UNIVERSIDAD DE MURCIA

ESCUELA INTERNACIONAL DE DOCTORADO

Integrative approaches to support coastal marine management: changes in sediment discharge and participatory habitat mapping

Enfoques integradores para el apoyo a la gestión de la zona marina costera: cambios en el aporte de sedimentos y mapeo participativo de hábitats

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2020

INTERNATIONAL SCHOOL OF DOCTORAL STUDIES

PhD programme “Biodiversity and Environmental Management”

Department of Ecology and Hydrology

University of Murcia

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to obtain the PhD degree with the International Mention
by the University of Murcia

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This thesis was supported by the project *Training Network for Monitoring Mediterranean Marine Protected Areas* (MMMPA), a Marie Curie Initial Training Network (Call FP7-PEOPLE-2011-ITN), funded by the European Commission within the 7th Framework Programme and has started on January 1st, 2012. (ITN-MMMPA project, FP7-PEOPLE-Marie Curie Actions-ITN – Contract no. 290056).

AGRADECIMIENTOS

Muchas personas han sido calves para llegar a este momento. Tengo que empezar con mi familia porque sin ellos hubiera sido imposible. Mi padre, mi madre y mis abuelos, ellos me inculcaron los valores de respetar, valorar y cuidar la naturaleza desde niño. Me apoyaron en todas y cada una de las decisiones que tome para llegar hasta aquí. Mi compañera de vida, Ivonne, no hay palabras para agradecer su apoyo en las buenas y en las malas. Le estaré siempre infinitamente agradecido. Y a Lucas, mi increíble mi hijo, que con su sonrisa hace que uno vaya hacia delante sin mirar hacia atrás. No importa que pasará, con ellos nunca hay malas decisiones, solo decisiones y retos que superar. Gracias por confiar en mi trabajo como biólogo marino.

Mi director de tesis, mentor y amigo, José Antonio García-Charton. Gracias por estar ahí desde el principio de mi carrera y apoyarme en los momentos difíciles, que los hubo. Siempre dando y buscando soluciones, siempre positivo y con la mano tendida para ayudar. Gracias por creer en mi e integrarme en tu familia como uno más.

Cuantos más años pasan, más valor doy a haber tenido la suerte de cruzarme con ellos. Marco y Ubaldo, mis dos ángeles de la guarda en Génova. Tuvieron la santa paciencia de cuidarme y ser mi familia por dos años. Siempre les estaré agradecido.

Gracias a todos los que hicieron posible el proyecto MMMPA, en especial a Giu, Katie, Antonio, Fabri, Paula, David, Paty, Eli y Seve que son y serán amigos de vida. Además, gracias a Carlo Cerrano y Massimo Ponti por creer en mí y darme la oportunidad de ser parte de la familia MMMPA.

Gracias a todo el grupo de investigación del departamento de Ecología de la Universidad de Murcia por hacerme sentir como en casa cada vez que llegaba. En especial, Irene y Pere por estar siempre ahí y no abandonarme con mis cientos de preguntas. Gracias por ser mi apoyo y referente en el departamento sin pedir nada a cambio. ¡Sois increíbles!

También quiero dar las gracias a mis amigos de toda la vida de Murcia y no digo nombres porque no tendría suficiente espacio. Gracias a ellos por hacerme sentir como si nunca me hubiera ido. Siempre ahí, con ganas de reír y disfrutar, alegrándose de mis logros y preocupándose por mis caídas. Gracias por estar siempre ahí.

Y por supuesto, gracias a esos mentores con los que me he encontrado a lo largo de este camino. Esos que en algún momento de este largo camino me dieron la oportunidad de crecer junto a ellos, esa oportunidad que todos necesitamos en algún momento para crecer. Esos que han cogido el teléfono cuando necesitaba un consejo y han tirado de mi cuando no sabía a donde ir. Ellos creyeron en mi como científico y como persona. Gracias Michelle Sharer, Richard Appeldoorn, Manolo Valdés-Pizzini, Idelfonso Ruiz, Dan Dorfman, Simon Pittman y Marina Antonopoulou entre muchos otros por hacerme llegar hasta aquí.

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RESUMEN

RESUMEN

Los ecosistemas marino costeros incluyen hábitats muy diversos y productivos proporcionando numerosos servicios ecosistémicos esenciales para el bienestar de los humanos y el desarrollo sostenible de la sociedad y la economía. Estos hábitats ocupan una de las zonas más dinámicas en la Tierra debido a la influencia de los eventos naturales y antropogénicos provenientes tanto de la parte terrestre como de la marina. Sin embargo, los hábitats marino costeros están siendo fuertemente impactados y su biodiversidad a nivel global se ha reducido drásticamente. Este efecto negativo es provocado por la acumulación de actividades antropogénicas como la modificación de usos de suelo, sobreexplotación de recursos naturales, desarrollo costero o el cambio climático; afectando a los servicios ecosistémicos que aportan estos hábitats. Dada la importancia de estos hábitats, ha surgido el interés en el uso sostenible de estos hábitats. Para ello, es importante que las iniciativas de conservación específicas para estos hábitats tengan un enfoque holístico basado en el ecosistema para comprender mejor las consecuencias de alterar algún elemento circundante al ecosistema.

Actualmente, el Convenio de Diversidad Biológica (CDB) considera crítico el conocimiento de la distribución espacial de importantes hábitats marinos costeros y los impactos potenciales sobre ellos. Esta información puede apoyar la conservación, restauración y gestión de los servicios del ecosistema y por lo tanto, para mantener un planeta saludable y brindar beneficios esenciales a las personas. En un océano saludable y resiliente, el papel de la protección y la necesidad de un uso sostenible de los recursos marinos para apoyar el desarrollo sostenible están estrechamente vinculados con la necesidad de información confiable y actualizada sobre la distribución y el estado de los hábitats costeros.

El manejo y conservación de los hábitats marino costeros requiere de información espacial y temporal. Esta información puede ser comunicada eficazmente con mapas y modelos que nos interpreten la distribución de los hábitats o cambios en el entorno que puedan impactar a estos hábitats. Esto convierte a los mapas y modelos en herramientas ideales para apoyar las decisiones en el manejo de estos ecosistemas con información científica. El uso de sensores remotos y sistemas de información geográfica (SIG) se han convertido en herramientas vitales para desarrollar esos mapas y modelos. Estas tecnologías tienen el potencial de mapear características de hábitat marino costero y monitorear los cambios que sufren a lo largo del tiempo. Sin embargo, aunque estas estas tecnologías han traído nuevas oportunidades, la implementación de estas tecnologías es limitada debido a sus costes y a factores ambientales que pueden ser limitantes; por ejemplo, la turbidez cuando queremos hacer un mapeo de los hábitats bentónicos costeros.

La integración de diferentes fuentes de información y metodologías está siendo una de las maneras en las que los científicos superan las limitaciones que cada metodología tiene. Interesantemente, fuentes como el conocimiento ecológico local han sido utilizadas de manera efectiva para apoyar la ciencia convencional que apoya los esfuerzos en el manejo y gestión de los recursos. Este conocimiento local tiene un gran potencial para contribuir a completar vacíos de información científica. Es importante considerar que la integración de fuentes de información se debe hacer de una manera transparente, repetible y con un método científico. Por ello, es importante desarrollar un marco de trabajo que guie la implementación de esos modelos o ejercicios de mapeo de una forma transparente y sistemática. Estos marcos de trabajo son importantes para los gestores de recursos naturales y otros científicos que pueden utilizarlos para replicar esos

estudios o construir sobre ellos para mejorarlos y adaptarlos a las necesidades del área de estudio. El conocimiento local es una de las fuentes de información que puede ser integrada en estos ejercicios donde no solo puede ayudar a complementar el conocimiento científico, sino que también la integración del conocimiento legal a través del proceso puede allanar el camino para el uso efectivo de la información obtenida. Y a su vez, esa información con el apoyo de las comunidades locales involucradas en el proceso puede facilitar la aceptación social y una gobernanza exitosa de los servicios ecosistémicos disponibles derivados del medio ambiente costero marino al igual que apoyar planes de conservación y manejo a largo plazo.

Debido a los paulatinos impactos a los que se enfrentan los hábitats marinos costeros en las últimas décadas, existe una necesidad urgente de proporcionar información fundamental para gestionar, monitorear y restaurar estos hábitats. La combinacion de múltiples fuentes de datos, incluyendo nuevas tecnologías, combinada con técnicas de análisis espacial que utilizan SIG puede dar como resultado soluciones para producir mapas o modelos de hábitat para predecir o comprender cambios en el ámbito marino costero. El objetivo principal de esta tesis fue proporcionar herramientas e información para manejar los hábitats marino costeros con un énfasis particular en la integración de metodologías y diferentes fuentes de información para superar o minimizar los factores ambientales y económicos a la hora de obtener esa información.

En el primer capítulo se evaluaron como afectaron los cambios en el tiempo de la cobertura terrestre de las cuencas de desembocadura a la cantidad de sedimento que desemboca en los hábitats marine costeros. El estudio se hizo en la costa del mar de Liguria, en el mar mediterráneo donde existen hábitats bentónicos que son muy sensibles a la turbidez del agua y la sedimentación. Esta zona además cuenta con cinco lugares marinos de importancia comunitaria y un Área Marina Protegida (AMP Portofino). Los principales objetivos del estudio fueron identificar cambios en erosión del suelo en múltiples cuencas y estimar la fuerza del cambio durante un período de tiempo definido. Entrega de sedimentos en la salida. Para ello, se integró el modelo Revised Universal Soil Loss Equation (RUSLE) y la metodología del índice de entrega de sedimentos (SDR). Los cambios más fuertes ocurrieron individualmente en dos diferentes cuencas en los períodos 1990-2000 y 2006-2012 mientras que el período 2000-2006 mostró varios cambios en varias cuencas con un menor impacto. Esta evaluación puede ayudar a mejorar decisiones de gestión de tierras costeras y a su vez ayudar a gestionar y/o restaurar ecosistemas marinos costeros. Además, esta metodología integradora de bajo costo debería ser un paso indispensable para monitorear los impactos sobre hábitat marino costeros en la desembocadura de las cuencas provocados por cambios en la cobertura del suelo, en las áreas costeras. En última instancia, este estudio sugiere que un enfoque holístico basado en el ecosistema del complejo tierra-mar es crucial. La identificación de los flujos de salida con posibles aumentos de la escorrentía es fundamental para el monitoreo temprano y la detección de cambios en la biodiversidad costera. Las medidas preventivas como la conservación de los bosques o las buenas prácticas agrícolas (por ejemplo, terrazas / muros de piedra, márgenes de pasto, agricultura de contorno) deben incorporarse en los planes de manejo de la tierra, dando prioridad a las cuencas que amenazan los hábitats marinos más sensibles o, al menos, considerando este aspecto, entre otros, en políticas ambientales bien integradas, más allá de la aplicación clásica de la gestión integrada de zonas costeras.

En el segundo capítulo se desarrolló un mapa de los hábitats marino costeros utilizando un método innovador donde se integran diferentes fuentes de información para superar factores ambientales limitantes como la turbidez del agua o la alta complejidad del área de estudio. El mapeo de hábitat se llevo a cabo en el norte de los Emiratos Árabes Unidos. Esta zona fue identificada como 1) un área con escasa información espacial de su hábitat marino costeros, 2) alta complejidad debido a sus lagunas costeras y el mosaico de hábitats que se genera en ellas, y 3) difícil de mapear con el uso de sensores remotos debido a la turbidez de sus aguas. A su vez, es un área amenazada por el desarrollo costero y cotizada por su alto valor ambiental, resaltando la importancia de obtener información espacial para informar a las autoridades encargadas de la gestión de los recursos naturales. Se mapearon los hábitats marinos costeros de> 400 km de costa utilizando una combinación de fuentes de datos que incluyo 1) sensores remotos, 2) un extenso trabajo de campo para visitar puntos creados aleatoriamente que se muestrearon con drones, cámaras subacuáticas desplegadas desde el barco, buceo, kayak para poder acceder a lugares de difícil acceso, 3) el conocimiento de expertos locales, y 4) información existente de reportes o publicaciones científicas. Se delinearon 17 hábitats, incluidos los hábitats críticos para la biodiversidad marina, como los arrecifes de coral, manglares y zonas colonizadas por ostras y pastos marinos profundos no mapeados previamente y de gran valor ecológico y cultural. Este innovador método de mapeo fue capaz de producir un mapa de hábitat marino costero con una precisión general del 77%. Este enfoque permitió la producción de una herramienta espacial adecuada para las necesidades de gestión y conservación en una zona de los Emiratos Árabes Unidos que anteriormente carecía de dicha información.

En el capítulo 3 se utilizó el trabajo realizado en el capítulo 2 como caso de estudio y se agregó otro estudio para desarrollar un marco de trabajo integrador, innovador y sistemático para el mapeo de hábitat marino costeros. Este marco se diseñó para poder integrar múltiples fuentes de información, entre ellas el conocimiento local, de una forma sistemática y para áreas de 100-1000km^2. De esta manera, se podrá obtener información espacial de forma precisa y eficiente a la vez que sirve para poder minimizar las limitaciones ambientales que puedan surgir, por ejemplo, la turbidez o la alta complejidad del área de mapeo, y que limitan a otras tecnologías. El marco de trabajo reconoció el valor del conocimiento local como una fuente importante de información espacial y como un valor añadido para la posterior toma de decisiones utilizando este mapeo. Por ello, el conocimiento local es integrado en todos los pasos del marco desde la planificación hasta la validación del mapa. De esta manera, el conocimiento local apoyo la creación conjunta de un producto de conocimiento integrado único y enriquecido. Este marco proporciona una forma transparente y sistemática de reproducir el mapeo del hábitat, con un método fácil de implementar, ya que el enfoque es simple, eficaz y rentable. Un marco de trabajo con las cualidades mencionadas apoyaría para una mejor gestión y conservación del ambiente marino costero, ya que es clave para una planificación estratégica a largo plazo, la aceptación social y la gobernanza exitosa de los servicios ecosistémicos disponibles derivados de estos ecosistemas.

Los diferentes componentes de esta tesis proporcionan herramientas eficientes y de bajo costo para apoyar el manejo de los ecosistemas costeros. La identificación de desembocaduras de cuencas que han incrementado la cantidad de sedimento descargado en el mar es de gran importancia para reducir el impacto y monitorear los cambios en importantes ecosistemas costeros. Para ello, un enfoque holístico que englobe la complejidad de la conexión entre ecosistemas de tierra y mar es crítico.

La aplicación de métodos integrados en el mapeo de hábitat marino costeros es un novedoso método que permite solventar limitaciones de métodos únicos y a la vez ayuda a obtener información robusta de una manera eficiente. Este método de mapeo de hábitats también puede expandir el conocimiento biótico y del status de los hábitats, lo que es una información valiosa para el manejo de los recursos marinos. Este método permite la replicación del mapeo de hábitat con menores costes proporcionando la oportunidad de un mejor monitoreo de los cambios de hábitat en el tiempo y apoyar iniciativas de conservación y manejo. Estos métodos integrados necesitan tener un marco de trabajo sistemático donde saber cómo y dónde integrar las diferentes fuentes de información, hacerlo de manera transparente y eficiente. De esta forma, la metodología tendrá suficiente flexibilidad para adaptarse a diferentes escalas. Una fuente de información importante es el conocimiento local y la integración de este conocimiento puede traer múltiples beneficios al proceso, desde proveer información actualizada de cambios en los hábitats hasta el apoyo en la toma de decisiones de manejo al final del mapeo de hábitat.

La combinación de tecnologías geoespaciales, sistemas de información georreferenciada y fuentes de información como el conocimiento local e información de estudios previos puede generar resultados robustos. Además, hay una necesidad de generar una mayor inclusividad en el diseño e implementación de proyectos como mapeo de hábitats en zonas costeras. Los marcos de trabajo sistemáticos pueden fomentar y simplificar la forma de integrar ese aporte de información.

