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Applying an integrated approach to coastal marine habitat mapping in the north-western United Arab Emirates

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ABSTRACT

Habitat mapping is essential for the management and conservation of coastal marine habitats. However, accurate and up-to-date habitat maps are rarely available for the marine realm. In this study, we mapped the coastal marine habitats of >400 km of coastline in the north-western United Arab Emirates (UAE) using a combination of data sources including remote sensing, extensive ground-truthing points, local expert knowledge and existing information. We delineated 17 habitats, including critical habitats for marine biodiversity such as coral reefs and mangroves, and previously unreported oyster beds and deep seagrasses. This innovative approach was able to produce a coastal marine habitat map with an overall accuracy of 77%. The approach allowed for the production of a spatial tool well-suited for the needs of environmental management and conservation in a previously data-deficient area of the United Arab Emirates.

1. Introduction

The coastal environment of the United Arab Emirates (UAE) hosts diverse and valuable habitats despite an extreme environmental setting. Seagrasses, mangroves, coral reefs, oyster beds, saltmarshes and other coastal habitats contribute to support local and regional biodiversity and provide numerous essential ecosystem services such as carbon sequestration, coastal protection, recreation, human well-being and sustainable economic growth (Burt, 2014; Friis and Burt, 2020; Sale et al., 2011; Vaughan et al., 2019). Coastal habitats also support commercially important marine species, which represent the second most valuable natural resource in the UAE after hydrocarbons (van Lavieren et al., 2011). Biological diversity within the UAE's coastal habitats is often higher than in the surrounding terrestrial deserts, and coastal productivity in this part of the Arabian Gulf is six times higher than in offshore ecosystems (Jones et al., 2002).

In recent decades, coastal habitats throughout the UAE have been rapidly degraded due to increasing pressure from natural and anthropogenic stressors (Sale et al., 2011; Sheppard et al., 2010; Burt, 2014). Major human stressors include extensive coastal development, industrial discharge plumes, dredging and fishing (Bauman et al., 2010; Dawoud, 2012; Grandcourt, 2012; Burt, 2014), and natural stressors like extreme thermal events and algal blooms are becoming more frequent and severe (Thangaraja et al., 2007; Burt et al., 2019). As a consequence, coastal habitats have become heavily degraded over the past half-century, including mangroves (Sheppard et al., 2010) seagrasses (Erftemeijer and Shuail, 2012) and corals (Riegl et al., 2018).

Despite the importance of UAE coastal habitats and the magnitude and widespread nature of events affecting them, there is a lack of comprehensive and up to date coastal marine habitat maps. Much of the knowledge of the distribution of coastal marine habitats in the UAE, with the exception of Abu Dhabi waters, is based on maps that are now

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outdated, inaccurate, and largely produced without detailed field surveys and/or built for specific objectives (British Admiralty, 1977, AGEDI, 2013, Grizzle et al., 2016; Moore et al., 2015). This has prevented an adequate assessment of the status, extent and condition of coastal habitats (Grizzle et al., 2016; van Lavieren et al., 2011). There is an urgent need for information on the spatial distribution of coastal marine habitats in the UAE, and this need is reflected as a priority action in the Convention on Biological Diversity (CBD) and the UAE National Biodiversity Action Plan 2014–2020. This information is essential to mitigate threats, to make informed decisions, to protect the UAE's shallow-water coastal areas, and to allow for sensitive habitats to be effectively monitored and managed in terms of their extent and condition (Norse, 2010; Ogden, 2008).

Comprehensive mapping of coastal and marine habitats in the UAE waters of the Arabian Gulf using remote sensing-based techniques is complex and challenging. Reasons include: (1) the water column is often well-mixed and turbid due to high wave action, especially those caused by strong northerly winds, limiting satellite penetration to just a few meters depth (Sheppard et al., 2010; Riegl and Purkis, 2012); (2) some coastal habitats are highly seasonally dynamic (e.g. springtime macro-algal beds) (John, 2012; Roelfsema et al., 2013); and (3) areas where there is a wide variety of substrates and habitats concentrated with the reflectance varying within a small range, i.e. the coastal lagoons ('khors') (Purkis and Riegl, 2005; Purkis, 2005). To overcome the limiting factors for remote sensing approaches and related techniques used for habitat mapping, more focus has recently been directed towards the use of integrative approaches that combine multiple data sources (Brown and Kyttä, 2018; Grizzle et al., 2016; Henriques et al., 2015). A better understanding of the area is also possible through to the integration of local ecological knowledge (LEK), which helps to identify and fill data gaps, to support map production and validation (Aswani and Lauer, 2006b; Baldwin and Oxenford, 2014; Brown and Kyttä, 2018).

To address knowledge gaps, and to provide information for improved conservation and natural resource management in the UAE, this study aimed to develop a comprehensive digital map of the coastal marine habitats of the north-western emirates across the waters of the Arabian Gulf in the UAE. The resulting habitat map serves as a tool for ecosystem management, and as a benchmark to assess future changes in both habitat condition and extent, complementing previous mapping efforts and ecological studies in the UAE waters of the Arabian Gulf (EAD, 2015; Parr et al., 2014). The combination of remote sensing analysis, LEK, recorded species presence as a proxy for habitat distribution, pre-existing georeferenced data and other ancillary information are key components when developing a database to support coastal marine habitat mapping (Lauer and Aswani, 2008; Adamo et al., 2016; Huntington, 2000). The generation of a geodatabase including all this information is a crucial step for scarce data areas and for framing realistic expectations (Teixeira et al., 2013; Martin et al., 2015). This study showcases the value of strong collaboration among stakeholders, including environmental authorities, research institutions, NGOs and the private sector to support the development of the first comprehensive coastal and marine habitat map of the north-western emirates.

2. Materials and methods

2.1. Study area and classification

The study area includes coastal marine habitats along the 400-km Arabian Gulf shoreline of the north-west UAE extending across four Emirates (Ajman, Ras Al Khaimah, Sharjah and Umm Al Quwain) and seaward to the 15-m depth contour, as well as the Sharjah offshore marine protected area (MPA) surrounding Sir Bu Nair Island (Fig. 1). The north-western emirates harbour a unique and complex biodiversity with extensive benthic and coastal habitats such as mangroves, intertidal mudflats, coastal lagoons ('khors'), seagrass beds, coral reefs and macroalgal assemblages. These habitats support abundant wading birds, marine turtles, fishes and invertebrates (Hornby, 1997; Sheppard et al., 2010). Our study area represents the least studied marine system in the UAE with few scientific studies published for this area to date.

The classification scheme for the habitat map broadly followed the levels-based approach set out by Coastal Marine Resources Ecological Classification System (CMRECS, 2010), as applied in previous initiatives in the UAE (EAD, 2015). This classification considered minimum mapping units (MMU) and the presence and status of critical habitats, defined as those habitats that are essential for the conservation of endangered species, and/or that may require special management and protection (i.e. coral reefs, seagrasses, mangroves). We used the habitat classes defined in Table 1 to map the study area.

2.2. Data collected and map production

The coastal marine habitat map presented herein was produced using

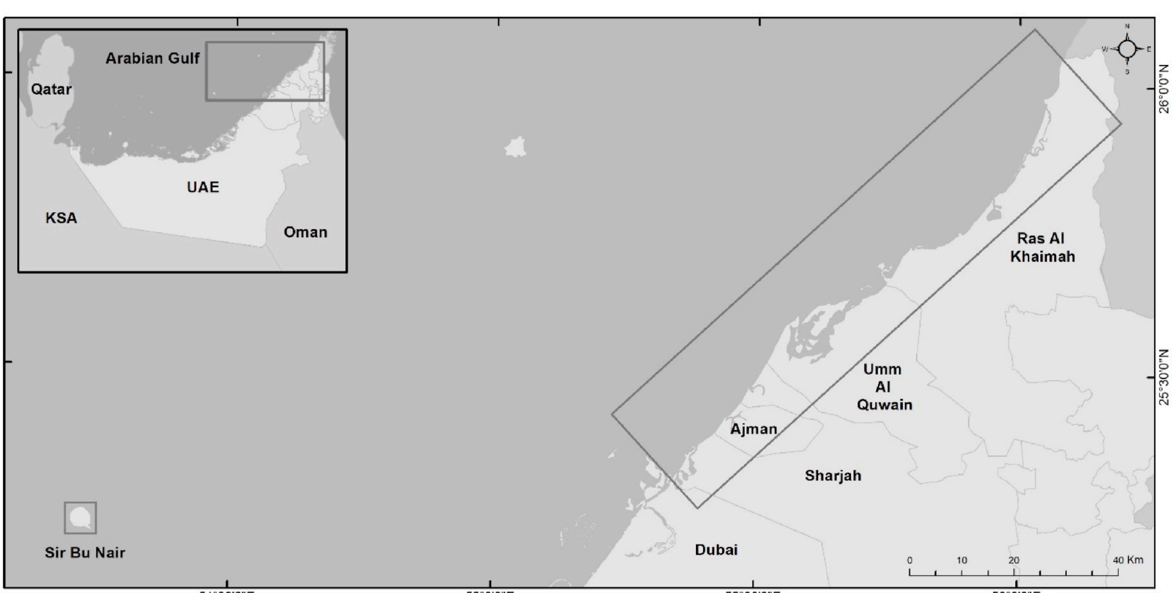

Fig. 1. Location of the study area in the northern UAE coastline and waters of the Arabian Gulf, including the offshore island of Sir Bu Nair (Sharjah).

