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Applying the ecosystem services - EBM framework to sustainably manage Qatar's coral reefs and seagrass beds

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A R T I C L E I N F O

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A B S T R A C T

Given the current natural and anthropogenic threats facing Qatar's marine environment and the consequential expected decline in ecosystem services, this paper examines the potential application of the Ecosystem Services-EBM framework developed by Granek et al. (2010) to sustainably manage Qatar's coral reef and seagrass bed ecosystems. Using interviews with stakeholders and field-collected data from sixteen coral reef sites and 6 seagrass meadows as well as secondary data, the paper presents new knowledge regarding the status of these ecosystems and the benefits they provide that are most valued by stakeholders. The research identifies existing and missing ecological and socio-economic data, as well as the processes and management strategies required to implement the five-step framework within a Qatari context. Key goals for implementing EBM identified by stakeholders include: adoption of scientific planning and valuation of marine environment, contextualizing and drafting legislation, regulations and policies in support of EBM; monitoring and enforcement of laws; and, promotion of public awareness and engagement. The article concludes with recommendations for filling remaining data gaps and highlights opportunities available to Qatar to become a leader in implementing EBM. These include maximizing the increasing role that stakeholders can play in mitigating further decline of the country's coastal ecosystems and leveraging mega events planned in Qatar, such as FIFA World Cup 2022.

1. Introduction

The Persian/Arabian Gulf (PAG) is bordered by eight nations that have undergone dramatic economic transformation since the oil boom of the 1970s (Spiess, 2008). A number of Gulf countries, including Qatar, now rank among the richest nations with the fastest growing economies in the world, and this economic growth supported a demographic swell: populations more than tripled in size in the past four decades, and their annual growth rate (2.1%) is nearly double the global average (1.1%) (Ali et al., 2020; Van Lavieren et al., 2011). With a land area of 11,586 km^2 and a coastline of 563 km (CIA, 2020), the region's entire 2.44 million people live within 100 km of the coast with the coastal population projected to increase in size and density in the coming decade (Van Lavieren et al., 2011). As infrastructure has expanded to support this growing population, of which around 88% are non-Qatari citizens, modification of the coastal and near-shore habitats has often outpaced environmental policy and regulation (Burt and Bartholomew, 2019; Sale et al., 2011). Like the situation in many other Gulf countries, this has resulted in rapid and widespread degradation of important coastal ecosystems in Qatar, including coral reefs and seagrass beds (Burt 2014; Burt et al., 2016, 2017).

Ecosystem-based management (EBM) has been identified as a viable

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approach for addressing the marine and coastal management challenges facing Qatar and, in particular, the negative consequences of sectorial, development-related decisions on coastal ecosystems (Ali et al., 2020; Burt et al., 2017). As a place-based, integrated management approach, EBM considers all major activities and their cumulative impacts affecting the services provided by natural ecosystems (Christensen et al., 1996; Hassan et al., 2005; Levin and Lubchenco, 2008). As noted by Curtin and Prellezo (2010), EBM "is a form of natural resource management … [that] has emerged from the widespread feeling that traditional types of natural resource management have failed and that a new more holistic way of understanding how ecosystems work is needed." (p.821). Given the commitment in the Qatar National Vision 2030 to implement a development approach that is compatible with the ongoing provision of ecosystem goods and services (Tan et al., 2014), as well as the recent efforts to develop an integrated coastal zone management plan for the country (Howard, 2014) and Qatar's Second National Development Strategy (2018–2022), there is an opportunity to begin the process needed to implement an EBM approach in Qatar. Implementing EBM is not without its challenges, especially in top-down, more centralized/authoritarian systems such as those found among the Gulf states. However, efforts to seize the benefits that can be achieved from its implementation have been called for and pursued by individual countries and regions within both the developed and developing world, including the Gulf region (Ali et al., 2020; Arkema et al., 2015; Fanning et al., 2011; Hamza and Munawar, 2009; Tallis et al., 2010).