GENERAL INTRODUCTION

GENERAL INTRODUCTION

Importance of coastal marine habitats

Coastal marine ecosystems include a diverse and productive set of habitats that occupy one of the most dynamic interfaces on Earth at the boundary between land and sea, which also includes the natural and anthropogenically driven land-sea interactions (Woodroffe, 2002; Eyre & Maher, 2011). These habitats provide essential and numerous ecosystem services contributing to the human well-being and sustainable economic and social development (SDG, 2016; Townsend et al., 2018).

However, global biodiversity in coastal marine habitats is experiencing detrimental effects. These negative impacts are caused by the rampant increase of cumulative human pressures, such as habitat modification, changes in land cover, marine pollution, overexploitation of natural resources, urban coastal development and climate change (Syvitski et al., 2005; Halpern et al., 2008; Shumchenia & King, 2010; Arthington et al., 2016; Mellin et al., 2016). These impacts affect the subsequent provisioning of ecosystem services (Sousa et al., 2016). Given the sensitivity, there is a resurgence of interest in the long-term sustainability of the coastal and marine environments. These environments provide opportunities for targeted conservation initiatives and management strategies (Buhl-Mortensen et al., 2015) and we need to consider a holistic ecosystem-based approach to better understand the consequences in the coastal marine habitats of altering land ecosystems (Stelzenmüller et al. 2013).

Currently, the Convention of Biological Diversity (CBD) considers critical the knowledge of the spatial distribution of important coastal marine habitats and potential impacts on them (CBD, 2010). This information can support the conservation, restoration and management of the ecosystem services, and therefore to sustain a healthy planet and deliver essential benefits to people (CBD Strategic Plan for Biodiversity 2011-2020). Healthy resilient ocean, the role of protection and the need for sustainable use of marine resources to support sustainable development are strongly linked with the need to reliable and up-to-date information on the distribution and status of coastal habitats as per state by the Sustainable Development Goal (SDG) 14 Life Below Water and Ramsar Convention on Wetlands of International Importance).

Data integration in Coastal marine habitat mapping and modelling to support conservation and resource management

Conservation and management of coastal natural resources typically require accurate and updated spatiotemporal data. Maps and models can communicate spatial data about current, predicted, and even past states of the environment which makes them ideal science-based decision support tools (Pınarbaşı et al. 2017). Scientific techniques, such as remote sensing technologies and geographical information systems (GIS), have become vital tools for marine scientists and coastal resource managers to map coastal marine habitat characteristics and to track and manage human-induced changes of coastal environments (Mumby et al., 1998; Greene et al., 1999a; Dahdouh-Guebas, 2002).

While the technology developed over the last decade has helped to bring new opportunities to coastal marine habitat mapping and modelling (CMHM), the cost-effective implementation of those technologies and limiting environmental factors are still a challenge. An example of the limiting environmental factors when applying new technology to CMHM, is the light attenuation in the water column as it limits the usage of optical methods for remote sensing to the intertidal or shallow depths of the vast sea beds and oceans (Kachelriess et al., 2014; Eugenio et al., 2017). Although acoustic methods (single- or multi-beam echo-sounders and side-scan sonar) are the best alternative to optical methods, they have the inconvenience of being highly expensive (Barrell et al., 2015; Ierodiaconou et al., 2018). In addition to this, these technologies provide little information on the biotic communities inhabiting the marine substrata and are ineffective for mapping marine habitats in large areas with shallow water (Markert et al., 2013). Overall, the CMHM for larger areas becomes quite expensive and ground-truthing exercises are next to impossible in certain scenarios (Smith et al., 2015; Pittman et al., 2017). Therefore, a multi-source data integration for CMHM is a practical alternative to provide cost-effective solutions to most limiting factors. This approach involves a minimum of clearly defined objectives, an evaluation of available sources of information to address the problem, and determination of appropriate data integration procedures to ensure robust outputs.

In CMHM, more attention has lately been pointed towards the use of integrative approaches which support the combination of multiple data sources (Henriques et al., 2015a; Brown et al., 2018). Interestingly, local ecological knowledge (LEK), including traditional (TEK) or indigenous (IEK) ecological knowledge (Davis and Ruddle 2010), may yield biological data relevant to conventional science to inform management and conservation efforts, especially in data-poor situations (Berkes et al., 2000 ; Huntington 2000 ; Anadón et al., 2009 ; Raymond et al., 2010 ; Thornton & Scheer 2012). In particular, LEK has been used to help in the mapping of benthic habitats (Teixeira et al., 2013) and species (Jones et al., 2016), reef condition (Loerzel et al., 2017), the spatial distribution of fishing effort (Léopold et al., 2014 ; St. Martin & Olson, 2017), the spatial distribution of harvested species

(Sánchez-Carnero et al., 2016), sediments (Jørgensbye and Wegeberg 2018), and other human uses (Levine & Feinholz 2015 , Monkman et al. 2018). Noteworthy, LEK has greater potential for contributing with relevant information for developing targeted investigation and filling geographic knowledge gaps at large spatial scales (Reed et al., 2009; Teixeira et al., 2013, Loerzel et al. 2017).

Furthermore, the integration of multiple data sources should follow a consistent, transparent, repeatable, and science-based approach for data collection and integration. The development of frameworks to assist in the implementation of mapping or modelling exercises is critical to the widespread use of these tools among conservation managers and other scientists. These frameworks will allow transparent structural approach where various technical, logistic and conceptual problems can be sequentially addressed in a stepwise manner. Comprehensive exercises not only provide scope for filling the knowledge gap in the region but also supports the incorporation of scientific observation with local ecological knowledge (LEK), thereby paving the way for successful cooperation at later stages of coastal and marine conservation and management plans in the region of interests. Finally, such a framework would provide a transparent provision of replication, which would be rather easier to implement, as far as the approach is simple and cost-effective. It would support conditions for marine conservation and management through long-term strategic planning, societal acceptance, and successful governance for the available ecosystem services derived from the coastal and marine environment.

Aim of the study

Due to the increasing impacts that coastal marine habitats are facing in the last decades, there is an urgent need to provide critical baseline information to manage, monitor and restore these habitats. The amalgamation of multiple data sources, including new technology, combined with spatial analytical techniques using GIS can result in solutions to produce habitat maps or models to predict or understand changes in the coastal marine realm. This approach has the potential to provide cost-effective solutions and overcome logistical and environmental limiting factors. Therefore, the aim of the present thesis is to provide critical tools and information to support the management of coastal marine habitats, with particular emphasis on the data integration to overcome liming factors such as environmental limiting factors and cost.

The thesis is structured in chapters, concerning different approaches for assessing the spatial distribution of coastal marine habitats and the potential impact of land cover changes on them. In Chapter I, we evaluated the likely change on basin's sediment delivery driven by the land cover changes on the coastal marine habitats of an MPA and surrounding waters. We combine the Revised Universal Soil Loss Equation (RUSLE) model and sediment delivery ratio (SDR) methodology to compare the estimations of sediment delivery yield at the outflow of each basin over time. In the last decades, land-cover in coastal areas of the Mediterranean Sea has been vastly altered by land development policies (Falcucci et al. 2006) having negative effects on benthic habitats due to increased water turbidity and siltation, and declines in water quality. In particular, increased turbidity is a major threat to seagrass meadows (Erftemeijer and Lewis, 2006), while increased siltation may have dramatic effects on subtidal macroalgal assemblages (Airoldi and Virgilio, 1998). In Chapter II, we developed a coastal and marine habitat map using an innovative and integrative approach to overcome multiple limiting factors, i.e. turbidity and cost. A resulting habitat map is a critical tool for ecosystem management, as well as a benchmark to assess future changes in both habitat condition and extent. In Chapter III, we produce a comprehensive integrative framework for coastal marine mapping. This framework aims to provide accurate and cost-effective coastal marine habitat maps across broad spatial scales (100-1000s km2) for regions with environmental conditions, such as turbidity and/or very dynamic environments, that challenge conventional approaches. The proposed innovative framework integrates multiple sources of information at different stages of the CMHM. Open-source satellite datasets, in addition to various proxy indicators for benthic habitats, such as historical database, species-based site-specific information, pre-existing materials, LEK, and ground-truthing evidence at different stages of data collection and data validation can support the production of detailed habitat maps effectively.

CHAPTER I

ASSESSING CONSEQUENCES OF LAND COVER CHANGES ON SEDIMENT DELIVERIES TO COASTAL WATERS AT REGIONAL LEVEL OVER THE LAST TWO DECADES IN THE NORTH-WESTERN MEDITERRANEAN SEA

Assessing consequences of land cover changes on sediment deliveries to coastal waters at regional level over the last two decades in the north-western Mediterranean Sea

Abstract

Human-induced changes to land cover and associated strong influence such changes have on sediment delivery to coastal waters are a well-recognized threat to nearshore marine habitats worldwide. Land cover has been commonly used as a proxy to document human alterations on sediment discharges. In the present study, changes in sediment delivery to coastal waters along the coastline of the Ligurian Sea (northwestern Mediterranean Sea) were estimated on the basis of land cover data. This area includes benthic habitats- areas that are very sensitive to water turbidity and sedimentation increase -and warrant protection demonstrated by the establishment of five marine Sites of Community Importance and a Marine Protected Area (Portofino MPA). The principal objectives of the study were to identify changes in soil erosion in multiple basins and estimate the strength of the change over a defined period of time in sediment delivery at the outflow. A combination of Revised Universal Soil Loss Equation (RUSLE) model and sediment delivery ratio (SDR) was applied. The strongest changes happened individually in two different basins in the periods 1990-2000 and 2006-2012 meanwhile the period 2000-2006 showed several changes in several basins with less estimated change. This assessment can help to make better coastal-land management decisions for managing or restoring coastal marine ecosystems.

Keywords

Land cover, soil erosion, sediment delivery, coastal habitats, Mediterranean Sea, ecosystem-based management.

1. Introduction

Changes in land cover can increase the runoff of sediments, pollutants and nutrients into coastal waters (Syvitski et al., 2005), having negative effects on benthic habitats due to increased water turbidity and siltation, and declines in water quality (McLaughlin et al., 2002; Restrepo and Syvitski, 2006; Wolanski et al., 2003). In particular, increased turbidity is a major threat to seagrass meadows (Erftemeijer and Lewis, 2006), while increased siltation may have dramatic effects on subtidal macroalgal assemblages (Airoldi and Virgilio, 1998; Airoldi, 1998).

In the last decades, land-cover in coastal areas of the Mediterranean Sea have been vastly altered by humans (Vallejo et al 2001; Falcucci et al 2006). Potential increases in soil erosion have drawn the attention of scientists and managers to study and assess current sediment delivery to coastal marine habitats. Besides the ecological effects, sediment discharges in port areas create a cost to port authorities (cleaning of sediments). The north-western Mediterranean coastline has a steep geography and is prone to land erosion because soils are subject to long dry periods followed by heavy rainfalls (Grimm et al., 2003; Knijff et al., 1999; Panagos et al., 2015). In addition, inappropriate agricultural practices, deforestation, overgrazing, fires and construction activities (Yassoglou et al., 1998) are common in the region and contribute further to the erosion problem.

The strong influence of land cover changes on the variation of sediment transport rates has been previously demonstrated (Pasquale Borrelli et al., 2014; Cebecauer and Hofierka, 2008; Van Rompaey et al., 2007). The impacts of land cover changes on sediment discharges may be effectively assessed using soil erosion modelling, when historic land cover data is available (Jordan et al., 2005). Both soil erosion loss and sediment delivery resulting from different land cover conditions, such as agricultural areas and disturbed forest lands, have been successfully estimated using the Revised Universal Soil Loss Equation (RUSLE) model (Angima et al., 2003; Mati et al., 2000; Renard and Foster, 1997). This model, when supported by Geographic Information Systems (GIS) and geo-statistical techniques, can be an important soil management tool to assess wider geographic ranges. The RUSLE model has been previously employed for the study of soil erosion loss in some Mediterranean countries (Hammad et al., 2004), and specifically in Italy (Knijff et al 1999, 2000; Grimm et al 2003; Terranova et al 2009). However, special attention should be given to the spatio-temporal distribution of changes in sediment delivery and potential impact this has on coastal benthic habitats. Such knowledge is crucial for taking effective land-sea management decisions, the mitigation of land runoff processes, and achieving long-term sustainable development.

This study used a simplified RUSLE model to assess the potential change on basin's sediment delivery driven by the land cover changes during the last two decades in the Tigullio Gulf and areas surrounding Portofino MPA. The basins with increased or decreased sediment delivery were identified and the main causes for these changes were determined. A better understanding of the potential impact of land cover changes in coastal ecosystems is critical to improve marine and coastal ecosystem-based management, and current management plans.

Material and methods

2.1 Study area

The study area extends 75 km of coastline, from the Paradiso Gulf to Manara Cape, along the Ligurian Sea (northwestern Mediterranean Sea), and includes 58,919 ha of water catchment area (Fig. 1). The stretch of coastline shared with the catchment area includes the Portofino national Marine Protected Area (Portofino MPA) established in 1999, and 5 marine Sites of Community Importance (SCIs, European Habitats Directive, 92/43/EEC). *Posidonia oceanica* (Linnaeus) Delile, 1813 meadows extend for about 296 ha along the coasts of the Paradiso and Tigullio Gulfs, while coralligenous habitats extend for about 51 ha in front of the Manara Cape and Portofino Promontory (Coppo et al., 2009). The whole coastal area of the study has an important role in the regional economy as it is extensively used for beach and nautical tourism, SCUBA diving, and fisheries, among others (Italian National Institute of statistics, ISTAT, 2007).

The inland area is characterized by a mountainous territory with steep seaward slopes (Rovere et al., 2011), which increases the quantity of terrigenous material draining to the Ligurian Sea shelf (Vietti et al., 2010) (Fig. 1). Liguria region has one of the highest mean annual precipitation (1000-3000 mm yr^{-1}) in Europe and it is defined as one of the most affected areas for the rainfall erosivity in Europe with extreme values higher than 1300 MJ mm ha^{-1} h^{-1} yr^{-1} (Panagos et al., 2015). Bioclimatic conditions change from coast to inland areas and rainfall distribution shows extreme variability in time, with sporadic torrential events during autumn and spring. The diverse climatic conditions provide a wide range of natural vegetation associations and allow different human traditional activities (e.g. homegrown agriculture), which results in higher diversities of land cover.

The whole catchment area considered in the study includes 14 SCIs, one Natural Reserve (Riserva Orientata Agorale di Sopra e del Mogetto), and two Regional Parks (Parco Naturale Regionale di Portofino, Parco Regionale dell'Aveto) covering more than 12,000 ha.