Table 1
Habitat classes and description used to map coastal marine habitats in the north-western emirates.

Class	Description
Unconsolidated Bottom	All unbound material of varying grain sizes encompassing silt and fine sediments, through to gravels, pebbles, cobbles, and small boulders.
Halophytes	Plants adapted to growing in saline conditions and may be described as saltmarsh in coastal area. The group includes a wide range of plant species including *Arthrocnemum macrostachyum*, *Halocnemon strobilaceum*, *Halopeplis perfoliata*, *Salsola drummondii* and *Suaeda vermiculata*. Often associated with sabkha.
Coastal Sabkha	Low lying hypersaline sand flats subject to periodic flooding and evaporation.
Beach	Pebble or sandy shore, found between the high and low tide watermarks.
Mud Flat	An intertidal habitat normally associated with khors and lagoons, consisting of fine sediments.
Mangrove	Salt tolerant trees represented by a single species, *Avicennia marina*.
Rocky Shore	Intertidal rock platform and rock boulder areas where exposed rock surfaces may be colonised by marine algae, bivalves, and other molluscs, and inhabited by gastropods, crabs, barnacles, and other invertebrates.
Algal Mat	A lower intertidal and nearshore subtidal habitat where high abundances of marine algae colonise unconsolidated fine sediments, primarily in sheltered lagoons.
Seagrass	Represented by three species: *Halodule uninervis*, *Halophila ovalis,* and *Halophila stipulacea*. These plants form beds of varying density in soft sediments in shallow coastal waters, channels, sheltered lagoons and khors. This habitat is highly seasonal in some areas.
Hard-bottom	Sedimentary rock platforms resulting from the deposition of fine sediments and subsequent compression into rock layers – typically extruding limestones, or other carbonate-based formations known regionally as Fasht or Caprock.
Hard-bottom + Macroalgae	Sedimentary rock platforms colonised by marine plants representative of green (Chlorophyta), brown (Phaeophyta), and red (Rhodophyta) macroalgae. Particularly larger brown algae such as *Hormophysa cuneiformis*, *Padina boergesenii*, *Sargassum latifolium* and *Cystoseira trinodis*, providing substantial cover (some of which is highly seasonal).
Hard-bottom + Coral	Sedimentary rock platforms colonised by non-accreting coral communities (poritid and faviid dominated communities). Species include *Dipsastraea favus, Favites pentagona, P. daedalea, Pocillopora damicornis, Porites harrisoni, P. lutea, P. nodifera, Turbinaria mesenterina, Goniopora lobata, and Stylophora pistillata.*
Hard-bottom + Pearl Oysters	In areas of exposed hardground which allow for attachment to the underlying rock platform. *Pinctada radiata* and *P. margaritifera.*
Reef framework	Accumulation of biogenic carbonates due to corals, coralline algae and foraminifera. It refers only to the carbonate reef matrix without living cover association.
Reef + Coral	Accreting coral communities dominated by faviids, poritiids as well as other boulder and encrusting corals for the most part - with the exception of Sir Bu Nair where *Acropora downingi* and *A. pharaonis* were still abundant.
Marine Construction	Human activities such as coastal developments, ports, pipelines etc.
Artificial Reef	Reef Balls and other deployed structures
Dredged Channel	Primarily dredged channels which were readily distinguishable (as opposed to borrow pits)

satellite imagery as the main data source, in combination with three other sources: 1) existing published and unpublished georeferenced information, including existing data on species satellite tracking as a proxy for habitats; 2) local ecological knowledge (LEK); 3) coastal and underwater ground-truthing, supported by aerial drone georeferenced images in specific hard to access areas.

2.2.1. Existing information

An extensive stakeholder engagement allowed us to produce a geodatabase using a compilation of existing data. The geodatabase included information from (i) published articles (e.g. Grizzle et al., 2016) and reports (e.g. Parr et al., 2014), (ii) unpublished reports, (iii) ancillary military maps (e.g. British Admiralty, 1977), (iv) confidential environmental impact assessments shared by the competent authorities only for this purpose, (v) green turtle satellite tracking data from Emirates Nature – WWF project (unpub. data), used as a proxy to guide the allocation of ground truthing effort for seagrass habitat presence (Fig. 2 and Supplementary Table S1). We consolidated all this information using QGIS to highlight complex areas where additional survey effort was allocated (i.e. secondary ground truthing).

2.2.2. Local ecological knowledge

Local experts from universities, environmental authorities, dive centers and the fishing community provided information about habitat distributions through participatory mapping exercises conducted in three workshops as well as individual interviews (Fig. 2 and Supplementary Table S1). We shared an A3 hard-copy map of each Emirate's coastal marine area (scale of 1:150,000) with relevant experts projecting the following information: (i) the satellite image (Sentinel-2), and (ii) pre-existing georeferenced data compiled during previous steps of the study. On these maps, the participants then delineated polygons representing the inputs of their working groups. This information was consolidated in QGIS and it was critical to support the secondary ground-truthing and post-classification improvement.

2.2.3. Ground-truthing

An extensive field survey of the study area was carried out between October 2017 and February 2018. We produced an unsupervised classification using preprocessed Sentinel 2 satellite imagery and K-means Cluster Analysis method. We allocated stratified random sampling points to the habitat classes determined during the unsupervised classification. Secondary manually allocated ground-truthing points were then included in areas of interest determined through screening Google Earth (Digital Globe) images, existing information and LEK collected.

The approach to ground-truthing was influenced by site location and accessibility. We used a georeferenced underwater drop-down video camera system as the primary method. The video camera (Seaviewer HD) was lowered over the side of the field survey vessel and 2–3 min of video georeferenced footage of the seabed was recorded at each of the ground truthing points. For beaches, mangroves, islets or mudflats, we made use of either a kayak, swimmer, car or unmanned aerial vehicles (UAVs) to obtain georeferenced photographs for interpretation. GPS positions were recorded using a hand-held Garmin GPSMap 62 S in line with the resolution of the mapping output, with waypoints made within <5 m of the planned survey points to maintain the overall accuracy of the mapping outputs and to allow high confidence-levels in mapping resolution. We also used the British Admiralty Bathymetry Chart (British Admiralty, 1977) for the Arabian Gulf and Navionics bathymetry map to navigate around the coastal and marine waters, in addition to measuring bathymetry *in situ* to support the remote sensing analysis. We surveyed 305 locations for the purposes of ground truthing the habitat map (Fig. 3).

2.2.4. Satellite data and image processing

Freely available Sentinel-2 imagery (2017) was obtained with the following data specifications; multispectral imagery, 10-m resolution, Level-1C products which have been subject to ortho-rectification, geometric correction and radiometric calibration of top-of-atmosphere (TOA) reflectance. Sentinel-2 high-frequency revisit times allow the user to access its satellite products for regular monitoring and mapping of coastal marine systems (Pahlevan et al., 2019). DubaiSat-2 imagery (2017–2018), was freely provided by Dubai Space Center, with the following specifications; high resolution optical images with 4-m multispectral (red, green, blue and near infra-red (NIR) band resolution. The DubaiSat-2 imagery was used to manually assign the mangrove class,