Given the current natural and anthropogenic threats facing Qatar's marine environment and the consequential expected decline in ecosystem services, this paper examines the potential application of the Ecosystem Services-EBM framework developed by Granek et al. (2010) to sustainably manage Qatar's coral reefs and seagrass beds ecosystems. Using both field collected and secondary data, it identifies existing and missing ecological and socio-economic data, as well as the processes and management strategies required to implement the five-step framework within a Qatari context. The article concludes with recommendations for filling remaining data gaps and a discussion on the increasing role that stakeholders can play in mitigating further decline of the country's coastal ecosystems and the services they provide.

2. Setting the context for marine EBM in Qatar

In addition to the economic wealth that currently sees Qatar as globally ranked second in terms of per capita income derived primarily from offshore hydrocarbon production (CIA, 2020), the Qatari coastal zone is rich in a variety of productive but sensitive ecosystems, namely coral reefs, seagrass beds and mangrove stands (Burt et al., 2017). Historically the population of Qatar has been oriented to the sea with an important heritage tradition of pearl diving, fisheries, trade and ship building (Mitchell and Curtis, 2018). The local dialect is rich in terms that describe the sea, the littoral environment, fish and other marine animals, as reflected in the local folklore of poetry, songs, proverbs and stories (Al-Ghanim, 2014). An essential part of EBM is to integrate knowledge of the natural environment with the cultural heritage and values of the population who use or are impacted by coastal and marine ecosystems. The ecosystem services and benefits they provide to Qatari society include provision of food, healthy coastal waters, recreation, tourism and other economic opportunities as well as aesthetics (Vaughan et al., 2019). The maintenance of such ecosystem services to current and future generations will depend on developing wise management and policy tools to accommodate sustainable human uses and mitigate impact, ensuring ecosystem health and resilience (Sale et al., 2011). However, before such tools can be developed, it is essential to have an understanding of the current state and pressures that are exerted on these ecosystems as well as the socio-cultural and political context underpinning human behaviour in an affluent Gulf state such as Qatar (Speiss, 2008).

2.1. The fragility of Qatar's marine systems

The PAG has environmental conditions that make its coastal ecosystems unusually fragile and susceptible to impacts from human activities. The Gulf is unusually shallow (mean depth <30 m), and the waters around Qatar are often <20 m in depth. These shallow depths result in dramatic seasonal changes in temperature (range >20 °C), and in the summer, waters around Qatar are among the hottest in the world (>34 °C for several months) (Riegl et al., 2011). Evaporation is also high in the Gulf, resulting in extreme salinity (generally >44 PSU to the east and >50 PSU to the west of Qatar, compared with ~37 PSU in the open ocean) (Sheppard et al., 1992). While marine fauna around Qatar are adapted to these conditions, the extreme nature of the environment puts these fauna at the margins of their physiological tolerance (Burt et al., 2019) and any further stress – such as from human activities – can push these species over the edge, and result in mass mortality of organisms across whole ecosystems.

Coral reef and seagrass habitats of Qatar are among the most biodiverse, productive, and economically important coastal ecosystems in the nation. Researchers have estimated 700 km^2 of hard-bottom habitat suitable for reef development within the Qatar Exclusive Economic zone (EEZ) (Ben-Hamadou, 2020). While the diversity of corals on these reefs and in the Gulf as a whole is relatively low due to the extreme environmental conditions, the reefs themselves provide habitat and food resources to support the most diverse community of associated fish and invertebrate species of all coastal ecosystems (Sheppard et al., 1992). Coral reefs in Qatar provide the biogenic structure, food resources, and shelter that serve as an important nursery habitat for juveniles and as a foraging area for adult fish, mollusks and crustaceans. A recent survey in waters adjacent to Qatar has shown that coral reefs support a fish biomass of up to 290 metric tons per square kilometer, which is dramatically higher than the 0.8–1.4 metric tons per square kilometer living in soft-sediment habitats (Grandcourt, 2012). Coral reefs are thus critically important for supporting not only diversity but also the highly valuable commercial fisheries industry which provides food commodities to society and a livelihood to individual fishermen and their families.