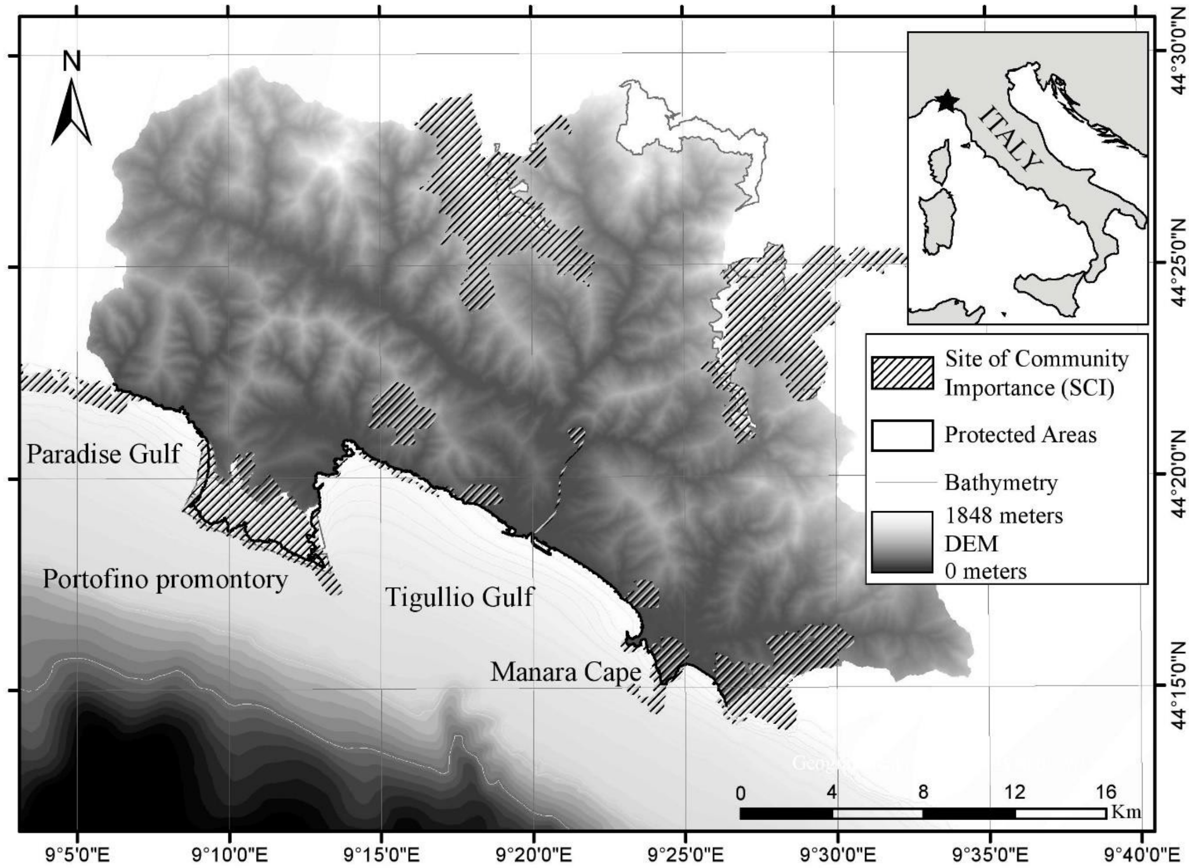


Fig. 1. Study area. DEM digital elevation model.

2 Basins delineation and outflows

The basin is a common unit of management for land and water authorities in many countries (Kingdom, 1998; Zalewski and Wagner-Lotkowska, 2004), since they link land areas with their outflows. The basin delineation was performed using the hydrology toolbox in Arc-View GIS 10.2 software and the Digital Elevation Model (DEM, resolution of 30 × 20 m) from US Geological Survey. From the DEM, flow direction and flow accumulation of the water were determined. The outflows of sediments to the coast were identified in high cumulative flow points, and basins were delineated using the flow direction and the outflows obtained previously.

In order to tie the land based source of sediment directly to coastal habitat, the basins delineated with the model were corroborated with Google Earth 3D images and, aerial photographs of the Italian National Geoportal were used to detect possible human alterations to the natural flow regimes of rivers at the outflows.

2.3 RUSLE and Sediment Delivery Yield

The Revised Universal Soil Loss Equation (RUSLE) has been selected among the applicable models thanks to its very simple structure and the parsimonious input of data in relation to the available data and the investigation scale. The combined RUSLE and sediment delivery ratio (SDR) methodology was used in this study to compare the estimations of sediment delivery yield (t ha^{-1}) at the outflow of each basin over time. The SDR value was added as a multiplier to the RUSLE equation (Renard and Foster, 1997; Wischmeier and Smith, 1978).

$$A = K \times L \times S \times R \times C \times P \text{ (Eq.1)}$$

Where A is the mean soil loss per season (October-December); R is the rainfall– runoff erosivity factor, K is soil-erodibility factor (Panagos et al., 2014); L is the slope–length factor and S is the slope–steepness factor (dimensionless); C is the land-cover/management factor that takes into account differences in density and structure of the vegetation cover reflecting its protective function and also the methods of land management (dimensionless); and P is the support-practice factor (dimensionless), which is not considered in this model. The temporal variability of *R-factor* is not considered in this study (due to lack of seasonal erosivity) while K, *L* and *S* factor are not changing during the time; so, those factors were treated as constant over this period of time.

2.3.1 Input parameters

Rainfall-erosivity factor was calculated using daily precipitation data from 2010 to 2012 in the rainiest season (September, October and November) in the study area. Data was collected from ten stations dispersed within the study area. The factor was calculated using the regression model suggested by Jung et al. (1983), RUSLE monthly R-factor: $R = 0.0378 \times X^{1.4190}$; X is the monthly rainfall amount (mm). Using the above regression model, the R-factor value for each station was computed and R-factor distribution map was made by Kriging interpolation (Khorsandi and Mahdian, 2012).

Land Cover/management factor was obtained from the CORINE Land Cover (Coordination of Information on the Environment Land Cover, CLC). The unified CLC methodology, a legend of 44 classes and a 1:100,000 scale, allows studying temporal changes in land cover and their impact on soil erosion processes with high precision. The C-factor values for CLC classes were estimated according to previous literature (Cebecauer and Hofierka, 2008; NS Department of Agriculture and Fisheries, 2001; Renard and Foster, 1997) (Table 1). The CLC maps correspond to the 1990 (CLC1990), 2000 (CLC2000), 2006 (CLC2006) and 2012 (CLC2012).

Table 1. Land cover/management (C-factor) derived from the CORINE land cover (CLC) classes (adapted from Renard and Foster 1997; NS Department of Agriculture and Fisheries 2001; Cebecauer and Hofierka 2008).

CLC class	Description	C-factor
231	Pastures	0.005
311	Broadleaved forest	0.005
312	Coniferous forest	0.005
313	Mixed forest	0.005
323	Sclerophyllous vegetation	0.005
324	Transitional woodland-shrub	0.007
321	Natural grasslands	0.050
243	Land principally occupied by agriculture, with significant areas of natural vegetation	0.100
242	Complex cultivation patterns	0.150
223	Olive groves	0.400
333	Sparsely vegetated areas	0.500
334	Burnt areas	0.500
111, 112, 121, 122, 123, 512, 523	Continuous urban fabric, Discontinuous urban fabric, Industrial or commercial units, Road and rail networks and associated land, Port areas, Water bodies, Sea and Ocean	0.000

The estimated sediment delivery yield corresponds to the relative amount of sediment moving out of a basin in a given time interval. In order to predict sediment yield (t ha^{-1}) in a basin, it was required to multiply products of total soil erosion by sediment delivery ratios (SDR). Since not all erosion makes its way to the river mouth, SDRs based on the basin size were applied in order to estimate relative sediment delivery at the river mouth. At a regional scale the most widely used method to estimate SDR values is through a SDR-area power function (Roehl, 1962):

$$SDR = 0.4720 \times \text{Catchment Area } (km^2)^{-0.125} \text{ (Vanoni, 1975)}$$

$$\text{Sediment delivery yield at the outflow} = A \times SDR$$

The set of model equations imply that any quantitative or spatial differences in sediment delivery yield detected between these years will be completely controlled by the land cover factors.

3. Results

The basin delineation model identified multiple outflows, 17 of which had an area higher than 50 ha. These 17 basins were selected for the analysis considering the finest available resolution for RUSLE factors. The size of the analysed basins ranged between 37188 ha of the Entella basin (WS12) to the 51 ha of Santa Margherita Ligure basin (WS9) (Table 2; Fig 2).

Table 2. Results of the calculated sediment delivery ratios (SDR) for the seventeen watersheds analysed.

Watershed	Area (ha)	SDR
WS0	1240.12	0.17
WS1	97.59	0.24
WS2	2375.01	0.16
WS3	752.38	0.18
WS4	338.62	0.20
WS5	154.66	0.22
WS6	64.75	0.25
WS7	382.53	0.20
WS8	2442.62	0.16

WS9	51.02	0.26
WS10	520.12	0.19
WS11	1094.47	0.18
WS12	37188.70	0.11
WS13	440.16	0.20
WS14	574.85	0.19
WS15	6044.04	0.14
WS16	2748.29	0.16
TOTAL	56509.92	

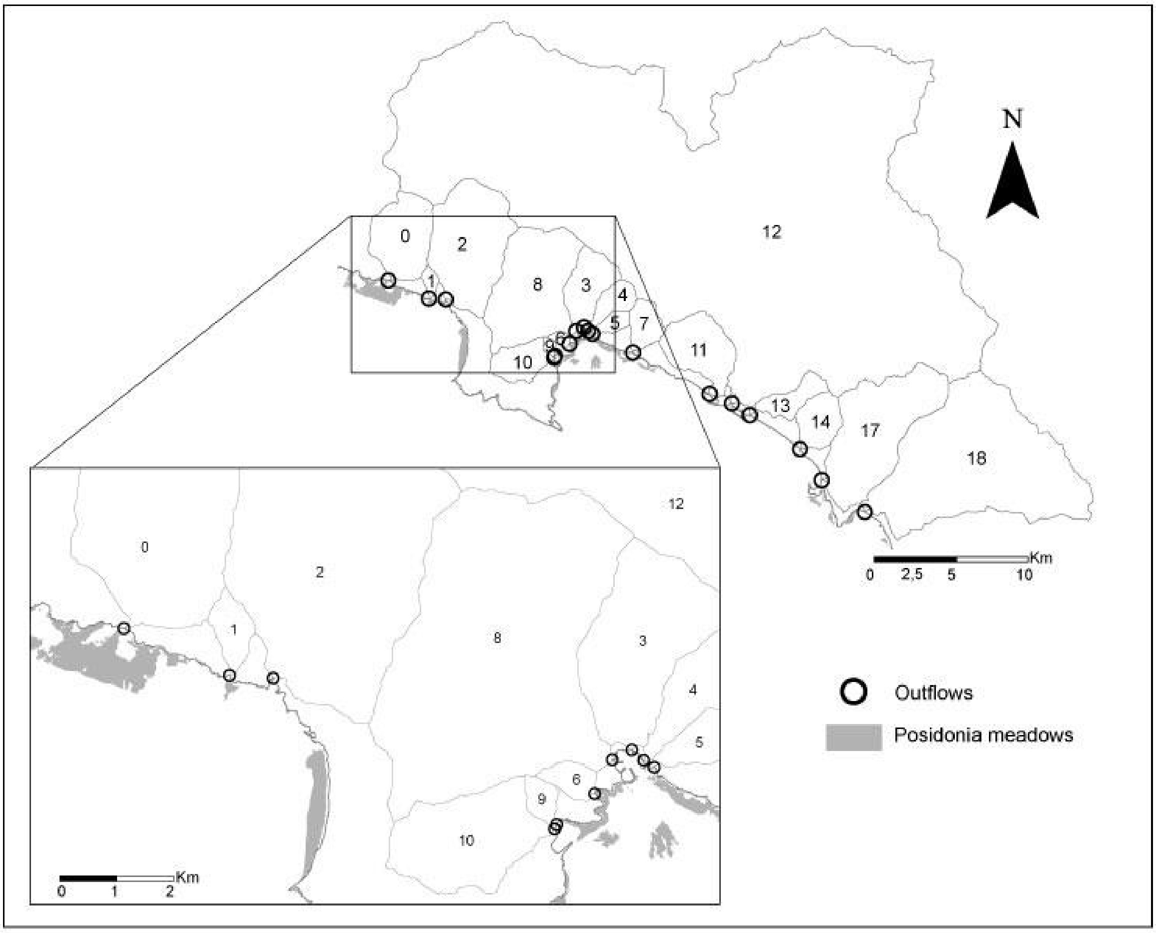


Fig. 2. Basins (indicated by numbers) and outflows analysed in the study area.

In the time frame 1990-2000, the results showed a change in the soil erosion map at Sestri Levante basin (WS16) (Fig. 3a). This change in soil erosion risk was provoked by the increase in area burned, from 550 to 900 km^2, destroying coniferous and mixed forest. This change generated a potential increase of more than 20% in the sediment delivery ratio to coastal areas from land (Fig. 4a). The rest of the area was almost stable with only minor changes to land cover, reducing the soil erosion risk in the hilly and mountainous parts of the WS12.

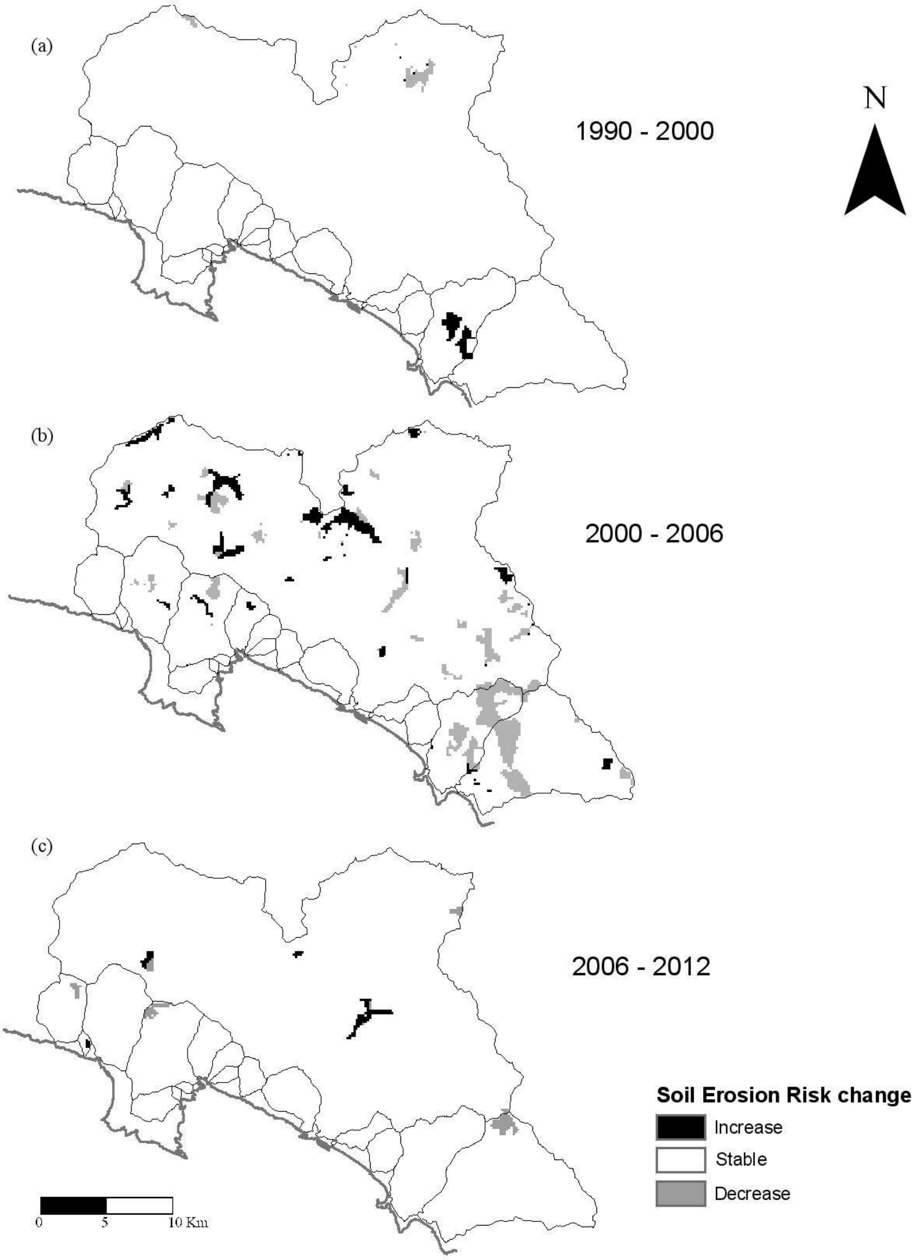


Fig. 3. Soil erosion risk changes in 1990-2000 period (a), 2000-2006 (b) and 2006-2012 (c).