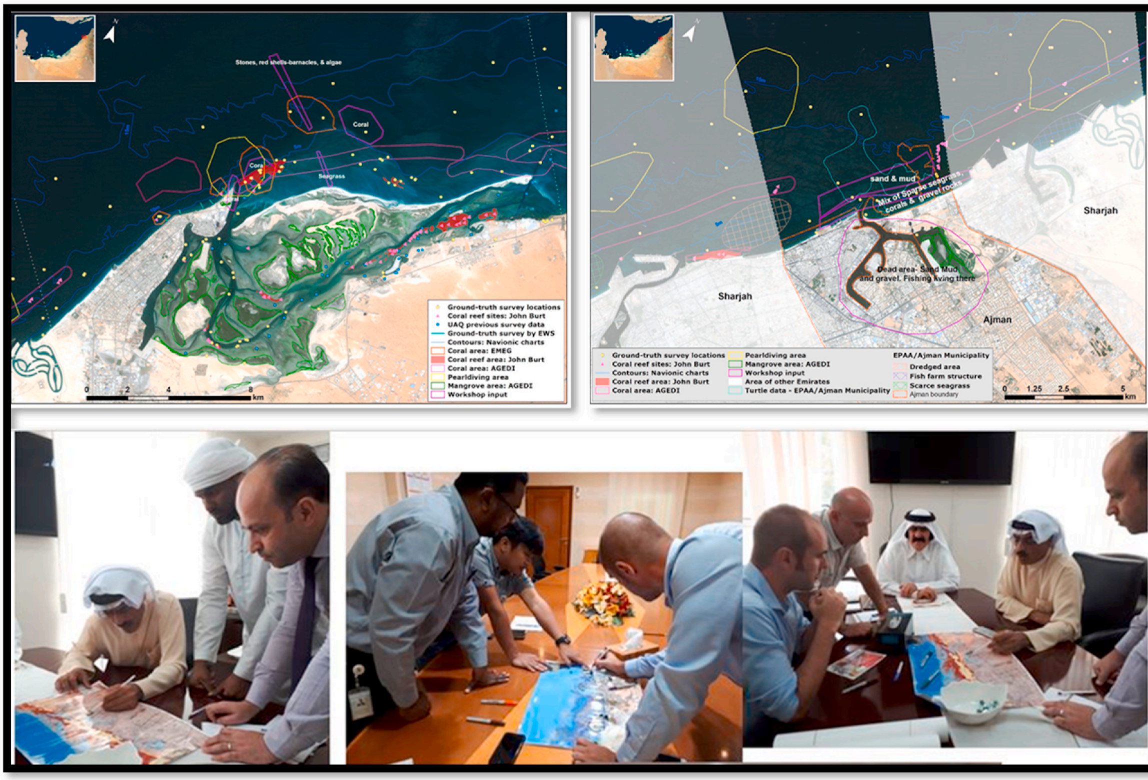

Fig. 2. The geodatabase produced compiles the existing data and local expert knowledge (LEK) in the study area.

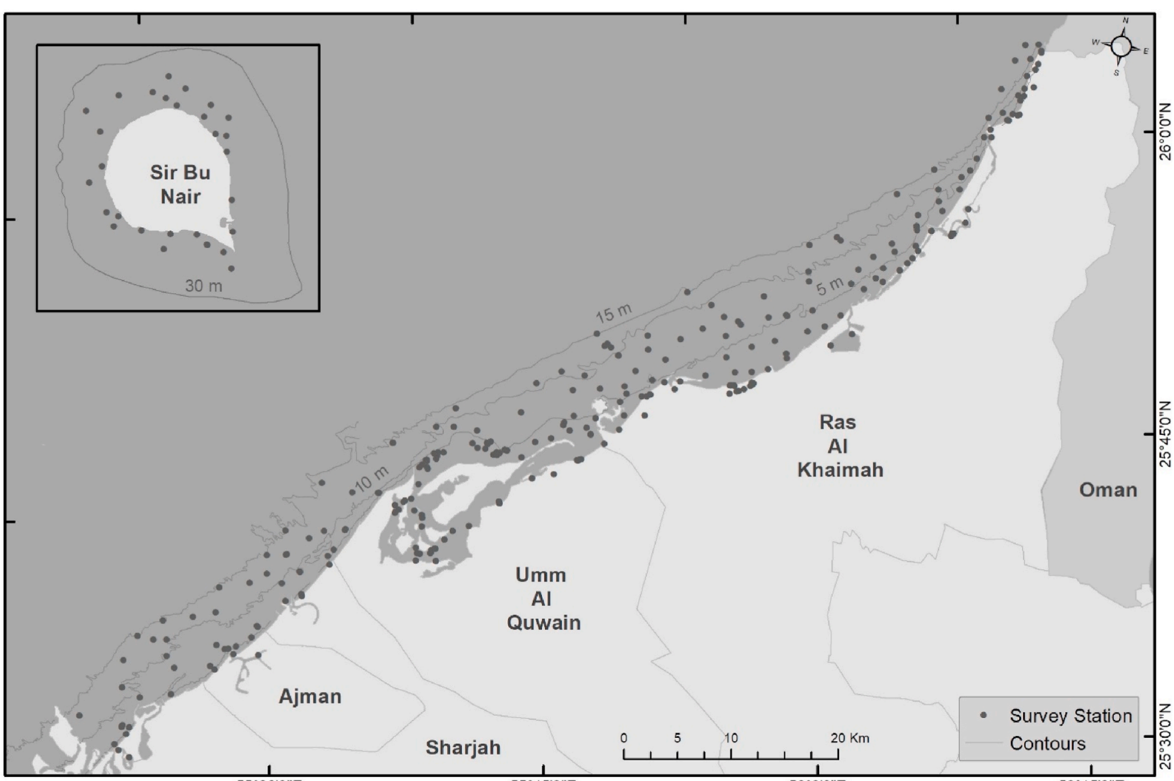

Fig. 3. Location of the survey points and isobaths in the northern emirates, Arabian Gulf, UAE.

and in combination with Google Earth were also used to support the delineation of coastal boundaries, to determine the presence and boundaries of habitats in shallow and intertidal coastal areas, and to detect recent modifications in the coastlines i.e. ports, coastal developments.

The process of selecting imagery focused on images taken between April–June because of the lower frequency of storms in this period (outside of the Shamal season - an Arabic reference to the north winds), which results in greater clarity of the water column and improved light penetration. Four Sentinel images were processed to cover all the study area. The core image processing software applied was The European Space Agency (ESA) Sentinel Application Platform (SNAP), with Sentinel toolboxes and third-party plugins, such as sen2cor and sen2-coral (http://step.esa.int/main/toolboxes/snap/). Sen2cor tool was used for the atmospheric correction and Sen2coral for sun glint and depth invariant index.

2.2.5. Image classification and classifier application

Choosing the best classification technique to generate a classified image depends on the training dataset and the region of its application (Richards, 2013). We evaluated three classification techniques available in SNAP: Maximum Likelihood (ML), Minimum Distance (MD), and Random Forest (RF); and identified the most suitable classification method for this study area. To this end, the Depth Invariant Index bands comprising the image(s) were classified with each supervised classification method using the training signature. The Minimum Distance (MD) approach showed the most accurate results for our study area.

The Minimum Mapping Unit (MMU), or size of the smallest feature which can be reliably mapped using the applied imagery, was based on 10×10 m resolution Sentinel-2 imagery, giving an MMU size of 100 m^2. Manually assigned polygons and features were in line with the MMU.

2.2.6. Post-classification improvement

Initial results of the map production process exhibited a speckled appearance in some areas due to small clusters of pixels. Results were smoothed by post-classification filtering of classified imagery. We changed the values of isolated pixels or enclosing pixel groups with an iterative process that involved filters and local expert inputs. We resolved incorrectly classified areas using knowledge-based image analysis. This is the most commonly used approach for integrating information from experts (Richards, 2013). Knowledge-based classification improved the process of discrepancy detection during the automated modelling technique, and it was especially useful for benthic habitats that had less ground-truthing information and more noise due to water turbidity. The existing information and LEK collected in earlier stages of the study were used at this stage to enhance the final composite classified habitat map.

2.2.7. Accuracy assessment

We applied a Confusion Matrix (CM) to calculate the associated overall accuracy and kappa coefficient. The overall accuracy is the percentage of the sum of all the correct classifications across the total number of validation data points. The kappa coefficient represents the proportion of correctly classified validation pixels after random agreement is removed. The mapping accuracy of the resulting classification was assessed using user's, producer's and overall accuracy approach (Congalton, 1991). One-third of the ground-truthing data, which included field survey data collected by the project, as well as other pre-existing sources of ground-truthing data provided by key stakeholders, was used for the accuracy assessment. The matrix highlights the classification accuracy for each habitat, represented as the percentage of correctly classified validation pixels per habitat. Also, the percentage of incorrect classifications and where the confusion lay in each case were shown.

3. Results

3.1. Classified coastal marine habitats

This study mapped the distribution of 17 different coastal marine habitats in the north-western emirates. Overall, we mapped 782.3 km^2 along a 400 km stretch of coastline covering intertidal and subtidal habitats down to 15 m depth (Fig. 4, Table 2).

The largest habitat class represented in the habitat map is 'Unconsolidated bottom', which covers 547 km^2, and represents 70% of the mapped area. Other habitat classes with relatively low biodiversity (if we compare them against the critical habitat classes) include 'Hard-bottom', 'Dredged channels' and 'Marine Construction' which cover 14% of the study area. Given the total area covered by these classes, only a relatively small area (<10% of the study area) support critical habitats.

