:** Writing – review & 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.

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