In the time frame 2000-2006, the study area showed a large amount of changes to land cover, 2000 ha (3.4% of the study area) (Fig.3b). Both, Sestri Levante (WS16) and Riva Ponente (WS15), basins showed the most noteworthy change in sediment delivery because of the decrease of the burned area which was generated previously to 1990 and in the period 1990-2000 (Fig. 4b). Post-fire recovery of ground vegetation i.e. initial stage (transitional woodland-shrub and sclerophyllous vegetation) altered land cover. These notable land cover changes reduced the risk of soil erosion for some areas within the basins (Fig. 3b), decreasing the sediment delivery in more than 80% in spite of appearance of new agricultural areas during this period.

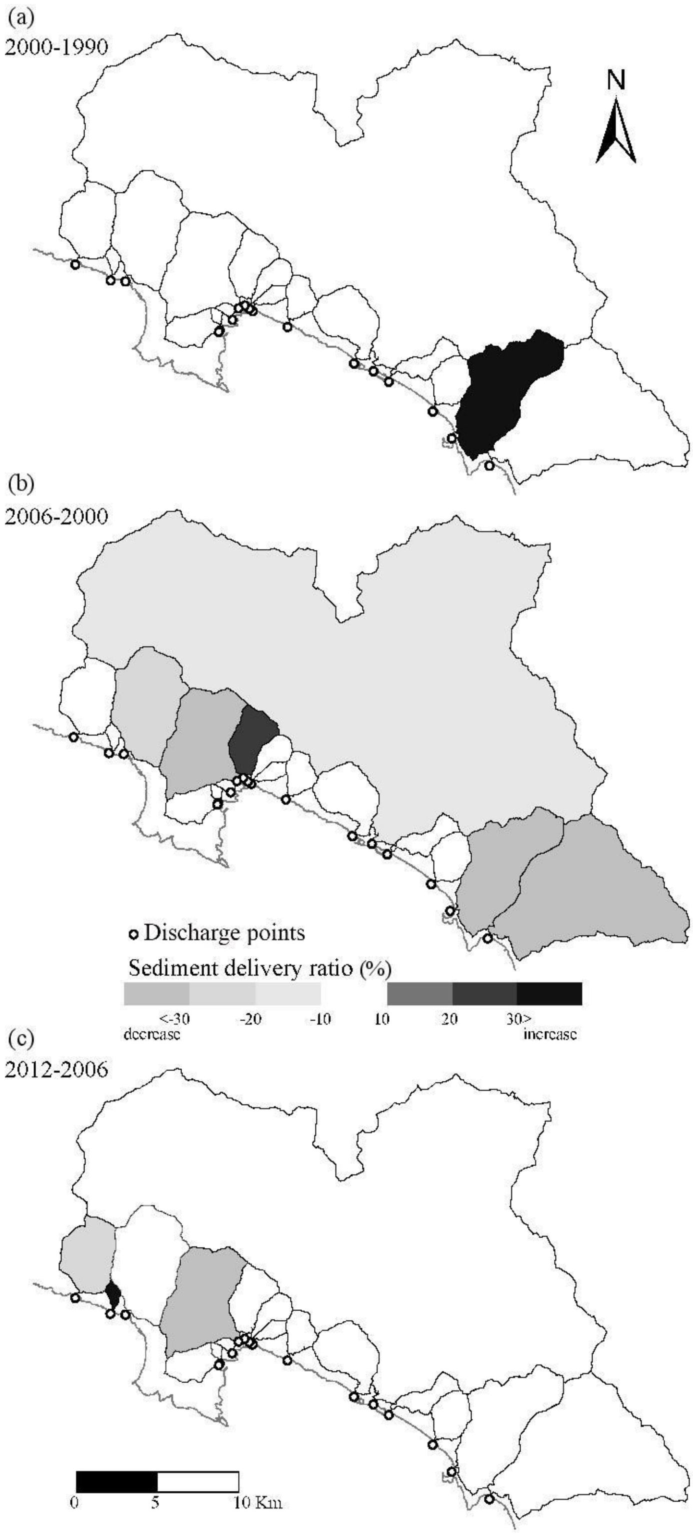


Fig. 4. Percentage of sediment delivery changes by watershed in in 1990-2000 period, 2000-2006 and 2006-2012.

In the same period (2000-2006) but at a lower rate, the analysis showed also positive changes in the reduction of the estimated sediment delivery in WS2, WS8 and WS12 (Fig. 4b); mainly due to the increase of 40 ha of broadleaved forest in the WS12, and the substitution of sparsely vegetated areas with the transitional woodland-shrub in WS8 and WS12. Only WS3 showed a potential increase in its sediment delivery ratio, increasing more than 20% of its potential sediment delivery to the Gulf of Tigullio (Fig. 4) because of the removal of 10 ha of forest for new agriculture terrain.

The last period of this study, 2006-2012, showed slight changes in sediment delivery yield of the outflows (Fig. 4c). The most impacted basin was WS5 which has an extension of 9.7 ha, 2.8 ha of which has increased the soil erosion risk because olive groves replaced pre-existing forest. For this reason, the estimated sediment delivery increased 5 times over this period with the outflow located closer (less 150 m) to a wide posidonia seagrass meadow (Fig. 2). On the other hand, some basins showed an estimated decrease in sediment delivery during this period (Fig. 4c) following a pattern of increase in the extension of transitional woodlands.

4. Discussion

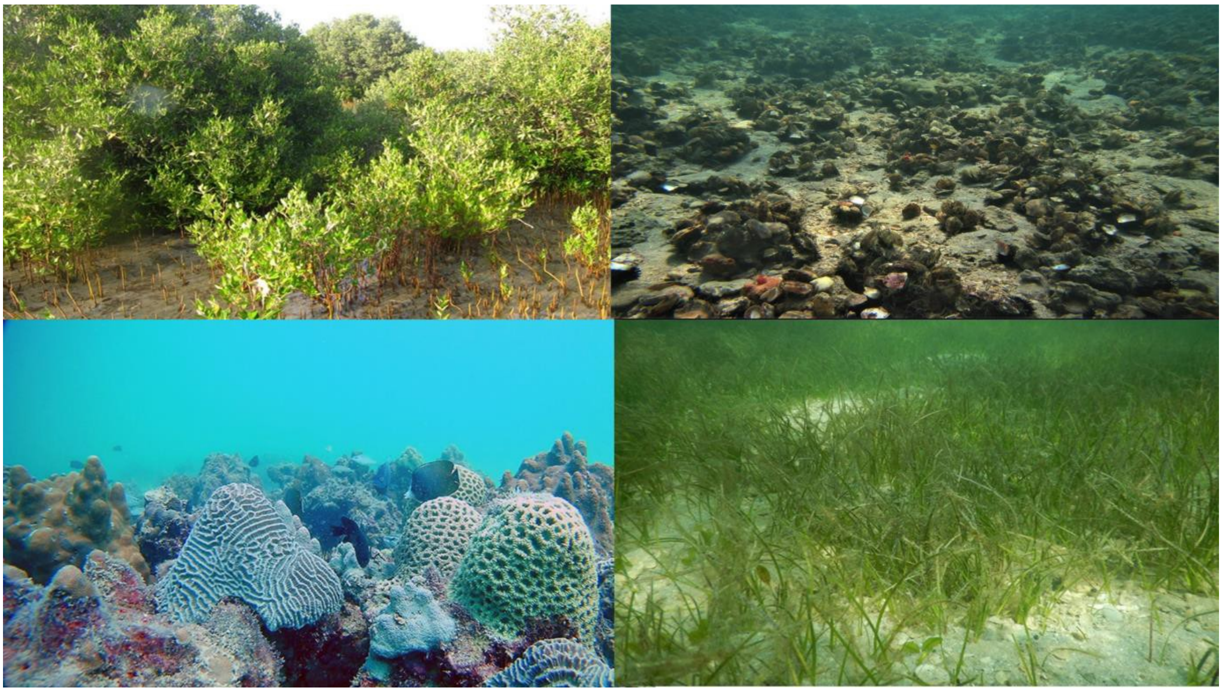
The potential changes in sediment delivery and soil erosion risk due to land cover changes were estimated for sixteen basins along 75 km of coastline, from the Paradiso Gulf to Manara Cape, in the Ligurian Sea (north-western Mediterranean Sea) over the last two decades. The results reveal that some basins showed important changes in their potential sediment delivery yield to coastal waters in the last two decades because of land cover changes. Some of these changes would increase or decrease the potential impact in the nearshore coastal marine habitats through the change of sediment load at the basin outflow.

The dramatic increase in soil erosion risk and potential sediment delivery of basins WS16 and WS5 in the period 1990-2000 and 2006-2012 respectively, was provoked by local deforestation. This loss of forest was caused by wildfires and/or intensification of agricultural lands in vulnerable areas (mountainous and sub- mountainous regions with high topographic potential for soil erosion). Liguria region is recognized as the most densely forested region in Italy with a coverage rate of 69.7% (INFC 2007). Yet, it has suffered a moderate decrease in its forest extension during the period 2002-2012 due to logging (Borrelli et al., 2014a, b). The loss of forest lands and its protective function against soil erosion is a precursor of water quality deterioration (Tong and Chen, 2002), and the land cover change to burnt ground or to agricultural land is recognized as a serious contributor of sediment yield in Mediterranean areas (Cerda et al., 2010). The importance of the identification of these basins with potential increases in sediment loads, and even in pollutants or nutrients from agriculture lands that occupied the place of the forest, is essential to control the potential impact on marine habitats closer to the outflow of the basins (Thrush et al., 2004). For example, the outflow of WS5 is located close to a large extension of healthy posidonia meadow, which is very sensitive to pressures such as sedimentation, pollution or turbidity (Montefalcone et al., 2009; Pergent-Martini et al., 2005). The high sensitivity of this endemic seagrass to human disturbances (Marba et al., 2013), its massive decline in the recent years (Hemminga and Duarte, 2000; Short and Wyllie-Echeverria, 1996), and its importance to sustain highly productive ecosystems of the Mediterranean Sea (Boudouresque et al., 2006) are reasons for which posidonia meadows have been included among the priority habitats of European Community interests (European Habitats Directive, 92/43/EEC) and requires the designation of SCIs and special conservation plans. Marine conservation plans need to give much greater consideration to the indirect effects from land-use and land cover to ensure more effective coastal ecosystem-based management. Their effectiveness is highly dependent on institutional and policy changes in the management of natural resources, and of the interdisciplinary collaboration such as the subscription and respect of the international Convention on Biological Diversity (Alvarez-Romero et al., 2011). This convention highlights the importance of the Integrated Coastal Zone Management (ICZM) concept and the need to carry out management actions at multiple scales like watershed view in a broad sense (Douvere and Ehler, 2009). An example of management action is the land conservation plan to reduce the soil loss established for agricultural lands in which farmers are receiving incentives from the European Union to comply with the obligation of the land under Good Agricultural and Environmental Condition (GAEC, 2009). Recent studies have demonstrated that the application of GAEC in Liguria region has reduced soil loss, especially in hilly areas, being Liguria region one of the most effective cases on management practices (terraces/ stonewalls, grass margins, contour farming) (Panagos et al., 2015b). However, the land conservation plan is completely disconnected to marine environment, which is the final receptor, and therefore not considers the sensitivity of marine habitats in defining the priority of interventions.

The period between the years 2000 and 2006 was the most unstable. The results indicate multiple land cover changes that, in general terms, caused a slight reduction in sediment deliveries. These reductions were due to recovery of vegetation lost in previous wildfires (even before 1990). The post-fire transitional vegetation (shrub to grass, burn to sclerophyllous vegetation or natural grasslands), afforded greater sediment stability and decreased the risk of soil erosion. These slight changes in the land cover highlight the importance of the unified CORINE land cover methodology used in this study, allowing a robust and accurate assessment of temporal changes in land cover and their impact on soil erosion processes. Both the demonstrated strong influence that land cover changes have on sediment delivery yield (Jordan et al., 2005; Van Rompaey et al., 2003) and the soil erosion modelling using historic land cover data, offers a unique opportunity to study impacts of land cover changes on erosion and sediment discharges over time (Jordan et al., 2005); and even the potential impact on nearshore marine ecosystems (Morrison and Kolden, 2015). The comparison over time of the soil erosion risk maps on a per cell basis supports better knowledge of the spatial extent of these changes, trends and even helps to understand changes in the potential sediment delivery at the outflow. It is important to mention that the comparative approach for regional scales of basin models generate more reliable results than the use of absolute values due to the complexities in basin sediment production, storage, transport, and delivery to coastal waters (Súri et al., 2002; Van Rompaey and Govers, 2002). Basin models require improvements through the use of more formal sediment budgeting approaches. However, the use of land cover changes as a proxy of potential sediment delivery changes at the outflows and the assessment of the erosion risk at regional scale are a crucial source of knowledge for actual, preventive and effective land and coastal management decisions. Ultimately, this study suggests that a holistic ecosystem-based approach to the land-sea complex is crucial. The identification of the outflows with potential runoff increases is critical for the early monitoring and detection of changes in the coastal biodiversity. Preventive measures like forest conservation or good agricultural practices (e.g. terraces/stone walls, grass margins, contour farming) should be incorporated in land management plans, giving priority to basins that threaten most sensitive marine habitats or, at least, considering this aspect, among others, into well integrated environmental policies, going beyond the classical application of integrated coastal zone management.

Chapter II

APPLYING AN INTEGRATED APPROACH TO COASTAL MARINE HABITAT MAPPING IN THE NORTH-WESTERN UNITED ARAB EMIRATES



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

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.

Keywords: habitat mapping, coastal marine habitats, data integration, United Arab Emirates, local ecological knowledge, integrated approach, innovative

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; 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 througout 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., 2011; 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 outdated, inaccurate, and largely produced without detailed field surveys and/or built for specific objectives (British Admiralty 1977, AGEDI 2016, Grizzle et al., 2016; Moore et al., 2014). 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) (CBD 1992) and the UAE National Biodiversity Action Plan (NBSAP) (NBSAP 2015). 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; Riegl and 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 2006; 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 2016; 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.

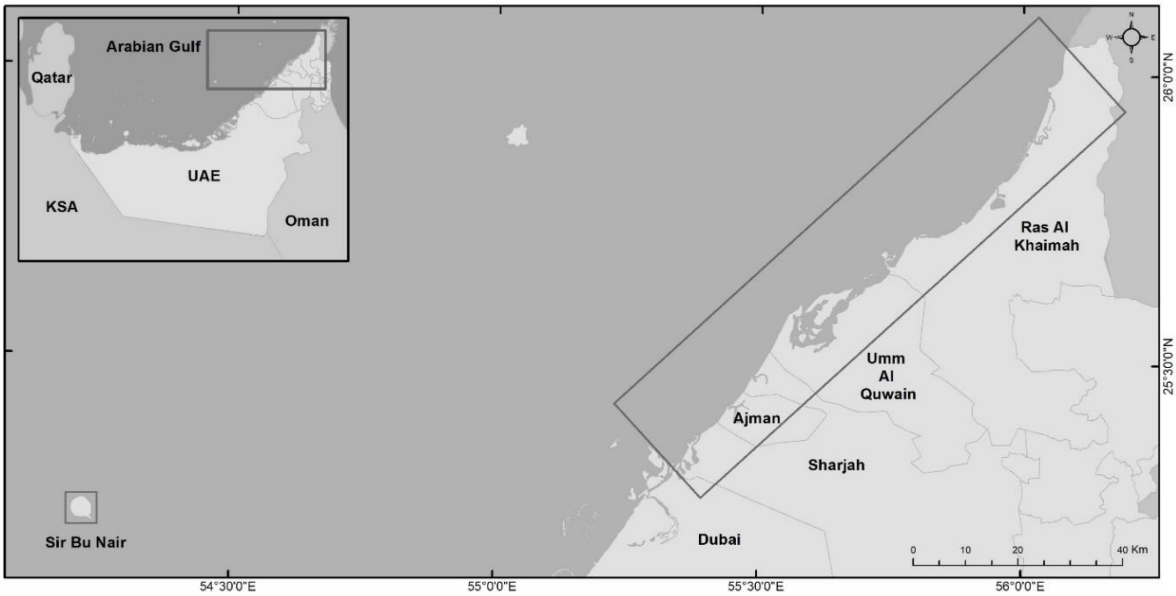


Figure 1: Location of the study area in the northern UAE coastline and waters of the Arabian Gulf, including the offshore island of Sir Bu Nair (Sharjah).