Sharjah and Ajman emirates harbour 80% of the total extent of 'Hard-bottom with oyster beds' habitat in the study area. Two large and continuous offshore oyster beds cover together 10 km^2, and four coastal oyster beds cover 6 km^2. The south area also includes the Al Zoura MPA, in Ajman, which has an important mangrove area of 0.89 km^2. Corals are abundant in the MPA Sir Bu Nair island, as this offshore island hosts 4.1 km^2 of 'Coral reef'' habitat and 2.4 km^2 of 'Hard-bottom with coral' habitat. This is the largest extent of 'Coral reef' habitat, as it occupies 86% of the total in the study area.

In the north, Umm Al Quwain (UAQ) and Ras Al Khaimah (RAK) contain a wide variety of habitats, including 'Coral reefs', 'Mangroves', 'Seagrass', 'Algal mats' and 'Sabkha'. The last three habitats only exist in these emirates across the study area, and 'Coral reef' habitats form two large patches that account for 14% of all the coral reef habitat in the study area. All five habitats are concentrated within and around five coastal lagoons (locally known as 'Khors'): Khor Muzahmi, Khor Ras al Khaimah, Khor Julfar and Khor Hulaylah in RAK emirate and Khor Beidah in UAQ. Seagrass beds in the north area grow in extreme conditions, at depths between 0 and 2 m. They colonise mudflats and tolerate being completely exposed to the sun at low tide. They also form sparse seagrass beds at their deeper distribution (7–10 m).

3.2. Accuracy assessment

The classified map showed 17 classes, of which 12 are represented within the accuracy assessment. The assessment included 327 independent ground-truth data points. We excluded those classes not subject to accuracy assessment based on (i) areas outside of the mapping unit (Land and Deep-Subtidal), and (ii) those which were manually digitised using high-resolution imagery or represented by only a small number of ground-truthing points (Artificial Reef, Dredged Area, Marine Construction). Overall accuracy was moderately high (OA = 0.77), with a high Kappa value of 0.70 representing a robust overall classification at the scale and resolution of the mapping undertaken (Table 3). The User's Accuracy (UA) and Producer's Accuracy (PA) values were high for most classes (maximum values of UÃ0.95 and PÃ0.88), with widespread classifications of 'Hard-bottom' and 'Hard-bottom with coral' habitats well represented in terms of sample size and overall accuracy. 'Reef' and 'Reef with coral' habitat classes were less well-represented in terms of the number of sample points, and the accuracy was lower in both instances (UA was 0.33, and PA was 0.5). 'Reef' classes were absent in most emirates, with only a small area present in Umm Al Quwain.

4. Discussion

The limitations of remote sensing on coastal and marine mapping can result in low accuracy of mapping outputs. Our study overcame these limitations by combining remote sensing and extensive ground-truthing field surveys with other sources of information such as LEKs and well-known species distributions. The amalgamation of multiple data sources not only supports an accurate and novel coastal and marine habitat

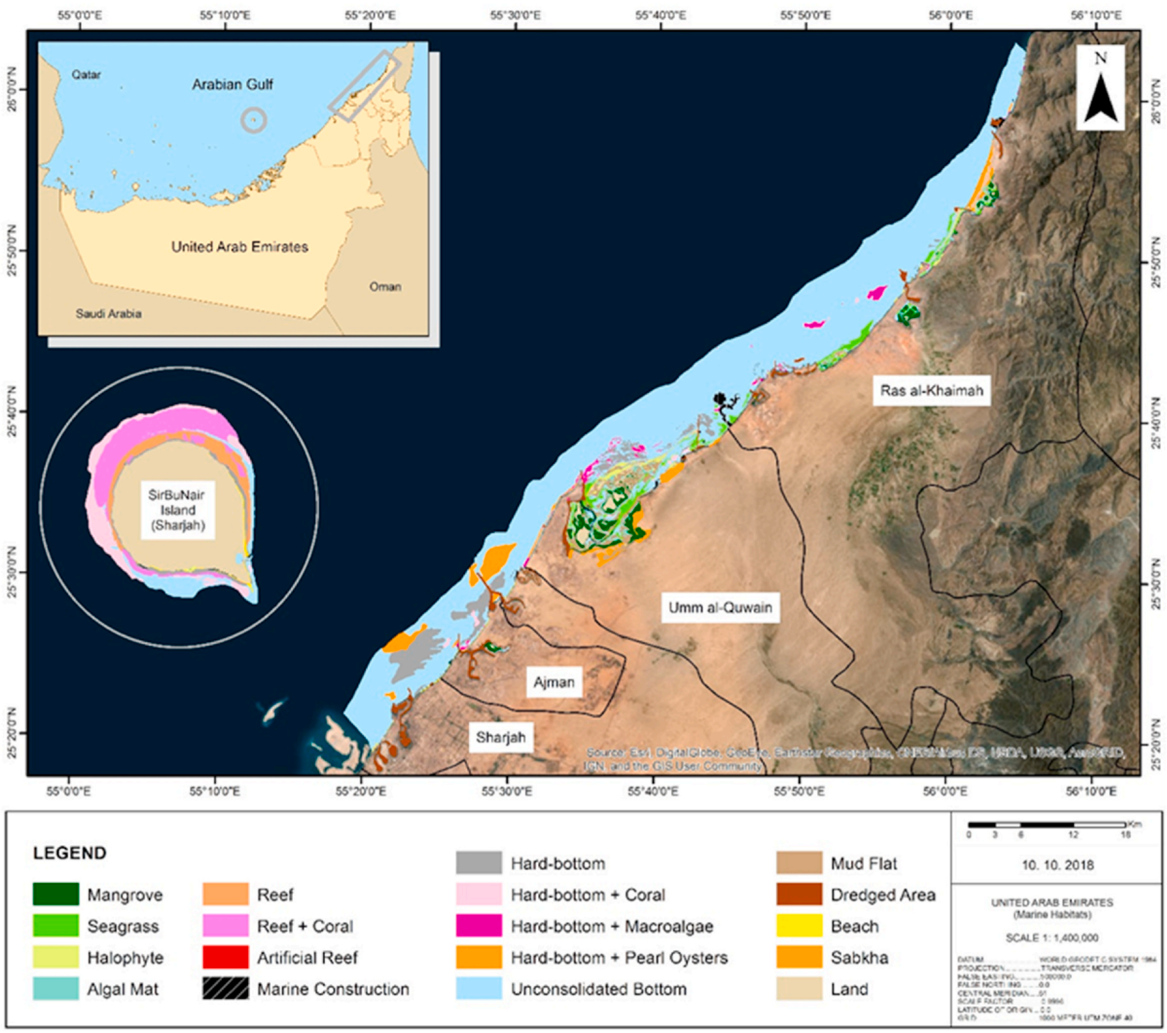

Fig. 4. Coastal Marine habitat map for the north-western emirates, UAE, 2019.

map (Bridle et al., 2013), but also provides substantial data to support a more detailed classification (i.e. the biotic component of the habitat classification). This type of classification offers a better understanding of the status of vulnerable ecological communities, such as corals, and can inform decision-makers with regards to habitat status, ultimately providing a basis for marine spatial planning.

This integrative approach produced a comprehensive digital map representing the distribution of 17 distinct coastal marine habitats in the north-western emirates. The accurate spatial distribution of those habitats is of great value to the UAE, allowing for the condition and extent of key areas to be better understood and monitored and managed further.

This study highlights the rich habitat diversity in the "Khors", local wetlands consisting of an interconnected 'mosaic' of different intertidal and subtidal habitats such as mangroves, seagrasses, mudflats, coral reefs, algal mats. Previous studies report the crucial ecological role of Khors such as breeding areas for the regionally endemic Socotra cormorant in UAQ (Muzaffar et al., 2017), as foraging ground for regionally vulnerable green turtles in UAQ and RAK (Pilcher et al., 2019) and harbouring extremely thermally-tolerant coral communities (Smith et al., 2017). Maintaining seascape connectivity between different habitat types is one of the key considerations to support resilient ecosystems (Mumby and Hastings, 2008), and these rich lagoons can offer a focus for future conservation actions. Additional studies to further characterise the spatial use of the 'Khors' by species, including commercial fishes, would complement our knowledge of the ecological importance of these sites.

Other habitats were also mapped by this project for the first time. This is the case with oyster beds and large areas of coral reefs, which are home and nursery ground for many species (Stunz et al., 2010), including commercially important fish and invertebrates (Grabowski et al., 2012); both habitats improve water quality (Newell, 2004), contribute to shoreline stabilisation, and buffer land from storms and Shamal events (Meyer et al., 1997). The extent, location, and condition of both oyster beds and coral reefs in the UAE have been greatly modified from the past due to multiple human and natural stressors. These ecosystems were previously known to cover extensive areas (Somer, 2003; Grizzle et al., 2016), but their current extent and distribution in the northwestern UAE was unknown before this study. Thus, although there is no quantitative data available on the loss of oyster beds and coral reefs in the study area, which prevents planning for effective trend-related conservation measures, future changes in the distribution of these ecosystems will be possible to detect using this map as baseline.