In addition to coral reefs, seagrasses are also critically important to human wellbeing and to ecology. All three seagrass species known for the Gulf occur in Qatar, with the main seagrass beds occurring in the northwest coast, between Qatar and Bahrain and on the east coast, around the Al Thakhira marine reserve. They also occur elsewhere in Qatar but remain poorly mapped (Erftemeijer and Shuail, 2012; Warren et al., 2016a). These seagrass beds are highly diverse and support over 500 species of invertebrates, as well as migratory populations of hawksbill and green turtles and dugongs (Erftemeijer and Shuail, 2012), and are considered the most biodiverse ecosystems outside of coral reefs in the Gulf (Basson et al., 1977). Seagrasses are also critically important in supporting juvenile and adult phases of a number of species of commercially important fish, shrimp, and pearl oysters and it has been estimated that seagrass beds support in excess of 4800 kg of fisheries production per square kilometer (Price et al., 1993). Thus, both coral reefs and seagrass beds represent critical resources for biodiversity and economics in Qatar. Despite this importance, efforts to comprehensively map and document the extent and diversity of these systems have been limited (Butler et al., 2020). Developing a better understanding of the location and status of these critical ecosystems is integral to improving management in Qatar.

2.2. Threats to coral and seagrass communities in the PAG

Many of the threats facing coral reef and seagrass ecosystems are common to areas beyond Qatar and the Gulf. However, impacts from climate change, coastal engineering, hydrocarbon exploitation, fishing and urban and industrial wastewater discharges impose added pressures on the resilience of these ecosystems (Vaughan et al., 2019).

2.2.1. Climate change

The PAG has suffered from several severe bleaching events in 1996, 1998, 2002 and most recently in 2010, 2015 and 2017 (Burt et al., 2019). The 1996 and 1998 events were associated with mass mortality of acroporid corals in shallow waters and by 2004 many of these areas had been reduced to rubble with little sign of recovery (Burt et al., 2016). The 2010 bleaching event was associated with extremely high temperatures (more than 3 weeks at temperatures >35 °C and 60–80% bleaching was detected throughout the SE PAG (Burt et al., 2019). The 2017 bleaching event was one of the most extreme on record, resulting in the loss of nearly three-quarters of remaining live coral across the southern Gulf (Burt et al., 2019), when a long period of low winds resulted in summer sea temperatures peaking above 37 °C (Paparella et al., 2019). The loss of adult corals on reefs is now affecting ecosystem-wide reproductive output, suggesting that the capacity for reefs to naturally recover is significantly impaired (Bento et al., 2017; Burt and Bauman, 2019). Such climate-change related impacts to ecosystems are likely to have significant cascade effects on fisheries productivity, and thus society (Wabnitz et al., 2018). These dire observations have led to questions about the future of Gulf reefs and increasingly vocal calls for improved marine management (Ali et al., 2020; Burt et al., 2017; Grizzle et al., 2016).

2.2.2. Coastal engineering

Land reclamation and dredging are major impacts to marine ecosystems in the PAG where more than 40% of the coastline has been altered (Erftemeijer and Shuail, 2012). Many coastal areas around cities and industrial installations are highly altered and sedimentation resulting from dredging and land reclamation can have serious direct and indirect impacts on coral and seagrass ecosystems (Burt 2014). In the vicinity of Doha, heavy mortality may have been exacerbated by siltation resulting from coastal development including the construction of a breakwater and land reclamation for the new Doha International Airport (Burt et al., 2016), the Hamad Sea Port (Karama, 2020), the Sharq Crossing in Doha Bay (Grichting Solder, 2016) and artificial islands, peninsulas and jetties (Darwish, 2014). Such developments also divert coastal currents, altering natural patterns of sedimentation and reduced ecosystem services (Yousif et al., 2018), some of which may be mitigated with ecological engineering (Burt and Bartholomew, 2019). However, these larger scale developments are likely to have serious impacts on marine ecosystems, some of which may include globally important and threatened species such as dugongs (Sheppard et al., 2010; Erftemeijer and Shuail, 2012).