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 2016). 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.

Table 1. Habitat classes and description used to map coastal marine habitats in the north-western emirates, UAE 2019.

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,

Class	**Description**
	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).

Class	**Description**
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)

2.2. Data collected and map production

The coastal marine habitat map presented herein was produced using 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., 2013), (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, 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).

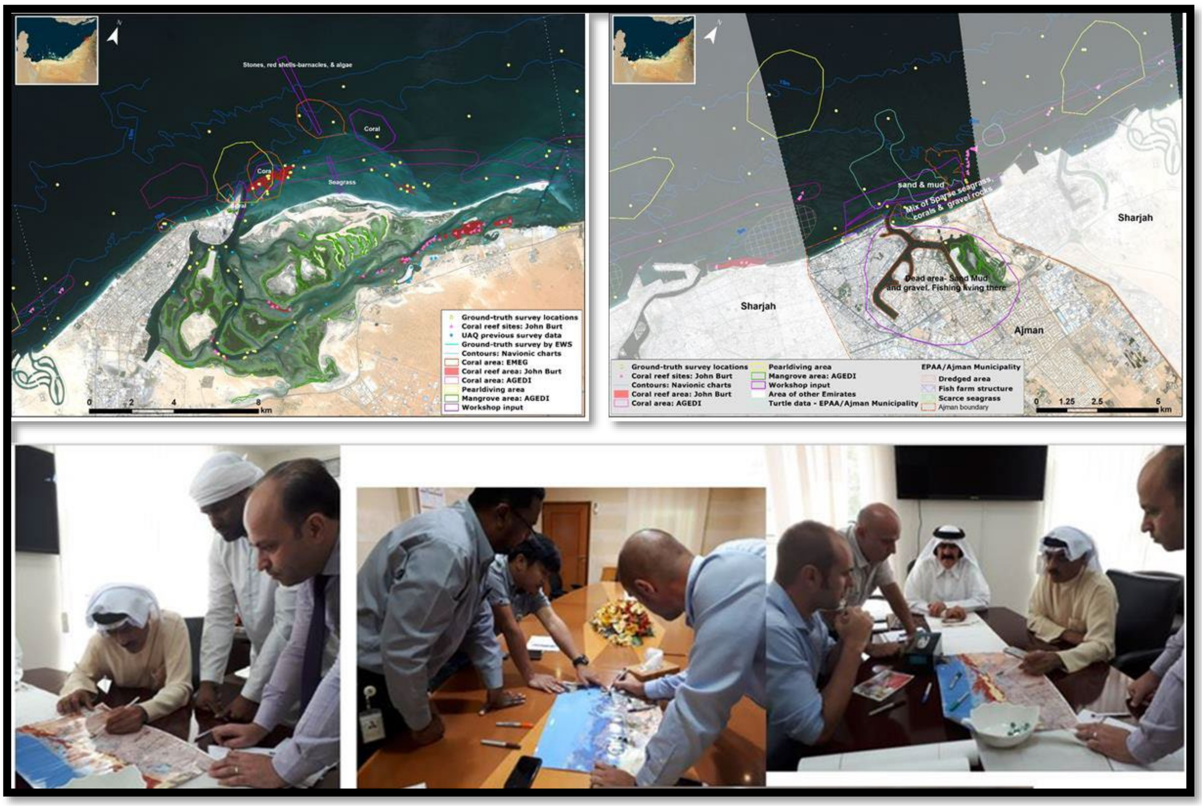


Figure 2. The geodatabase produced compiles the existing data and local expert knowledge (LEK) in the study area.

2.2.2 Local ecological knowledge

Local experts from universities, environmental authorities, dive centres 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 pre-processed 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 minutes 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 vehicules (UAVs) to obtain georeferenced photographs for interpretation. GPS positions were recorded using a hand-held Garmin GPSMap 62S 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).

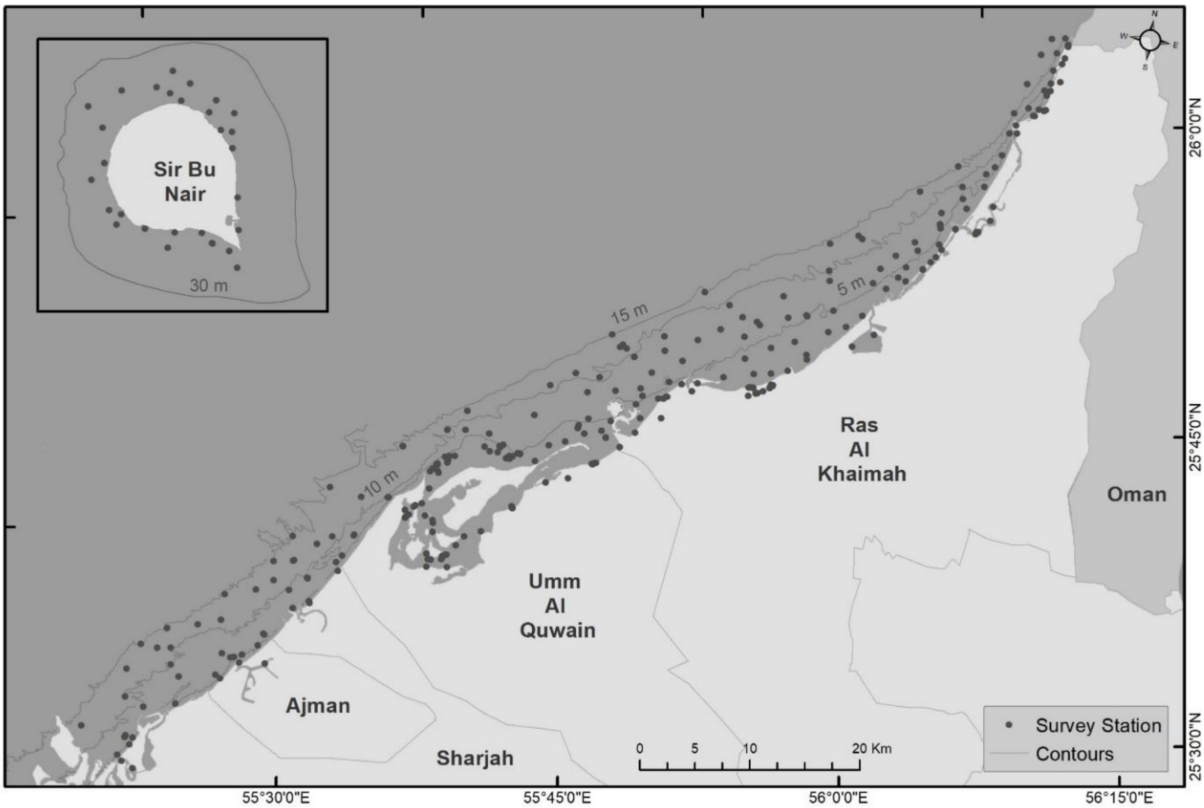


Figure 3. Location of the survey points and isobaths in the northern emirates, Arabian Gulf, UAE.

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 (https://scihub.copernicus.eu/). 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, 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 sen2coral (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.

2.2.5 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.

2.2.6 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).

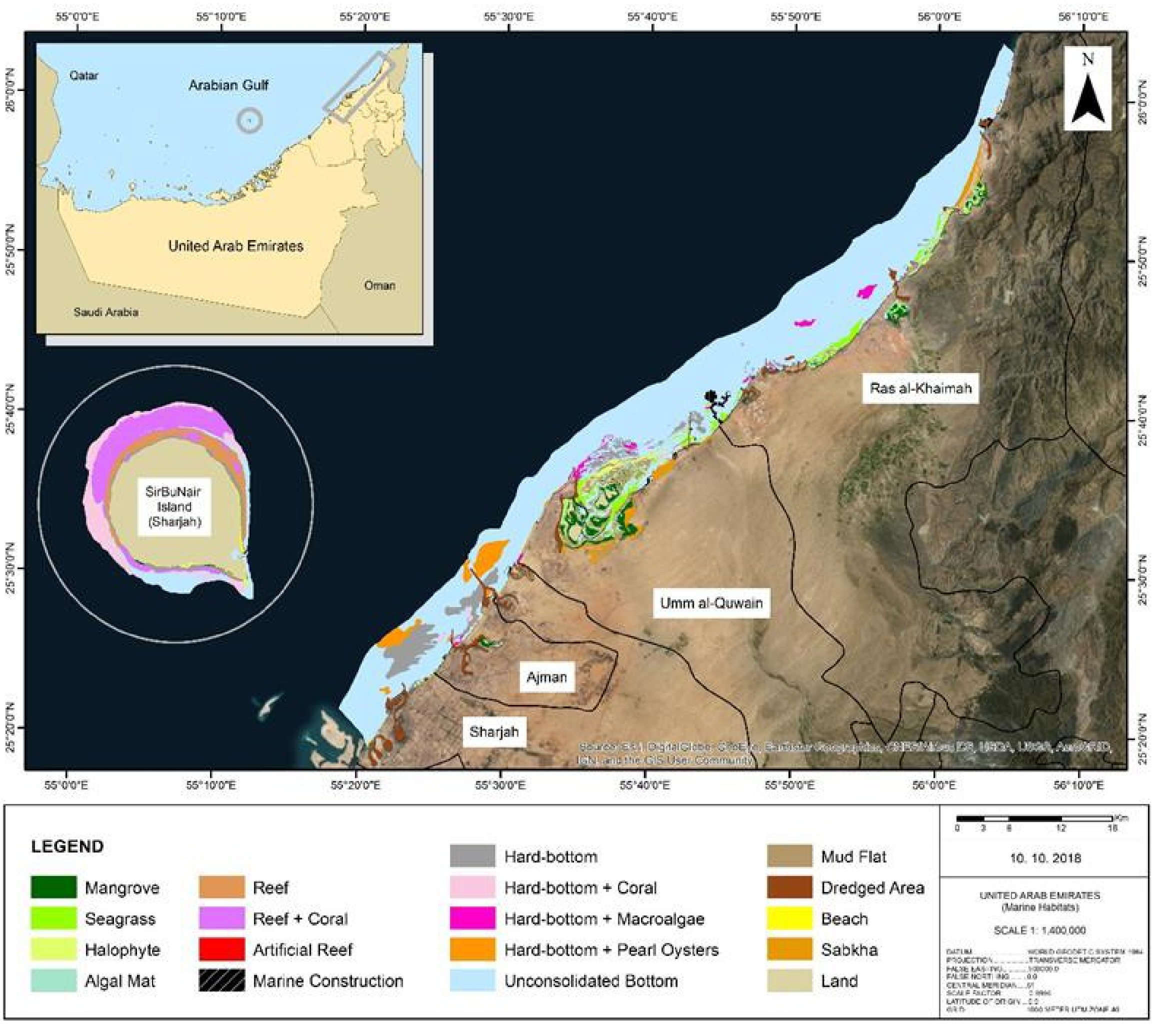


Figure 4. Coastal Marine habitat map for the north-western emirates, UAE, 2019.

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).

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. Figure 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

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 UA~0.95 and PA~0.88), 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.

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**	

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 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 (Newel 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 north-western 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 (>7m) 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 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., 2013).

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 decision-making, 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 (Abdulla et al., 2009, Hogg et al., 2018; 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 TEK-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.

SUPLEMENTARY MATERIAL

Supplementary Table S1. List of data sources used in combination with remote sensing analysis. Area cover: UAQ = Umm Al Quwain, RAK = Ras Al Khaimah. Data used: GR = Georeferenced.

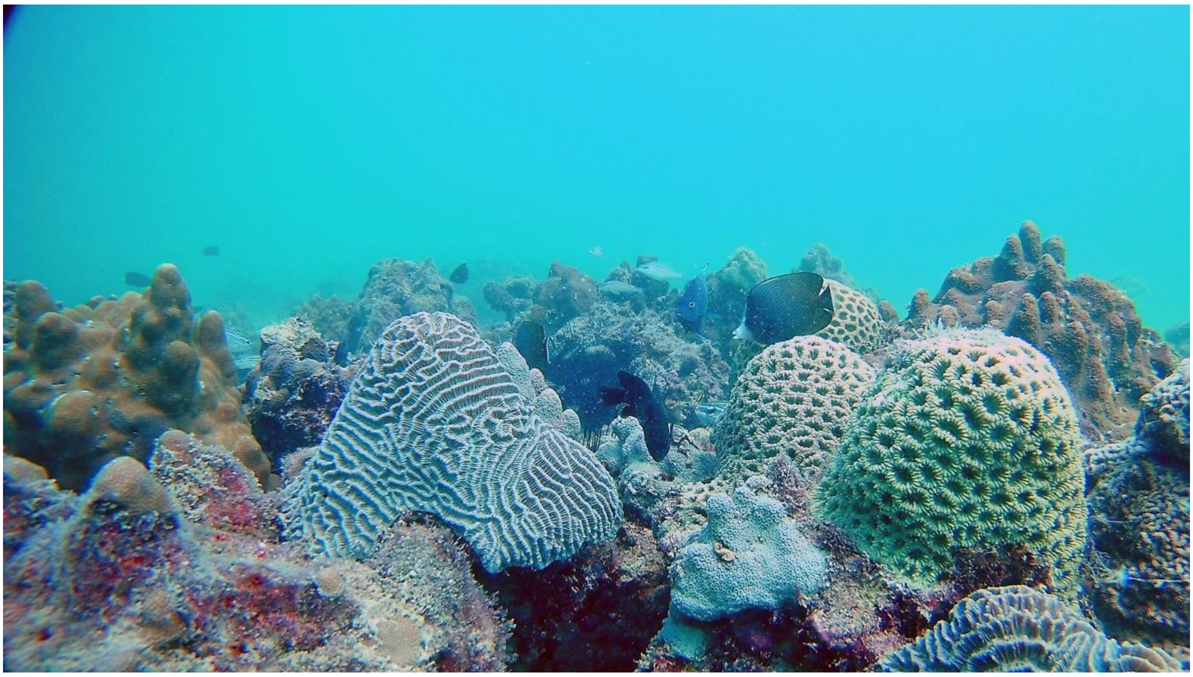
Geodatabase	Type of data source	Area cover	Habitat	Data used
Grizzle et al., 2016	Existing information (Published article)	Study area	Coral + reef	GR Points
Parr et al., 2013	Existing information (Published article)	Study area	Multiple habitats	GR Points and polygons
John Burt	Existing information (Unpublished report)	Study area	Coral + reef, hardbottom + reef, Reef framework	GR Points
AGEDI	Existing information (Unpublished report)	Study area	Mangroves	GR Polygons
Emirates Nature - WWF	Existing information	UAQ and RAK	Seagrass	GR Polygons and points

	(Unpublished report)			
Environmental Impact Assessments provided by Env. authorities	Existing information (confidential reports)	Study area	Multiple habitats	GR points and polygons
AGEDI	Existing information (Report)	Study area	Mangroves	GR Polygons
Emirates Diving Association	Existing information (ancillary map)	Study area	Oyster beds	Polygons
British Admiralty 1977	Existing information (ancillary map)	Study area	Multiple habitats	Polygons
Emirates Marine Environmental Group	Existing information (confidential report)	Sharjah	Multiple habitats	GR polygons and points
Ajman municipality	LEK	Ajman	Multiple habitats	Non - GR polygons
EPAA	LEK	Sharjah	Multiple habitats	Non - GR polygons

Sharjah Fishermen Coop	LEK	Ajman, Sharjah	Multiple habitats	Non - GR polygons
Ajman Fishermen coop	LEK	Ajman, Sharjah, UAQ and RAK	Multiple habitats	Non- GR polygons
Emirates Marine Environmental Group	LEK	Sharjah and UAQ	Multiple habitats	Non- GR polygons
Dive centres	LEK	UAQ, RAK	Coral + reef, hardbottom + reef, Reef framework	Non – GR polygons

Chapter III

An Integrative and Participatory Framework for Coastal Marine Habitat Mapping



An Integrative and Participatory Framework for Coastal Marine Habitat Mapping

Abstract

Coastal and marine habitat mapping is increasingly recognized as an essential decision support tool in conservation and management. Habitat mapping is typically carried out by remote sensing experts and rarely integrates local ecological knowledge (LEK) from stakeholders. A more inclusive participatory mapping process has multiple benefits to help overcome environmental challenges, increase local relevance, incorporate detail not available in remote sensing data, enable knowledge exchange and take account of socio-ecological factors. We present an integrative and participatory framework to produce accurate and cost-effective coastal and marine habitat maps to inform conservation planning strategies in the Arabian Gulf, United Arab Emirates.