The overall mapping accuracy of 77% obtained is enough to confidently produce a habitat map for the study area. The accuracy assessments for seagrass habitat was approximately 65%, which is relatively high for such a seasonal habitat that also represents a challenge due to its occurrence in deeper waters (>7 m) and in mixed intertidal habitat. The misclassification of this habitat can be expected due to the inherent similarity between seagrass and fleshy macroalgae in spectral terms, as well as the presence of sparse (low density) seagrass meadows. The combination of all the data sources, and especially green turtle satellite tracking data, was critical to help identify sparse seagrass in RAK's deep

Table 2
Areas (in km^2) covered by different coastal marine habitats in the study area. "North-western emirates" refers to the entire study area from Sharjah to Ras Al Khaimah, whereas "Sharjah", "Ajman", "Umm Al Quwain" and "Ras Al Khaimah" refer to each emirate in detail, located throughout the study area (cf. Fig. 1).

Habitat (km^2)	North-western Emirates	Sharjah	Ajman	Umm Al Quwain (UAQ)	Ras Al Khaimah (RAK)
Unconsolidated Bottom	547.14	71.15	39.77	148.19	294.15
Hard-bottom	42.44	13.38	17.38	10.50	1.17
Dredged Area	27.26	13.64	4.44	4.46	6.70
Mud Flat	23.29	–	0.06	21.44	1.79
Seagrass	21.57	–	–	11.10	10.47
Hard-bottom + Oysters bed	20.00	13.77	3.53	2.50	0.20
Mangrove	19.73	–	0.89	14.17	4.67
Coastal Sabkha	13.67	–	–	9.51	4.16
Hard-bottom + Macroalgae	8.18	0.03	0.50	3.43	4.22
Halophyte	6.95	0.05	–	5.63	1.27
Marine Construction	5.45	8.98	0.10	0.59	4.39
Algal Mat	5.16	–	–	4.82	0.34
Hard-bottom + Coral	5.03	2.37	1.16	1.21	0.30
Reef + Coral	4.79	4.10	–	0.62	0.06
Reef framework	3.56	1.78	–	–	–
Beach	1.57	0.8	0.38	0.11	0.35
Artificial Reef	0.03	–	–	–	0.03
TOTAL AREA (km^2)	755.8	71.15	39.77	148.19	294.15

Table 3
Accuracy assessment statistical summary using independent ground-truthing data for the Northern Emirates.

Class	User's Accuracy (UA)	Producer's Accuracy (PA)
Halophytes	1	0.64
Mud flat	0.71	0.56
Mangrove	0.63	1
Algal Mat	0.89	0.89
Unconsolidated bottom	0.84	0.88
Seagrass	0.64	0.67
Hard-bottom	0.60	0.71
Hard-bottom + Macroalgae	0.57	0.62
Hard-bottom + Coral	0.81	0.85
Hard-bottom + Pearl Oysters	0.95	0.88
Reef	0.33	0.50
Reef + Coral	0.50	0.47
Overall Accuracy	**0.77**	
Kappa	**0.70**	

waters which have low detection by remote sensing methods. The accuracy assessment for 'Reef with coral' was 50% due to two main aspects, the low coral cover found along the coast (except Sir Bu Nair island) and limited number of areas with presence of this habitat. Both aspects made difficult the detection of this habitat as well as the accuracy assessment. The combination of recent coral reef studies with the extensive groundtruthing was essential to partially overcome this challenge. This medium accuracy obtained opens room for further study and development of additional complementary methods. It is evident that such considerations may have caused coral area to be overestimated in previous studies in this region (Parr et al., 2014).

4.1. Management considerations

Cost-effective coastal and marine habitat mapping techniques are required to provide scientific support for the implementation of adequate conservation policies (Baker and Harris, 2020; Bunce et al., 2013). The presence of rich, yet vulnerable, coastal and marine habitats in the northern Emirates, in the context of the continuous expansion of coastal development in the UAE and the region, points to the need to address direct pressures to avoid further biodiversity loss and degradation and ultimately loss of the UAE's natural capital. Habitat inventories offer the foundation for science-based decision making relevant to spatial management, planning and conservation action that can ultimately be integrated into national and emirate-level regulatory frameworks, policies and plans. Spatial management tools ranging from Environmental and Social Impact Assessments (ESIAs) and Environmental Management Plans (EMPs) can help mitigate environmental impacts generated by both single and multiple development projects. The emirate of Abu Dhabi has published Technical Guidance Documents for project proponents and developers introducing the concept of a mitigation hierarchy (Al Dhaheri et al., 2017) including specific advice on the range of issues ESIAs should consider. ESIAs and EMPs also need to be integrated into larger scale, broader policies and plans that assess cumulative impacts on marine ecosystems and associated ecosystem services. Marine spatial planning (MSP) and Strategic Environmental Impact Assessments (SEAs) are increasingly acknowledged as effective area-based management tools that can guide policy development and balanced decision making addressing cross-sectoral integration and management in the marine realm. MSP has also been recognised as a practical approach towards implementing ecosystem-based management (Ehler and Douvere, 2007; Douvere, 2008) which offers a holistic framework for long-term sustainability that is linked with the resilience of marine ecosystems and the services they provide (McLeod and Leslie, 2009; Katsanevakis et al., 2011). Building from existing global (IIED and UNEP-WCMC, 2017) and local (Al Dhaheri et al., 2017) guidelines to support mainstreaming of biodiversity in decisionmaking, the results of habitat mapping, such as that accomplished here, provide a critical step towards strengthening or launching spatial planning processes at an emirate and federal level.

Habitat maps are increasingly recognised as tools that can support ecosystem-based management (EBM) (Cogan et al., 2009; Andersen et al., 2018; Elliott et al., 2018), including an Ecosystem Approach (EA) to fisheries management (Garcia, 2010; Trochta et al., 2018; Lidström and Johnson, 2019), moving away from single species stock management towards understanding the interaction of fisheries and ecosystems. The EA for fisheries management emphasises the need to ensure ecosystem functioning, through habitat protection and/or management, rather than the target species being the management priority (Jennings et al., 2014). Habitat maps can be used to identify suitable habitats for commercially important species, especially by using species distribution models (e.g. Costa et al., 2014; Le Pape et al., 2014; Laman et al., 2018). As many fish species depend on specific habitats throughout their life cycle, identifying and conserving these essential habitats can be integrated into wider fisheries management plans and policies (Moore et al., 2016; Levin et al., 2018). Such ecosystem-based management approaches are still at the developmental stages in much of the Gulf (e.g. Burt et al., 2017; Burt et al., 2016), but habitat maps such as those produced in this study, are a critical first step towards their development.

Habitat mapping can inform the process of planning and implementing MPA networks, by ensuring the representativeness of the habitat included within their limits (Lamine et al., 2020; Hogg et al., 2018; Abdulla et al., 2009; Stevens and Connolly, 2005), detecting vulnerable or threatened species and habitats to be protected (Copeland et al., 2013; Ferrari et al., 2018), identifying essential habitats for target fishes and other key species (e.g. spawning aggregations, recruitment sites, etc.) (Grüss et al., 2019; Le Pape et al., 2014; Schmiing et al., 2017), establishing the conservation status of habitats (Loerzel et al., 2017), mapping human uses (Levine and Feinholz, 2015; St. Martin and Olson, 2017), guiding monitoring plans (Lacharité and Brown, 2019), etc. Accurate habitat maps are considered essential for the correct management of existing MPAs in our study area, which currently includes just three MPAs (Sir Bu Nair island in Sharjah, Al Zoura MPA in Ajman and Khor Muzambi in Ras Al Khaimah), as well as the designation of new MPAs or management actions targeting areas such as Khors (e.g. Khor Al Beidah). In addition, the utility of LEK to assist in MPA planning integrated with science-based approaches (Aswani and Lauer, 2006a, 2006b; Ban et al., 2009; Colpron et al., 2010; Jones et al., 2016; Jørgensbye and Wegeberg, 2018; Teixeira et al., 2013) has been demonstrated as an optimal way to launch participative governance schemes at the very beginning of the MPA process, which encourages local support for conservation initiatives in the long term (Bennett et al., 2019).

5. Conclusions

In summary, we showed the appropriateness of a novel approach to mapping marine habitats using information a variety of different data sources, and combining the use of remote sensing, pre-existing georeferenced habitat data, LEK, species records as proxies for the distribution of their habitats, and other ancillary information. To illustrate such an approach, we have mapped the spatial distribution of coastal marine habitats in the northern emirates of the Arabian Gulf, overcoming the limitation of turbid waters and habitat seasonality. The resulting maps revealed the spatial distribution of critical habitats with an overall accuracy of 77%. This result provides a robust baseline of information to monitor, preserve and manage those habitats, and potentially forms the basis for more detailed marine spatial planning. This habitat map and cost-efficient approach should contribute to support decision making in the study area, facilitate the replication of this habitat map to monitor changes over time, and support any future conservation and management initiatives to be taken by the competent authorities.

CRediT authorship contribution statement

Daniel Mateos-Molina: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Funding acquisition, Writing - original draft. **Marina Antonopoulou:** Conceptualization, Methodology, Funding acquisition, Investigation, Writing - review & editing. **Rob Baldwin:** Conceptualization, Supervision, Writing - review & editing. **Ivonne Bejarano:** Investigation, Validation, Writing - review & editing. **John A. Burt:** Validation, Writing - review & editing. **Jose A. García-Charton:** Supervision, Validation, Writing - review & editing. **Saif M. Al-Ghais:** Resources, Validation, Writing - review & editing. **Jayanthi Walgamage:** Data curation, Formal analysis, Investigation, Methodology, Writing - review & editing. **Oliver J.S. Taylor:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, 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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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.marenvres.2020.105095.

References

Abdulla, A., Gomei, M., Hyrenbach, D., Notarbartolo-di-Sciara, G., Agardy, T., 2009. Challenges facing a network of representative marine protected areas in the Mediterranean: prioritizing the protection of underrepresented habitats. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 66, 22–28. https://doi.org/10.1093/icesjms/fsn164.

Adamo, M., Tarantino, C., Tomaselli, V., Veronico, G., Nagendra, H., Blonda, P., 2016. Habitat mapping of coastal wetlands using expert knowledge and Earth observation data. J. Appl. Ecol. 53, 1521–1532. https://doi.org/10.1111/1365-2664.12695.

British Admiralty, 1977. Admiralty Chart of the Persian Gulf, Sheet No. 2847, Scale 1: 750,000. British Admirably, London.

AGEDI, 2013. Final technical report local, national, regional biodiversity rapid assessment. In: Report: MU000945_F11_01_01. Abu Dhabi: Local, National, and Regional Climate Change Programme, Abu Dhabi Global Environmental Data Initiative (AGEDI). www.agedi.org.

Al Dhaheri, S., Javed, S., Alzahlawi, N., Binkulaib, R., Cowie, W., Grandcourt, E., Kabshawi, M., 2017. Abu Dhabi Emirate Habitat Classification and Protection Guideline. Environment Agency Abu-Dhabi. Environment Agency–Abu Dhabi (EAD).

Andersen, J.H., Manca, E., Agnesi, S., Al-Hamdani, Z., Lillis, H., Mo, G., Populus, J., Reker, J., Tunesi, L., Vasquez, M., 2018. European broad-scale seabed habitat maps support implementation of ecosystem-based management. Open J. Ecol. 8, 86–103. https://doi.org/10.4236/oje.2018.82007.

Aswani, S., Lauer, M., 2006a. Benthic mapping using local aerial photo interpretation and resident taxa inventories for designing marine protected areas. Environ. Conserv. 33, 263–273. https://doi.org/10.1017/S0376892906003183.

Aswani, S., Lauer, M., 2006b. Incorporating fishermen's local knowledge and behavior into Geographical Information Systems (GIS) for designing marine protected areas in Oceania. Hum. Organ. 65, 81–102. https://doi.org/10.17730/humo.65.1.4y2q0vhe4l30n0uj.

Baker, E.K., Harris, P.T., 2020. Habitat mapping and marine management. In: Harris, P. T., Baker, E.K. (Eds.), Seafloor Geomorphology as Benthic Habitat: GeoHab Atlas of Seafloor Geomorphic Features and Benthic Habitats, second ed., pp. 17–33. https://doi.org/10.1016/B978-0-12-814960-7.00002-6.

Baldwin, K., Oxenford, H.A., 2014. A participatory approach to marine habitat mapping in the Grenadine islands. Coast. Manag. 42 (1), 36–58. https://doi.org/10.1080/08920753.2013.863725.

Ban, N.C., Picard, C.R., Vincent, A.C.J., 2009. Comparing and integrating community-based and science-based approaches to prioritizing marine areas for protection. Conserv. Biol. 23, 899–910. https://doi.org/10.1111/j.1523-1739.2009.01185.x.

Bauman, A.G., Burt, J.A., Feary, D.A., Marquis, E., Usseglio, P., 2010. Tropical harmful algal blooms: an emerging threat to coral reef communities? Mar. Pollut. Bull. 60 (11), 2117–2122. https://doi.org/10.1016/j.marpolbul.2010.08.015.

Bennett, N.J., Di Franco, A., Calò, A., Nethery, E., Niccolini, F., Milazzo, M., Guidetti, P., 2019. Local support for conservation is associated with perceptions of good governance, social impacts, and ecological effectiveness. Conserv. Lett., e12640 https://doi.org/10.1111/conl.12640, 2019.

Bridle, H., Vrieling, A., Cardillo, M., Araya, Y., Hinojosa, L., 2013. Preparing for an interdisciplinary future: a perspective from early-career researchers. Futures 53, 22–32. https://doi.org/10.1016/j.futures.2013.09.003.

Brown, G., Kyttä, M., 2018. Key issues and priorities in participatory mapping: toward integration or increased specialization? Appl. Geogr. 95 (June), 1–8. https://doi.org/10.1016/j.apgeog.2018.04.002.

Bunce, R.G., Bogers, M.M., Evans, D., Halada, L., Jongman, R.H., Mucher, C.A., Bauch, B., De Blust, G., Parr, T.W., Olsvig-Whittaker, L., 2013 Oct 1. The significance of habitats as indicators of biodiversity and their links to species. Ecol. Indicat. 33, 19–25. https://doi.org/10.1016/j.ecolind.2012.07.014.

Burt, J.A., 2014. The environmental costs of coastal urbanization in the Arabian Gulf. City 18 (6), 760–770. https://doi.org/10.1080/13604813.2014.962889.

Burt, J.A., Coles, S., van Lavieren, H., Taylor, O., Looker, E., Samimi-Namin, K., 2016. Oman's coral reefs: a unique ecosystem challenged by natural and man-related stresses and in need of conservation. Mar. Pollut. Bull. 105, 498–506. https://doi.org/10.1016/j.marpolbul.2015.11.010.

Burt, J.A., Ben-Hamadou, R., Abdel-Moati, M.A.R., Fanning, L., Kaitibie, S., Al-Jamali, F., Range, P., Saeed, S., Warren, C.S., 2017. Improving management of future coastal development in Qatar through ecosystem-based management approaches. Ocean Coast Manag. 148, 171–181. https://doi.org/10.1016/j.ocecoaman.2017.08.006.

Burt, J.A., Paparella, F., Al-Mansoori, N., Al-Mansoori, A., Al-Jailani, H., 2019. Causes and consequences of the 2017 coral bleaching event in the southern Persian/Arabian Gulf. Coral Reefs 38, 567–589. https://doi.org/10.1007/s00338-019-01767-y.

Cmrecs, 2010. Prepared by Applied Science Associates, Prepared for EAD.

Cogan, C.B., Todd, B.J., Lawton, P., Noji, T.T., 2009. The role of marine habitat mapping in ecosystem-based management. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 66, 2033–2042. https://doi.org/10.1093/icesjms/fsp214.

Colpron, E., Edinger, E., Neis, B., 2010. Mapping the Distribution of Corals in the Northern Gulf of St. Lawrence Using Scientific and Local Ecological Knowledge. Canadian Science Advisory Secretariat.

Congalton, R.G., 1991. A review of assessing the accuracy of classifications of remotely sensed data. Remote Sens. Environ. 37 (1), 35–46. https://doi.org/10.1016/0034-4257(91)90048-B.

Copeland, A., Edinger, E., Devillers, R., Bell, T., LeBlanc, P., Wroblewski, J., 2013. Marine habitat mapping in support of Marine Protected Area management in a subarctic fjord: Gilbert Bay,Labrador, Canada. J. Coast Conserv. 17, 225–237. https://doi.org/10.1007/s11852-011-0172-1.

Costa, B., Taylor, J.C., Kracker, L., Battista, T., Pittman, S.P.J., 2014. Mapping reef fish and the seascape: using acoustics and spatial modeling to guide coastal management. PloS One 9 (1), e85555. https://doi.org/10.1371/journal.pone.0085555.

Dawoud, M.A., 2012. Environmental impacts of seawater desalination: Arabian Gulf case study. Int. J. Environ. Sustain. 1 (3) https://doi.org/10.24102/ijes.v1i3.96.