Keywords: Mapping framework, coastal and marine habitats, local ecological knowledge (LEK), data integration, Arabian Gulf.

1. Introduction

Coastal and marine habitats are among the most biologically diverse, productive and vulnerable regions on Earth, and they provide critical ecosystem services supporting human health and well-being (Barbier et al. 2011, Sousa et al. 2016).

Spatial information on the distribution, structure and condition of coastal and marine habitats is central to effective decision making in modern marine management. Digital habitat maps are widely recognized as operationally important tools supporting diverse decision-making in ecosystem-based management and biodiversity conservation (Cogan et al. 2009; Buhl-Mortensen et al. 2015; Caldow et al. 2015; Malcolm et al. 2016). Habitat maps act as a spatial proxy for mapping essential habitats for specific species and assemblages (Ward et al. 1999), predicting species distributions (Pittman et al. 2007), mapping ecosystem services (Harborne et al. 2008; Bianchi et al. 2012; Vassallo et al. 2018), and supporting spatial conservation planning, management and monitoring of these habitats (Cogan et al. 2009; Pittman et al. 2011; Caldow et al. 2015).

Remote sensing technologies have enabled comprehensive mapping at high resolution over broad geographical and temporal scales, thus providing tools to locate and track human-induced changes to coastal landscape and seascapes (Mumby et al. 1998; Greene et al. 1999a; Dahdouh-Guebas, 2002). Constraints arising from sub-optimal environmental conditions for data acquisition, such as cloud cover, water turbidity or limited access to ground-truthing locations, however, can adversely affect the performance of low-cost optical remote sensing methods for mapping shallow and spatially complex nearshore habitats (Kachelriess et al. 2014; Smith et al. 2015; Eugenio et al. 2017). Integrative approaches which utilise multiple data sources in the mapping process (Henriques et al. 2015; Brown et al. 2018), provide a solution to overcome many of the limitations in conventional remote sensing for habitat mapping.

In data-poor situations, or where community connections to coastal ecosystems remain culturally and ecologically integrated, local ecological knowledge (LEK), including traditional (TEK), or indigenous ecological knowledge (IEK) (Davis & Ruddle 2010) offers great potential to inform and improve marine mapping and monitoring (Addison et al. 2018, Kaiser et al.

2019). Although rarely harnessed to enhance habitat mapping, LEK has great potential to guide targeted investigations and to address broad scale geographic knowledge gaps (Reed et al. 2009; Teixeira et al. 2013, Loerzel et al. 2017). LEK often provides a large observational base across longer time periods (Jones et al. 2016). For example, LEK has been successfully used to help map benthic habitats (Lauer and Aswani 2008; Teixeira et al. 2013; Jones et al. 2016), coral reef features, condition, threats and human use (Loerzel et al. 2017), spatial distribution of fishing effort (Léopold et al. 2014; St. Martin & Olson, 2017), habitat connectivity (Berkström et al. 2019), sediments (Jørgensbye and Wegeberg 2018) and spatial distribution of harvested species (Sánchez-Carnero et al. 2016; Monkman et al. 2018). In marine conservation planning scenarios, Ferrari et al. (2018) conclude that the best conservation outcomes were achieved by incorporating local knowledge in the planning process. Furthermore, a more inclusive participatory approach to mapping is more culturally sensitive and, depending on specific objectives, may benefit from humanizing the data collection process and the final mapping product resulting in enhanced relevance to local communities and facilitating adaptive and collaborative management co-management (Baldwin & Oxenford 2014).

Here we present a step-by-step data integration framework for participatory coastal and marine habitat mapping as a pragmatic alternative to conventional habitat mapping. This framework provides a cost-effective and more inclusive approach to addressing several major barriers to both production and application of relatively high-resolution (100 m^2 resolution) habitat maps across broad spatial scales (100-1000s km^2) for regions with dynamic conditions such as varying water turbidity that challenge conventional remote sensing approaches. The habitat mapping framework has four primary performance characteristics: (i) well-planned and timely generation of accurate information, (ii) cost-effective generation of robust baseline data, (iii) efficient results for broad geographical extent with heterogenous depth conditions, variable water clarity regimes and dynamic environments, and (iv) effective integration of the available data sources, such as LEK.

We show how open-source satellite datasets, in addition to various proxy indicators for benthic habitats, such as historical database(s), species-based site-specific information, pre-existing materials, LEK, and ground-truthing evidence can be integrated in the production of detailed marine habitat maps in the Arabian Gulf. The research forms part of a multi-stakeholder systematic conservation planning project for the United Arab Emirates to help address actions to conserve marine biodiversity and ensure that critical coastal and marine habitats and priority species are well represented in regional integrated coastal zone planning frameworks.

2. Methodology

The integrative habitat mapping framework has four key stages (Fig 1) that create a logical sequence of steps to deliver effective spatial decision support tools: (1) Planning, (2) Data Collection, (3) Map Production and Evaluation, and (4) Map/Data Application. The planning stage involves identification of stakeholders and potential data sources, review of existing data and ancillary materials, determining relevant geographical extent(s), and identifying limitations and/or challenges of project-specified goals and objectives. The Data Collection stage entails cataloguing existing information, collating LEK, and procuring satellite or airborne spectral images. Map production and evaluation consist of data analysis, but it is not limited to, the following segments: selection of habitat classification scheme, data processing, image classifications, accuracy assessments, and ground-truthing surveys. Finally, Map/Data application refers to data usage by producing recommendations and management applications to directly address coastal and marine management issues in the area. Each stage of the process is discussed in the following subsections in detail.

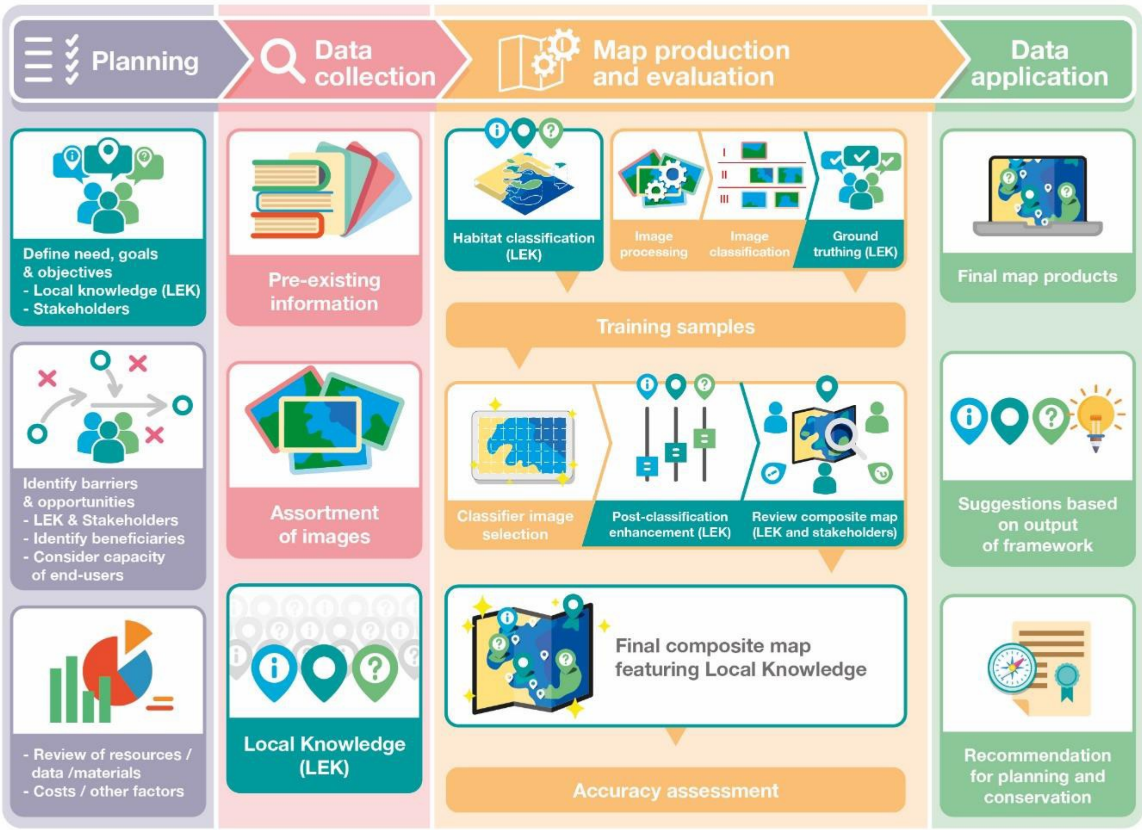


Figure 1: The integrative and participatory framework for coastal marine habitat mapping (CMHM). Four major components support the habitat mapping process: (i) Stage 1: Planning, (ii) Stage 2: Data Production and Evaluation, (iii) Data Production and Evaluation, and (iv) Data Application.

2.1 Stage 1: Planning

The success of developing an effective habitat mapping framework to support management needs begins with a dialogue between key partners, scientific and geospatial experts, environmental managers and other stakeholders (Caldow et al. 2015). The planning stage identifies specific management applications, required spatial extent and spatial resolution, limitations, expectations, and realistic outcomes for map products. Engagement with relevant stakeholders and identification of existing and accessible information sources is of utmost importance for the strategic planning of the habitat mapping process (Pomeroy & Douvere, 2008). This not only provides links to missing information sources, but also charts out hypotheses on how to include and ensure prospective participation during formulation of policies and institutional reforms to achieve result-oriented cooperation (Russel et al. 2018).

Geospatial decision support tools (Battista & O'Brien 2015, Kendall et al. 2018) can be extremely valuable in the efficient review and assessment of spatial information gaps and guiding the geographical prioritization of data collection efforts. However, the decision on where the mapping is needed can benefit from stakeholder input addressing additional critical questions such as: types of map required, budget constraints, timeframes for applications, and a rationale to justify priorities (Kendall et al. 2018). To understand the pathway to impact map products, broad stakeholder engagement and sharing of local knowledge is important and can include local communities such as fishermen and scuba divers, data experts such as scientists, researchers, and consultants and other relevant organizations (non-governmental and governmental institutions).

The involvement of LEK from multiple stakeholders at the initial stage of any habitat mapping project allows efficient communication of information which is especially important in data-deficient situations (Berkes et al. 2000). After compilation and review of available information, including LEK by focus groups, the data are mapped to determine spatial coverage and extent. This will help determine the techniques that are required for planning, collecting, and segregating data collected through field-based surveys. In practice, the spatial extent will be determined by project-specific goals and objectives in combination with the results of data evaluation. In ecosystem-based approaches that consider regional context and connectivity, it is recommended to extend the area of interest beyond the primary focal management jurisdictions (Caldow et al. 2015).

Detailed information about the study area will not only provide the foundation of existing data sources, but will also eventually aid in the data collection process of the habitat mapping framework (Doria et al. 2018). By cataloguing pre-existing resources, data materials, and other ancillary information at the initial stage, the framework will assist in understanding strengths, challenges, and limitations of any habitat mapping project. At the end of the planning stage, the following questions should be addressed:

a) Who are the major stakeholders in the area of interest? Could they contribute to decision making in the habitat mapping planning process and provide site-specific information to aid the mapping process?
b) What are the mapping priorities and applications?
c) What other additional information is available related to the current, as well as past coastal and marine habitat distribution?
d) What are the limitations and the challenges? Are there any solutions and/or alternatives?

2.2 Stage 2: Data collection

In this framework, we suggest a sequential three-step process for collecting the following sources of information in the area of interest: (i) pre-existing information, (ii) satellite or airborne spectral images, and (iii) local ecological knowledge (LEK).

Pre-existing information. Habitat mapping typically integrates multiple data types generated from different survey techniques. For example, benthic habitat maps may rely on the utilization of both passive and active remote sensing datasets such as satellite-based data, or single- and multi-beam sonar, or bathymetric Light Detection and Ranging (LiDAR), as well as, in-water grab sampling and other physical ground-truthing information that can be integrated to inform and evaluate map production (Zavalas et al. 2014; Collings et al. 2018; Ierodiaconou et al. 2018). However, this approach is usually expensive, time-consuming and resource-intensive, and can take a few years from the first field-based survey to a final habitat map (Vasquez et al. 2015). Therefore, prior to venturing into collection of such datasets, understanding the need, as well as the type of datasets based on project goals and objectives(s) is crucial for realistic expectations and can be assisted by an inventory of existing geospatial data (Battista and O'Brien 2015). The pre-existing information could include environmental impact assessments, routine benthic monitoring surveys, species-based site-specific information, ancillary maps, etc. Such targeted information, especially including the presence of well-studied species, provides proxies for critical habitats, and therefore can be of significance in data-scarce regions (Martin et al. 2015).

Selecting imagery from air, water and space-borne sensors. Raw datasets for habitat mapping often originate from many different institutions, and are collected by a wide array of active and passive sensors mounted on different platforms (e.g., aircraft, drones, ships, satellites) with varying sampling characteristics (spatial and temporal resolution, spectral capabilities, errors, etc.) and interpretative challenges (Vanden Borre et al. 2011; Valentini et al. 2015). For example, seafloor mapping has been conducted using data from satellite-based sensors (Eugenio et al. 2017; Pu & Bell, 2017; Kovacs et al. 2018), ship-based acoustic sensors (single and multi-beam echo-sounders, including low-cost non-scientific devices; side-scan sonar) (Li et al. 2017; Ierodiaconou et al. 2018; Sánchez-Carnero et al. 2018), as well as aerial photography and airborne LiDAR (Light Detection And Ranging) (Pittman et al. 2013; Santos et al. 2016; Ventura et al. 2018). Combinations of various methodologies have also been applied for mapping coastal and marine habitats (Zhang, 2015).

In general, the spatial extent and physical access to the study area along with project goals and objectives will determine data requirements for habitat mapping. The choice of datasets would depend on a number of factors including: (i) study area (geographic location and weather conditions), (ii) temporal domain (one- time or two- time por multiple time scale), (iii) seasonality (daily, monthly, seasonally, inter-annually), (iv) project costs and constraints, (v) time and resources available, and most importantly, (vi) level of classification to be attempted in the mapping exercise based on project goals and objectives(s) (Fig 2).