Douvere, F., 2008. The importance of marine spatial planning in advancing ecosystem-based sea use management. Mar. Pol. 32, 762e771.

Ead, Environment Agency Abu Dhabi, 2015. Enviroportal (environment agency - Abu Dhabi Geoportal). https://enviroportal.ead.ae/map/.

Ehler, C., Douvere, F., 2007. Visions for a sea change. Report of the first international workshop on marine spatial planning. Intergovernmental oceanographic commision and man and the biosphere programme. In: IOC Manual and Guides, vol. 46. UNESCO, Paris, pp. 1–82.

Elliott, S., Guérin, L., Pesch, R., Schmitt, P., Meakins, B., Vina-Herbon, C., González-Irusta, J.M., de la Torriente, A., Serrano, A., 2018. Integrating benthic habitat indicators: working towards an ecosystem approach. Mar. Pol. 90, 88–94. https://doi.org/10.1016/j.marpol.2018.01.003.

Erftemeijer, P.L.A., Shuail, D.A., 2012. Seagrass habitats in the Arabian Gulf: distribution, tolerance thresholds and threats. Aquat. Ecosys. Health Manag. 15, 73–83. https://doi.org/10.1080/14634988.2012.668479.

Ferrari, R., Marzinelli, E.M., Ayroza, C.R., Jordan, A., Figueira, W.F., Byrne, M., Malcolm, H.A., Williams, S.B., Steinberg, P.D., 2018. Large-scale assessment of benthic communities across multiple marine protected areas using an autonomous underwater vehicle. PloS One 13 (3), e0193711. https://doi.org/10.1371/journal.pone.0193711.

Friis, G., Burt, J.A., 2020. Evolution of mangrove research in an extreme environment: Historical trends and future opportunities in Arabia. Ocean Coast. Manage. 195, 105288. https://doi.org/10.1016/j.ocecoaman.2020.105288.

Garcia, S.M., 2010. Governance, science and society: the Ecosystem Approach to Fisheries. In: Grafton, R.Q., Hilborn, R., Squires, D., Tait, M., Williams, M. (Eds.), Handbook of Marine Fisheries Conservation and Management. Oxford University Press, pp. 87–98.

Grabowski, J.H., Brumbaugh, R.D., Conrad, R.F., Keeler, A.G., Opaluch, J.J., Peterson, C. H., Piehler, M.F., Powers, S.P., Smyth, A.R., 2012 Oct 1. Economic valuation of ecosystem services provided by oyster reefs. Bioscience 62 (10), 900–909.

Grandcourt, E., 2012. Reef fish and fisheries in the Gulf. In: Coral Reefs of the Gulf. Springer, Dordrecht, pp. 127–161.

Grizzle, R.E., Ward, K.M., AlShihi, R.M.S., Burt, J.A., 2016. Current status of coral reefs in the United Arab Emirates: distribution, extent, and community structure with implications for management. Mar. Pollut. Bull. 105 (2), 515–523. https://doi.org/10.1016/j.marpolbul.2015.10.005.

Grüss, A., Biggs, C.R., Heyman, W.D., Erisman, B., 2019. Protecting juveniles, spawners or both: a practical statistical modelling approach for the design of marine protected areas. J. Appl. Ecol. 56, 2328–2339. https://doi.org/10.1111/1365-2664.13468.

Henriques, V., Guerra, M.T., Mendes, B., Gaudêncio, M.J., Fonseca, P., 2015. Benthic habitat mapping in a Portuguese marine protected area using EUNIS: an integrated approach. J. Sea Res. https://doi.org/10.1016/j.seares.2014.10.007.

Hogg, O.T., Huvenne, V.A.I., Griffiths, H.J., Linse, K., 2018. On the ecological relevance of landscape mapping and its application in the spatial planning of very large marine protected areas. Sci. Total Environ. 626, 384–398. https://doi.org/10.1016/j.scitotenv.2018.01.009.

Hornby, R.J., 1997. A survey of the habitats, invertebrate fauna and environmental sensitivity of the mainland coast of the UAE, with information on status and distribution of Crustaceans. Tribulus Bull. Emir. Nat. Hist. Group 7 (2), 11–17.

Huntington, H.P., 2000. Using traditional ecological knowledge in science: methods and applications. Ecological applications. Ecological Society of America. https://doi.org/10.1890/1051-0761(2000)010[1270:UTEKIS]2.0.CO;2.

Jennings, S., Smith, A.D.M., Fulton, E.A., Smith, D.C., 2014. The ecosystem approach to fisheries: management at the dynamic interface between biodiversity conservation and sustainable use. Ann. N. Y. Acad. Sci. 1322, 48–60. https://doi.org/10.1111/nyas.12489.

John, D.M., 2012. Marine algae (seaweeds) associated with coral reefs in the Gulf. In: Riegl, B., Purkis, S. (Eds.), Coral Reefs of the Gulf, Coral Reefs of the World, vol. 3. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-3008-3_14.

Jones, D.A., Price, A.R.G., Al-Yamani, F., Al-Zaidan, A., 2002. Coastal and marine ecology. In the Gulf Ecosystem Health and Sustainability, pp. 65–103. https://doi.org/10.14321/j.ctt1tm7jkg.12.

Jones, E.G., Morrison, M.A., Davey, N., Hartill, B.W., Sutton, C., 2016. Biogenic Habitats on New Zealand's Continental Shelf. Part I: Local Ecological Knowledge. New Zealand Aquatic Environment and Biodiversity Report No. 174. Ministry for Primary Industries, p. 95.

Jørgensbye, H., Wegeberg, S., 2018. Mapping of marine sediments on the Greenland West Coast: contributions of Fishers' ecological knowledge. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 75, 1768–1778. https://doi.org/10.1093/icesjms/fsy040.

Katsanevakis, S., Stelzenmüller, V., South, A., Sorensen, T.K., others, 2011. Ecosystem-based marine spatial manage- ment: review of concepts, policies, tools, and critical issues. Ocean Coast Manag. 54, 807–820.

Lacharité, M., Brown, C.J., 2019 Jun. Utilizing benthic habitat maps to inform biodiversity monitoring in marine protected areas. Aquat. Conserv. Mar. Freshw. Ecosyst. 29 (6), 938–951.

Laman, E.A., Rooper, C.N., Turner, K., Rooney, S., Cooper, D.W., Zimmermann, M., 2018. Using species distribution models to describe essential fish habitats in Alaska. Can. J. Fish. Aquat. Sci. 75, 1230–1255. https://doi.org/10.1139/cjfas-2017-0181.

Lamine, E.B., Mateos-Molina, D., Antonopoulou, M., Burt, J.A., Das, H.S., Javed, S., Muzaffar, S., Giakoumi, S., 2020 Jun 30. Identifying coastal and marine priority areas for conservation in the United Arab Emirates. Biodivers. Conserv. 1–7. https://doi.org/10.1007/s10531-020-02007-4.

Lauer, M., Aswani, S., 2008. Integrating indigenous ecological knowledge and multi-spectral image classification for marine habitat mapping in oceania. Ocean Coast Manag. https://doi.org/10.1016/j.ocecoaman.2008.04.006.

Le Pape, O., Delavenne, J., Vaz, S., 2014. Quantitative mapping of fish habitat: a useful tool to design spatialised management measures and marine protected area with fishery objectives. Ocean Coast Manag. 87, 8–19. https://doi.org/10.1016/j.ocecoaman.2013.10.018.

Levin, P.S., Essington, T.E., Marshall, K.N., Koehn, L.E., Anderson, L.G., Bundy, A., Carothers, C., Coleman, F., Gerber, L.R., Grabowski, J.H., Houde, E., Jensen, O.P., Möllmann, C., Rose, K., Sanchirico, J.N., Smith, A.D.M., 2018. Building effective fishery ecosystem plans. Mar. Pol. 92, 48–57. https://doi.org/10.1016/j.marpol.2018.01.019.

Levine, A.S., Feinholz, C.L., 2015. Participatory GIS to inform coral reef ecosystem management: mapping human coastal and ocean uses in Hawaii. Appl. Geogr. 59, 60–69. https://doi.org/10.1016/j.apgeog.2014.12.004.

Lidström, S., Johnson, A.F., 2020 Jan. Ecosystem-based fisheries management: a perspective on the critique and development of the concept. Fish Fish. 21 (1), 216–222.

Loerzel, J.L., Goedeke, T.L., Dillard, M.K., Brown, G., 2017. SCUBA divers above the waterline: using participatory mapping of coral reef conditions to inform reef management. Mar. Pol. 76, 79–89. https://doi.org/10.1016/j.marpol.2016.11.003.