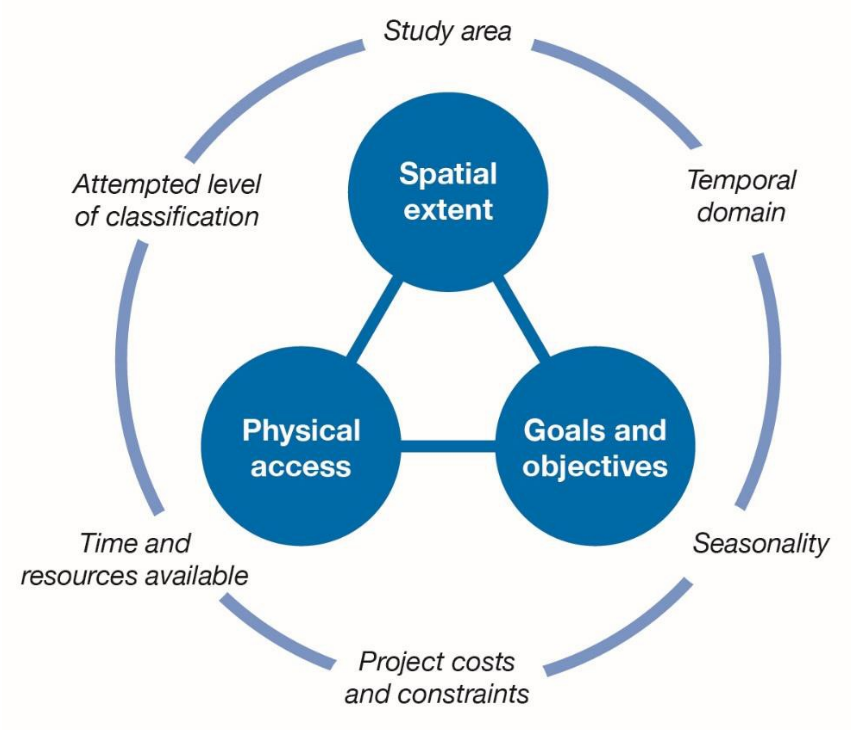


Figure 2. Factors determining the data requirements and limitations for CMHM.

Low-cost and free remotely sensed data are increasingly available through online data portals. Assessment of data quality and suitability should be conducted to evaluate factors such as, seasonality, geographic location, sun angle, water turbidity and roughness and atmospheric conditions such as cloud cover to identify most suitable images for production of habitat maps. In addition to these, it is important to note that the selection criteria would have various trade-offs between, for example, the area of interest, spatial resolution and errors. At the end of the data collection stage, the following key questions are addressed:

a) Does the data structure cover the spatial extent of the region of interest with sufficient spatial resolution to meet the objectives?
b) What are the water depth limitations of the data?
c) What is the optimal season (time period) for data acquisition?
d) How dynamic is the seascape structure relative to the available data?

Local ecological knowledge (LEK). The integrated habitat mapping framework recognizes the value of LEK as an important source of geospatial information in the mapping process. Integration of LEK can be achieved through participatory activities with different stakeholders, such as focus group discussions and key informant interviews using maps, drawings and digital geospatial tools. Devices such as mobile phone and web-based map applications can also be used effectively to crowdsource geospatial information to inform or validate habitat mapping (Heipke 2010, Loerzel et al. 2017, Pittman et al. 2018). Lived experience, sometimes referred to as Experts by Experience, and deep local knowledge of coastal and marine environments provides unique and complementary information on the local importance, structure and dynamics of seascapes.

Although stakeholder involvement at some stage of the mapping process is not unusual, inclusive and diverse participation and integration of

LEK in the habitat mapping process is still uncommon. Deeper more inclusive consultation and participatory mapping will not only benefit the final product (e.g., thematic targeting, gap filling, field work support), but will also increase the interest, acceptance and relevance and potential for application, of the mapping process (Cárcamo et al., 2014; Röckmann et al., 2015). In addition to local scientists from various environmental agencies, governmental institutions and universities, involvement of local communities, such as fishers and scuba divers, will add detail that may not be available through existing scientific knowledge. When integrated, LEK can help inform habitat delineation and identification of sites for conducting ground-truthing surveys. An integrated co-production approach in habitat mapping from planning through development and application of habitat maps will result in the emergence of a map product that is greater than the sum of its individual contributions and a better fit-for-purpose. Evaluation of data quality is also important in the utilization of LEK and should be documented in product metadata.

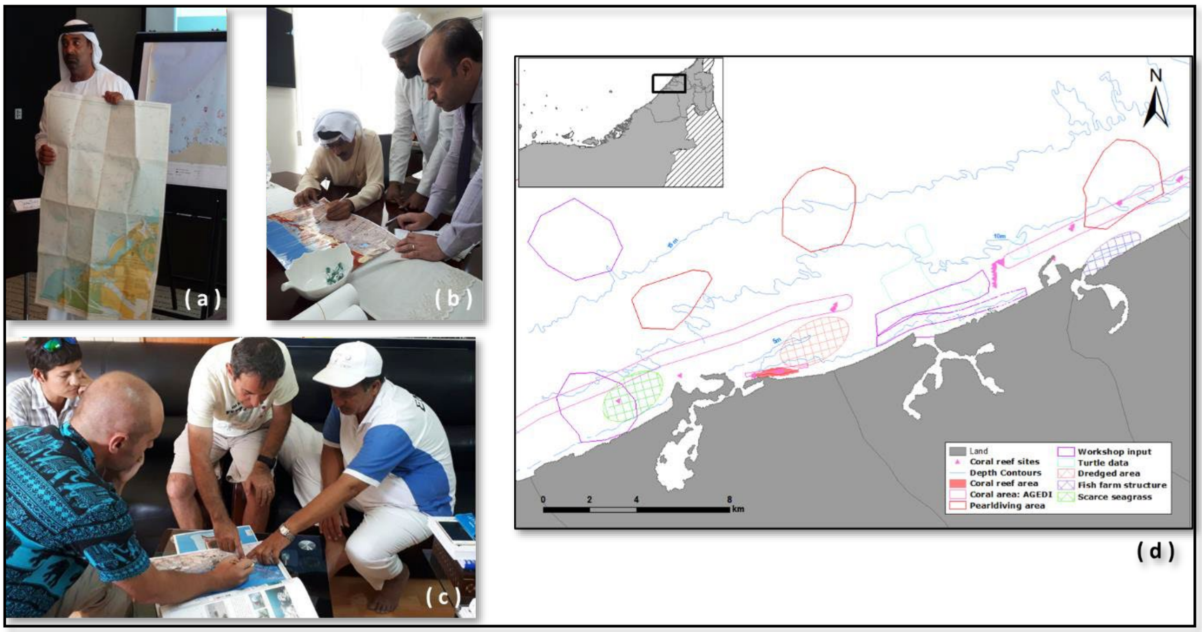


Figure 3. Example of how LEK was mapped and integrated in a GIS database for the coastal and marine habitat mapping of the northern emirates (Mateos-Molina et al. 2020). (a) Ancillary maps, (b) participatory mapping with local experts, (c) data integrated in GIS format to support next steps in the mapping.

2.3 Stage 3: Map production and evaluation.

The data analysis for the integrative habitat mapping framework is structured into seven major steps as follows:

2.3.1. Habitat classification: The habitat classification provides a language through which data and information regarding habitats can be communicated, managed and standardised. A clear and uncluttered classification scheme is usually desirable (Greene *et al.*, 1999b). If the objective is to meet the needs of a wide range of users, then a hierarchical classification scheme is recommended (Costello 2009; Pittman et al. 2012). Hierarchical classifications are multidimensional providing multiple levels of information that may vary in thematic content and resolution. This scheme will allow systematic grouping of various marine habitat types based on their common ecological and geomorphological features, as well as aggregation of lower levels in the hierarchy. Local stakeholders can play an important role through sharing of LEK to guide the development of the classification scheme with regard to intended applications (Costello et al. 2009). In order to develop the classification scheme for the framework, a number of important factors are taken into account:

a) How would the classification scheme relate to any existing classification systems applied in the area of interest, and how existing data might, therefore, be utilised?

b) What should be the mapping units, and how to define those units?

2.3.2. Image processing: This task includes two data pre-processing stages for the selected remotely sensed scenes (i.e. satellite and/or aerial images) (Fig. 3). Where required, images should be pre-processed to reduce the impact of atmospheric, surface and water column water conditions that reduce classification effectiveness. Images may need to be corrected for sensor-specific and/or platform-specific radiometric and geometric distortions in the data (Eugenio *et al.*, 2017; Thompson *et al.*, 2017; Ierodiaconou *et al.*, 2018). For example, reflectance can be exponentially attenuated by water column height requiring radiometric corrections to obtain true benthic reflectance in coastal and marine environments. Spectral radiance of raw images can be influenced by changes in scene illumination, atmospheric conditions, water column/depth, viewing geometry, and instrument response characteristics (Ju *et al.*, 2012; Bunting, 2017; Young *et al.*, 2017).

2.3.3 Image classification: This typically involves unsupervised image classification (ISODATA or K-means clustering). This is important, especially in data-scarce regions, where no training data is available. Instead, rudimentary classifications can be achieved by simply differentiating spectral information into a specified number of clusters (Buhl-Mortensen *et al.*, 2015; Carey *et al.*, 2015). This will allow users to design random or random-stratified sampling surveys (*fourth* phase).

2.3.4 Ground truthing surveys: The data gathered in this phase can be supplemented with information collected at stage two (i.e. data collection) through pre-existing information and local ecological knowledge (LEK). The following questions should be addressed during ground-truthing surveys:

a) How can we assimilate different levels of information (pre-existing maps and other data sources) based on their accessibility, and how can we allocate ground-truthing efforts?
b) Is the information collected sufficient, including training samples for supervised image classification and accuracy assessments?
c) Can the sampling design for acquisition of ground-truthing data cover all of the habitat classes?

2.3.5 Classifier image selection: Over the last decade, non-parametric classifiers (such as tree-based classifiers and machine learning algorithms) have emerged as more useful and reliable classification methods than parametric classifiers (Elith et al. 2006). The strengths of machine learning include the capacity to handle data of high dimensionality and to map classes with very complex characteristics providing efficient solutions in dynamic and spatially heterogeneous coastal areas (Strong & Elliott, 2017; (Maxwell et al. 2018). In some instances, observational data (i.e. remote sensing datasets) can be supplemented with non-spectral ancillary data and LEK for viable and replicable habitat information (Olsen *et al.*, 2015).

2.3.6 Manual, semi-automated and automated post-processing: Data post-processing of the classified images involving manual, semi- and automated post-processing can further enhance the performance of the final map. With a standard series of steps integrating stakeholder input, the classified product can be generalized, or statistically smoothed, by changing the values of isolated pixels to match the value or class to that of the majority of pixels in a user-defined neighbourhood.

To resolve any incorrectly classified area, knowledge-based image analysis is the most common mechanism for integrating expert information (scientists, researchers, governmental agencies, or local communities) (Richards & Jia, 2006). Thus, pre-existing information and local ecological knowledge (LEK) through various stakeholder inputs collected in stage two (i.e. data collection) can be used again in post-classification image enhancement process to develop the final composite classified habitat map. It should be noted that combining multiple information sources to produce a composite map can be challenging if an elaborate ancillary database on ground-truth information is missing. Hence, extensive ground-truthing surveys (i.e. ground truthing in stage three) are very important for developing accurate representation of coastal and marine environments. The following questions should be addressed at the conclusion of this phase:

a) Was the semi-automated or the fully automated image classification technique able to capture and discriminate classes representing meaningful coastal and marine habitats?
b) Which classes have not been interpreted appropriately? Do we have enough ground-truthing information to manually post-process and enhance the classified images?

2.3.6 Expert review of map products: Local experts review the first draft of the map to provide feedback to help evaluate and refine the final map. Map product reviews are critical steps to increase confidence and ownership in the information produced, as well as underscoring the stakeholder's role in marine resource management (Baldwin and Oxenford 2014).

2.3.7 Accuracy Assessment: Validation of classified habitat maps through previously geo-referenced data and ground-truthing data points is crucial for determining and communicating uncertainty. Spatial uncertainty or errors, inherent in mapping due to the complexity of collecting, processing and classifying imagery can be communicated via mapping spatial pattern of the errors in combination with ecological knowledge (Barry and Elith 2006; Lechner *et al.*, 2012).

2.4 Stage 4: Data Application

An important challenge for data application is the dialogue between a human and a map which is mediated through a computing device or in-print format. Where digital map products are accessible through computers, spatial decision support tools provide effective ways to explore and interact with maps. The application of the map as a decision support tool includes the identification of gaps of information to plan future data gathering priorities. The map can be used for integration in planning processes, for systematic spatial conservation prioritisation and to focus discussion for a wide range of other coastal management activities. Coastal and marine habitat maps support actions to achieve multiple goals and targets required for addressing international, regional and national policies and strategies for biodiversity conservation and sustainable development. Furthermore, the integration of LEK and stakeholder guidance during the mapping process raises awareness of the existence of important habitats and paves the way for integration of habitat maps into operational planning systems.

3. Case study: Mapping coastal and marine habitats of the United Arab Emirates (UAE)

Managing for healthy, diverse, productive and resilient coastal and marine habitats to support opportunities for economic diversification including the growth of a sustainable blue economy is a high-level policy goal for the United Arab Emirates. In 2018, Emirates Nature in association with the World Wide Fund for Nature (Emirates Nature-WWF) coordinated a multi-stakeholder coastal and marine habitat mapping project. The project delivered reliable new information on priority coastal and marine habitats to support the United Arab Emirates (UAE) commitment to the Convention on Biological Diversity (CBD 1992) implemented through the UAE's National Biodiversity Strategy and Action Plan (NBSAP 2015).

The project created the first habitat map for the coastal and marine habitats of the north-western emirates using addressing a major knowledge gap in the UAE (Mateos-Molina et al. 2020). The project mapped 17 habitat types across 783 km^2 of seabed. The same mapping framework was then also applied to create a new unified national habitat map for the entire marine realm of the UAE Arabian Gulf including offshore areas (EN-WWF 2019). The unified habitat map provided a critical information to identify Areas of Particular Importance for Marine Biodiversity (APIMBs) (Lamine et al. 2020) (Fig. 4).

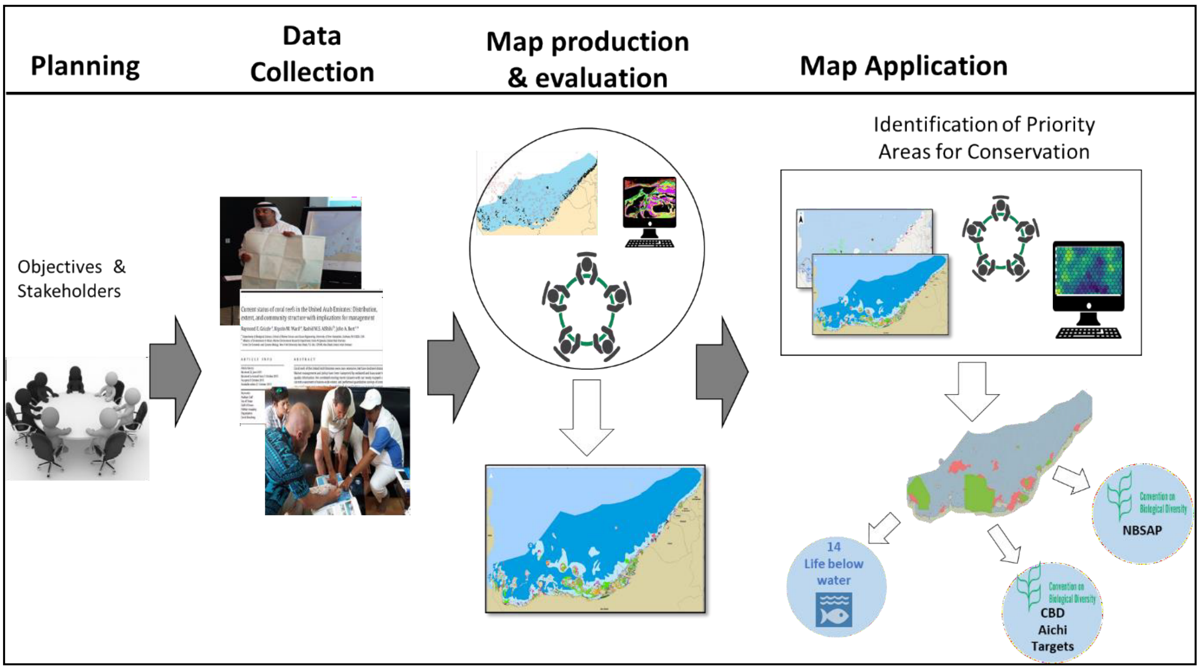


Figure 4. A flowchart of the four-stage habitat mapping methodology from the initial planning with stakeholders to delivery of information products for conservation planning applications to help the United Arab Emirates achieve national and international policy targets for biodiversity conservation.

The four-stage habitat mapping framework was implemented as follows:

Stage 1: Planning. The objective of the mapping focused on mapping priority habitats for conservation with an accurate classification of biological cover types that describe the species composition and the condition of habitats, as well as their geographical distributions. Planning tasks included identifying stakeholders, reviewing existing resources, defining objectives, pinpointing challenges and potential solutions and determining the extent of the study area.

Stage 2: Data Collection. Existing relevant information was compiled from the review of scientific literature (published and unpublished journals, book chapters, conference papers/proceedings, reports and maps), species-based site-specific information (e.g. green turtle satellite tracking to identify deep seagrass used as foraging areas). High resolution Sentinel-2 (10 m) and DubaiSat2 (1 m panchromatic & 4 m multispectral) satellite images of the region were acquired based on spatial, temporal and compositional preference of the project. All spatial data were managed within a Geographical Information System (GIS) database with metadata. Local ecological knowledge (LEK) was gathered through dialogue with local fishers, scuba divers and technical teams from environmental authorities. The integration of local ecological knowledge (LEK) informed ground truthing which increased the efficiency of the fieldwork in Stage 3.

Stage 3: Map production and evaluation. A new habitat classification scheme was created by combining classes from existing habitat maps (EAD, 2015) with additional classes/conservation features recommended by expert stakeholders. A semi-automated method was used to delineate the patch boundaries using manual digitization and editing, as well as machine learning algorithms to classify complex spectral information from satellite data. A total of 1910 ground-truthing points was acquired, including 371 georeferenced ground observations (land surveys, kayak and snorkeler surveys and drop cameras from boats) to validate the map, and 583 to measure quantitatively the map accuracy. All stakeholders involved in the project contributed to the evaluation and validation of the final habitat map. This exercise further delineated unique and vulnerable habitats creating an additional layer of information for managing and understanding critical coastal and marine habitats in the UAE Arabian Gulf.

Stage 4: Applications. Workshops and meetings have disseminated project products and associated knowledge to a wide range of stakeholders. The habitat map is expected to inform regional conservation planning, sustainability policy, science and research, inform accounting of natural capital and to consider critical habitat in the development of a sustainable blue economy. The immediate application is to support strategies for biodiversity conservation through ecosystem-based management actions including Marine Protected Areas (MPA) and Other Effective forms of area-based Conservation Measures (OECM). UAE has eleven MPAs in the Arabian Gulf for a total of fifteen MPAs in the UAE, covering 11% of the UAE Exclusive Economic Zone, that exceed the current CBD Aichi Target 11 goal of 10% (MOCCAE 2018). However, UAE has more ambitious national target for expansion to 14% protected by 2021 (NBSAP 2015). Qualitative targets for representativeness of the region's important habitats and species covered by conservation measures, ecological coherence in MPA network and integration of these measures into the wider landscape and seascape are all supported with the habitat map (Rees et al. 2018). The success or failure in achieving the quantitative and qualitative biodiversity conservation policy targets can depend on how habitats are defined and represented in maps.

4. Discussion

We describe and demonstrate an integrative participatory approach to habitat mapping as an effective spatial tool to support stakeholder decision making in modern marine management. Our approach provides a logical stepwise operational framework for enhanced engagement and knowledge sharing with stakeholders to produce digital coastal and marine habitat maps. The design of the integrative habitat mapping framework was guided by the principle of coordination among multiple stakeholders with overlapping priorities, resulting in collaborative effort and effective sharing of resources and knowledge.

At the core of this framework, there is a suite of interoperable geospatial technologies, including remote sensing (satellite-based image analysis, classification algorithms for data mining, geodatabase management of mapped outputs) and geographic information system (GIS) (data management, map production and statistical analysis). In addition, historical information on habitat distributions, site-specific information on species, and local ecological knowledge (LEK) supported the design and effectiveness of ground truthing efforts further strengthening the framework as a highly collaborative mapping tool. As a result, the input from local stakeholders such as fishers, government agencies/institutions, scientists/researchers, and corporate stakeholders not only benefit data interpretation by addressing data gaps, but also support validation of habitat maps (Vergara-Asenjo et al., 2015).

Through its systematic approach the framework provides a transparent, replicable and cost-effective methodology with sufficient flexibility for broad-scale habitat mapping applicable to landscapes and seascapes in any region. For instance, the integrative habitat mapping framework does not focus on any particular hierarchical system of coastal marine habitat classification scheme, but rather allows for implementation of a targeted classification based on the project-specified goals and objectives.

Interdisciplinary and participatory methodologies permit exchange of information among individuals with different expertise and backgrounds, ultimately resulting in novel solutions and unique products (Bridle et al., 2013; Kendall et al., 2018). For instance, combining scientific technologies with local ecological knowledge (LEK) often allows for more efficient, easily accessible, and cost-effective means of generating baseline information (Lauer & Aswani, 2008b). A systematic approach that incorporates stakeholder engagement methods with local communities for the planning reviewing and data collection elements also promotes societal acceptance of the project and greater uptake of products. Furthermore, successful collaboration builds trust and confidence which may lead to more successful cooperation and partnership work for subsequent projects.

This new framework for integration of multiple sources of information, including LEK across all the stages of the habitat mapping process, however, remains constrained by data quality. One major limitation is the potential for misleading or contradictory LEK, and variable data quality, as well as the socio-political implications of decisions to include or exclude data may have consequences for the effectiveness of conservation planning. Careful verification and quality control of potentially spurious information or erroneous data is therefore essential. The inclusion of an educational element during early consultative discussions, and transparency in data use and interpretation can help to address this limitation and will also highlight data gaps that can be presented in map format.

The Arabian Gulf case study exemplifies the value of integrating LEK at every stage of the mapping process. In fact, the project recognizes the potential for developing and expanding LEK in the mapping process, providing for more robust data input in future. Given that the mapping process is inherently iterative this is an important consideration. In addition, data accessibility should not be overlooked and sharing the results with all data and knowledge contributors can increase the sense of ownership of the final product among key stakeholders and habitat users, ultimately supporting the future application of the map and its derivatives.

This paper focusses on the need to broaden inclusivity in the design and implementation of habitat mapping for coastal and marine environment and encourages streamlined pathways towards knowledge integration. We contend that a more dialectical process has many benefits to both map production and map application helps to share knowledge, avoid conflicting end user requirements and manage stakeholder expectations and ultimately make reliable products that are fit-for-purpose for spatial coastal and marine conservation and management.

General Discussion

General Discussion

Coastal marine habitats occupy the dynamic interface between land and sea and are among the most biologically diverse and productive regions on Earth (Woodroffe, 2002; Eyre & Maher, 2011). These habitats provide many essential ecosystem services supporting human health and well-being, coastal protection and socio-economic development (UN, 2017). However, coastal marine habitats are declining in area, biodiversity and ecological integrity worldwide due to cumulative human impacts (Halpern et al., 2008, 2019; Mooney et al., 2009 Sandifer et al., 2015), which impair the provisioning of ecosystem goods and services (Sousa et al., 2016). Recovery of marine biodiversity is still possible provided that major pressures are mitigated (Duarte et al. 2020); for doing that, however, conservation and management of coastal natural resources typically require accurate and updated, spatiotemporal data; and maps and models are science-based decision support tools able to communicate spatial data about current, predicted, and even past states of the environment.

The knowledge of the important coastal marine habitats and associated species, and the potential impact is indispensable to achieve the 20 CBD Aichi Biodiversity Targets (UNEP/CBD/COP/10/27/Annex) and implement the National Biodiversity Strategy and Action Plans (NBSAPs) of each country. Furthermore, the 2030 Agenda for Sustainable Development, especially Sustainable Development Goal (SDG) 14 Life Below Water, highlight the importance of sustainably manage and protect marine coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration to achieve healthy and productive oceans. Therefore, ongoing efforts at the policy level indicate the importance of improving conservation, restoration, and management of the coastal marine habitats.

Although we understand the value of coastal marine habitat, there is still critical gaps of information regarding the spatial distribution, status and impacts that they receive. Therefore, the importance of spatiotemporal information on these three aspects is key to support the implementation of adequate conservation, restoration and management measures. Besides, cost-effective and replicative tools are indispensable to provide accurate and updated information (Bunce et al. 2013). To produce outputs with those characteristics and overcome limiting factors, integrative approaches using Geographic Information System tools have been shown as good option.

Changes in land cover can increase the runoff of sediments, pollutants and nutrients into coastal waters (Syvitski et al., 2005), having negative effects on benthic habitats due to increased water turbidity and siltation, and declines in water quality. **Chapter II** showed the value of combining the Revised Universal Soil Loss Equation (RUSLE) model and the sediment delivery ratio (SDR) methodology to compare the estimations of sediment delivery yield at the outflow of each basin over time. This low-cost integrative methodology should be an indispensable step to monitor potential outflow impacts, provoked by land cover changes, in coastal areas. Understanding the consequences of land cover changes and the resulting changes in the sediment discharge point is especially important when considering the effect occurring in coupled ecosystems like nearshore coastal marine ecosystems and its adjacent terrestrial watersheds. Ultimately, this study suggests that a holistic ecosystem-based approach to the land-sea complex is crucial. The identification of the outflows with potential runoff increases is critical for the early monitoring and detection of changes in the coastal biodiversity. Preventive measures such as forest conservation or good agricultural practices (e.g. terraces/stone walls, grass margins, contour farming) should be incorporated in land management plans, giving priority to basins that threaten most sensitive marine habitats or, at least, considering this aspect, among others, into well-integrated environmental policies, going beyond the classical application of integrated coastal zone management.

Coastal marine habitat inventories offer the foundation for science-based decision making relevant to spatial management, planning and conservation action that ultimately needs to be integrated into regulatory frameworks, policies and plans. Habitat maps can act as a proxy for articulating spatial patterns of local species diversity (Gray, 1997; Ward *et al.*, 1999) and for spatial prediction of biological distributions (Pittman *et al.* 2007), provide foundations for mapping ecosystem services (Harborne *et al.* 2008; Bianchi *et al.*, 2012; Vassallo *et al.*, 2018), as well as supporting spatial conservation planning, management and monitoring of these habitats (Pittman *et al.* 2011; Caldow *et al.* 2015; Ferrari *et al.* 2018). With the application of spatial pattern metrics CMHM provides quantitative information on the composition and spatial configuration of the seascape (Wedding *et al.* 2011) which is fundamental to our ecological understanding of these ecosystems and our ability to prioritise conservation and restoration actions (Olds *et al.* 2016; Pittman *et al.* 2018,). However, the composition and spatial arrangement of coastal and marine ecosystems are often unknown or poorly described compared to their terrestrial counterparts (Buhl-Mortensen *et al.*, 2015b) and even less well mapped than the surface of some neighbouring planets (Costello, 2019), because of the operational challenges of mapping marine habitats including habitat complexity, water quality conditions, accessibility to these habitats, cost, technological barriers, etc. (Martin *et al.*, 2015).

The combination of scientific technologies with local ecological knowledge (LEK) and their practices often allows more efficient, easily accessible, and cost-effective solutions towards the generation of baseline material through hybrid approaches for accurate coastal and marine habitat maps (Lauer & Aswani, 2008b). **Chapter III** shows the value of combining different data sources to overcome limitations and provide a robust coastal and marine habitat map. The amalgamation of data sources not only supports an accurate and novel map but also provides substantial data to support a more detailed classification i.e. the biotic component of the habitat classification. The map was able to reflect with a 77% of accuracy the habitat diversity and distribution of the study area, and map for the first time key ecological habitats such as oyster beds, coral reefs and deep seagrasses. LEK was crucial in helping to accurately map the complex mosaic habitats of the *khors* and to locate important oyster beds and coral reefs to later ground truth. This mapping exercise is a robust baseline of information to support competent authorities in any future conservation and management initiatives.

Integrative approaches are a pragmatic alternative to conventional habitat mapping and can be greatly beneficiated by the LEK at different stages of the mapping process. It is important, especially for integrative approaches, to develop transparent structural frameworks where various technical, logistic and conceptual problems can be sequentially addressed in a step-wise manner. This framework must clearly defined objectives, an evaluation of available sources of information to address the problem, and determination of appropriate data integration procedures to ensure robust outputs.

Furthermore, the mapping framework should aim to achieve three primary performance characteristics: (1) timely and efficient development of a spatially reliable baseline of information on coastal and marine habitats, (2) efficient methodology to accurately map habitats across broad geographical areas that experience dynamic conditions with varying depth, water clarity and seafloor composition, and (3) effective integration of diverse and best available data sources including LEK. **Chapter IV** presents a logical, stepwise and highly participatory framework for coastal and marine habitat mapping. The mapping framework recognised the value of local knowledge as an important source of geospatial information and this knowledge was integrated at every step of the process. Bringing the LEK into the habitat mapping process from planning through to map validation resulted in effective and collaborative problem-solving and the co-creation of a unique and enriched integrated knowledge product. Furthermore, the framework provides a transparent provision of replication of the habitat mapping, which would be rather easier to implement, as the approach is simple, effective, and cost-effective. It would support conditions for marine conservation and management through long-term strategic planning, societal acceptance, and successful governance for the available ecosystem services derived from the coastal and marine environment.

CONCLUSIONS

Conclusions

Chapter 1 Assessing consequences of land cover changes on sediment deliveries to coastal waters at regional level over the last two decades in the north-western Mediterranean Sea

1. The potential sediment delivery yield to coastal waters in the last two decades showed important changes because of land cover changes.
2. The land cover changes would increase or decrease the potential impact in the nearshore coastal marine habitats through the change of sediment load at the basin outflow.
3. The identification of the outflows with potential runoff increases is critical for the early monitoring and detection of changes in the coastal biodiversity
4. A holistic ecosystem-based approach to the land-sea complex is crucial.

Chapter 2 Applying an integrated approach to coastal marine habitat mapping in the north-western United Arab Emirates

5. This novel integrative approach is appropriate to overcome limiting factors and provide a cost-efficient, robust habitat map.

6. The amalgamation of multiple data sources not only supports an accurate coastal marine habitat map but also provides substantial data to support a more detailed classification i.e. the biotic component of the habitat classification i.e. the biotic component of the habitat classification

7. This study highlights the rich habitat diversity in the "Khors", local wetlands consisting of an interconnected 'mosaic' of different intertidal and subtidal habitats

8. 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.

Chapter 3. An integrative and participatory framework for coastal and marine habitat mapping

9. Through its systematic approach, the framework for coastal and marine habitat mapping provides a transparent, replicable and cost-effective methodology with sufficient flexibility for broad-scale habitat mapping applicable to landscapes and seascapes in any region.

10. The combination of geospatial technologies, geographic information systems and other sources of information such as LEK and historical data can provide robust outputs.

11. There is a need to broaden inclusivity in the design and implementation of habitat mapping for the coastal and marine environment and this framework encourages streamlined pathways towards knowledge integration.

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