Martin, C.S., Tolley, M.J., Farmer, E., Mcowen, C.J., Geffert, J.L., Scharlemann, J.P.W., Thomas, H.L., van Bochove, J.H., et al., 2015. A global map to aid the identification and screening of critical habitat for marine industries. Mar. Pol. 53, 45–53. https://doi.org/10.1016/j.marpol.2014.11.007.

McLeod, K.L., Leslie, H.M., 2009. Why ecosystem-based management?. In: Ecosystem-Based Management for the Oceans, pp. 3–12.

Meyer, D.L., Townsend, E.C., Thayer, G.W., 1997 Mar. Stabilization and erosion control value of oyster cultch for intertidal marsh. Restor. Ecol. 5 (1), 93–99.

Moore, C., Drazen, J.C., Radford, B.T., Kelley, C., Newman, S.J., 2016. Improving essential fish habitat designation to support sustainable ecosystem-based fisheries management. Mar. Pol. 69, 32–41. https://doi.org/10.1016/j.marpol.2016.03.021.

Moore, G.E, Grizzle, R.E., Ward, K.M, Alshihi, R.M., 2015. Distribution, pore-water chemistry, and stand characteristics of the mangroves of the United Arab Emirates. J. Coast Res. 31, 957–963. https://doi.org/10.2112/JCOASTRES-D-14-00142.1.

Mumby, P.J., Hastings, A., 2008. The impact of ecosystem connectivity on coral reef resilience. J. Appl. Ecol. 45, 854–862. https://doi:10.1111/j.1365-2664.2008.01459.x.

Muzaffar, S.B., Clarke, C., Whelan, R., Gubiani, R., Cook, T.R., 2017. Short distance directional migration in the threatened Socotra cormorant: link to primary productivity and implications for conservation. Mar. Ecol. Prog. Ser. 575, 181–194. https://doi.org/10.3354/meps12209.

Newell, R.I., 2004 Apr 1. Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve molluscs: a review. J. Shellfish Res. 23 (1), 51–62.

Norse, E.A., 2010. Ecosystem-based spatial planning and management of marine fisheries: why and how? Bull. Mar. Sci. 86 (2), 179–195.

Ogden, J.C., 2008. Ecosystem-based marine spatial planning & management. Training 58 (53), 27–31. Suppl 3. http://www.ncbi.nlm.nih.gov/pubmed/21830723.

Pahlevan, N., Chittimalli, S.K., Balasubramanian, S.V., Vellucci, V., 2019. Sentinel-2/Landsat-8 product consistency and implications for monitoring aquatic systems. Remote Sens. Environ. 220, 19–29. https://doi.org/10.1016/j.rse.2018.10.027.

Parr, S., Holness, S., Glavan, J., 2014. Systematic Conservation Planning Assessments and Spatial Prioritizations for the Emirate of Abu Dhabi, the United Arab Emirates and the Arabian Peninsula.

Pilcher, N.J., Rodriguez, J., Antonopoulou, M., Das, H.S., Bugla, I., Ghais, SM Al, 2019. Gulf Green Turtle Conservation Project 2016-2019: Final Scientific Report. Emirates Nature-WWF, Abu Dhabi, United Arab Emirates, p. 73.

Purkis, S.J., 2005. A "reef-up" approach to classifying coral habitats from IKONOS imagery. IEEE Trans. Geosci. Rem. Sens. 43, 1375–1390. https://doi.org/10.1109/TGRS.2005.845646.

Purkis, S., Riegl, B., 2005. Spatial and temporal dynamics of Arabian Gulf coral assemblages quantified from remote-sensing and in situ monitoring data. Mar. Ecol. Prog. Ser. 287, 99–113. https://doi.org/10.3354/meps287099.

Richards, J.A., 2013. Remote sensing digital image Analysis : an introduction. Springer. https://doi.org/10.1007/978-3-642-30062-2.

Riegl, B.M., Purkis, S.J., 2012. Coral reefs of the Gulf: adaptation to climatic extremes in the world's hottest sea. In: Riegl, B., Purkis, S. (Eds.), Coral Reefs of the Gulf. Coral

Reefs of the World, vol. 3. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-3008-3_1.
Riegl, B., Johnston, M., Purkis, S., Howells, E., Burt, J., Steiner, S., Sheppard, C., Bauman, A., 2018. Population collapse dynamics in *Acropora downingi*, an Arabian/Persian Gulf ecosystem-engineering coral, linked to rising temperature. Global Change Biol. 24, 2447–2462. https://doi.org/10.1111/gcb.14114.
Roelfsema, C., Kovacs, E.M., Saunders, M.I., Phinn, S., Lyons, M., Maxwell, P., 2013. Challenges of remote sensing for quantifying changes in large complex seagrass environments. Estuar. Coast Shelf Sci. 133, 161–171. https://doi.org/10.1016/j.ecss.2013.08.026.
Sale, F., Feary, D.A., Burt, J.A., Bauman, A.G., Cavalcante, G.H., Drouillard, K.G., Kjerfve, B., Marquis, E., Trick, C.G., Usseglio, P., Van Lavieren, H., 2011. The growing need for sustainable ecological management of marine communities of the Persian Gulf. Ambio 40 (1), 4–17. https://doi.org/10.1007/s13280-010-0092-6.
Schmiing, M., Fontes, J., Afonso, P., 2017. Predictive mapping of reproductive fish habitats to aid marine conservation planning. Can. J. Fish. Aquat. Sci. 74, 1016–1027. https://doi.org/10.1139/cjfas-2015-0538.
Sheppard, Charles, Al-Husiani, Mohsen, Al-Jamali, F., Al-Yamani, Faiza, Baldwin, Rob, Bishop, James, Benzoni, Francesca, et al., 2010. The Gulf: a young sea in decline. Mar. Pollut. Bull. 60 (1), 13–38. https://doi.org/10.1016/j.marpolbul.2009.10.017.
Smith, E.G., Vaughan, G.O., Ketchum, R.N., McParland, D., Burt, J.A., 2017. Symbiont community stability through severe coral bleaching in a thermally extreme lagoon. Sci. Rep. 7, 2428. https://doi.org/10.1038/s41598-017-01569-8.
Somer, 2003. State of the Marine Environment Report.ROPME/GC-11/003. ROPME, Kuwait, p. 217.
St Martin, K., Olson, J., 2017. Creating space for community in marine conservation and management: mapping 'Communities at Sea. In: Levin, P., Poe, M. (Eds.), Conservation in the Anthropocene Ocean. Elsevier, pp. 123–141. https://doi.org/10.1016/B978-0-12-805375-1.00007-6.
Stevens, T., Connolly, R.M., 2005. Local-scale mapping of benthic habitats to assess representation in a marine protected area. Mar. Freshw. Res. 56, 111–123. https://doi.org/10.1071/MF04233.
Stunz, G.W., Minello, T.J., Rozas, L.P., 2010. The relative value of oyster reef as habitat for estuarine nekton in Galveston Bay, Texas. Mar. Ecol. Prog. Ser. 406, 147–159. https://doi.org/10.3354/meps08556.
Teixeira, J.B., Martins, A.S., Pinheiro, H.T., Secchin, N.A., Moura, R.L., Bastos, A.C., 2013. Traditional ecological knowledge and the mapping of benthic marine habitats. J. Environ. Manag. 115, 241–250. https://doi.org/10.1016/j.jenvman.2012.11.020.
Thangaraja, M., Al-Aisry, A., Al-Kharusi, L., 2007. Harmful algal blooms and their impacts in the middle and outer ROPME sea area. Int. J. Oceans Oceanogr. 2 (1), 85–98.
Trochta, J.T., Pons, M., Rudd, M.B., Krigbaum, M., Tanz, A., Hilborn, R., 2018. Ecosystem-based fisheries management: perception on definitions, implementations, and aspirations. PloS One 13 (1), e0190467. https://doi.org/10.1371/journal.pone.0190467.
Iied and Unep-Wcmc, 2017. Mainstreaming biodiversity and development: guidance from African experience 2012-17. IIED, London. https://www.cbd.int/financial/un/wcmc-mainstreamingafrica2017.pdf.
van Lavieren, H., Burt, J., Feary, D., Cavalcante, G., Marquis, E., Benedetti, L., Trick, C., Kjerfve, B., Sale, P.F., 2011. Managing the growing impacts of development on fragile coastal and marine systems: lessons from the Gulf. A Policy Report. United Nations University - Institute for Water, Environment, and Health, Hamilton, ON, Canada. http://inweh.unu.edu/wp-content/uploads/2013/05/PolicyReport_LessonsFromTheGulf.pdf.
Vaughan, G.O., Al-Mansoori, N., Burt, J.A., 2019. The Arabian Gulf. In: Sheppard, C. (Ed.), World Seas: an Environmental Evaluation, second ed., vol. 2. Academic Press, pp. 1–23. https://doi.org/10.1016/B978-0-08-100853-9.00001-4. 2.