2.2.3. Oil exploitation

The Gulf states produce approximately one-quarter of the world's oil and have seen some of the largest oil spills in history (Sale et al., 2011). The high temperatures, evaporation and photooxidation rates of crude oil in the region can lead to a rapid degradation and dispersal of oil spills, limiting the impacts on the subtidal areas such as coral reefs and seagrass beds (Downing and Roberts, 1993). However, spills have caused large-scale and long-lasting impacts in intertidal systems where spill volume or proximity led to inundation of intertidal areas such as mangrove stands, beaches, and mudflats (Price, 1998). Smaller-scale chronic oil pollution, for example, from ballast water discharge and tar balls, continues to affect many coastal areas across the Gulf (Vaughan et al., 2019).

2.2.4. Fishing

Fishing can lead to the selective elimination of commercial species from marine ecosystems with resulting cascade effects damaging habitats such as coral reefs. Gillnets, traps and the anchors from fishing boats all damage coral and seagrass communities within the PAG region (Grandcourt et al., 2012). Although bottom trawling is totally banned in Qatar since 1992 (Walton et al., 2018), the prevalent use of the multi-hooked grapple known as "manshal" to retrieve the traditional fish traps (gargoors) from the seafloor also has a considerable impact on benthic habitats (Al Maslamani et al., 2018). This is of concern as these habitats are essential to the life history of commercially valuable shellfish and finfish but are also, in the case of seagrasses, important feeding grounds for threatened species. The extent of this problem is largely undocumented in Qatar and elsewhere in the Gulf and was considered by Grandcourt et al. (2012) to be likely substantial, given the highly overfished nature of many shared stocks across the region. According to the latest national fisheries statistics report for Qatar, the percentage of fish stocks within safe biological limits is showing a downward trend, declining from 72% in 2010 to 68% in 2015 (Ministry of Development Planning and Statistics, 2017).

2.2.5. Industrial and urban effluents

Water discharged from coastal power and desalination plants often has a temperature 5–10 °C above ambient and, in the case of the latter, have elevated levels of salinity which can negatively impact marine ecosystems which are already at the limit of their physiological tolerance (Missimer and Maliva, 2018). According to Ali et al. (2020), some outfalls from industrial zones in Qatar may discharge more than one million m^3/h into the marine environment while drainage of ground and surface water around Doha contributes nearly 75.5 million m^3/year. Other effluents may also be present in such discharge waters including antifoaming agents, biocides, antiscalants, cleaning acids and other chemicals with the potential to harm marine life (Erftemeijer and Shuail, 2012).

In Qatar, attention has been given to addressing the above threats in policy documents such as Qatar National Vision 2030 (Qatar, 2008) and the 2018–2022 Second National Strategic Plan of Qatar (Qatar, 2018). These documents speak to the need to achieve environmental sustainability by striking a balance between economic and social development and the preservation of the environment and natural heritage. However, efforts to implement the actions needed to achieve these goals are challenged by a variety of factors. These include the lack of consideration of the cumulative effects of multiple human activities Qatar's coastal zone, attention to and support for other national priorities, a lack of ocean literacy amongst populations in the Gulf States and a limited demand for citizen engagement by decision makers (Sale et al., 2011; Sheppard et al., 2010; Spiess, 2008; Van Lavieren et al., 2011). Within the Gulf States, the latter two identified constraints present additional challenges for Qatar to embrace EBM as the authoritarian mode of governance that has been in existence for centuries within the region limits the involvement of citizen participation. At the same time, the low level of public awareness of marine ecosystem services, coupled with a perceived sense of general well-being among Qataris, minimizes the interest among potential stakeholders to be engaged in decision making (Spiess, 2008).

3. Identifying a framework for EBM in Qatar

An EBM framework is an integrated set of principles, goals, objectives and procedures that together seek to ensure the coexistence of healthy, fully-functioning ecosystems and human communities at multiple scales (Cardinall et al., 2004). Regardless of the location, there are many challenges associated with implementing an EBM approach, not the least of which is the complexity of the socio-ecological interactions that takes place in the area to be managed. Additionally, there is the recognition that decisions being made will have socio-political implications as they have the potential to affect a multitude of stakeholders using the targeted area – some negatively, others positively. As a result, EBM efforts may fail due to competing influences among differing stakeholders, a failure of an effective governance system needed to implement EBM, limited attention to the influence of political and cultural factors, especially in non-westernized settings where stakeholder participation is not encouraged and/or a lack of scientific understanding of the factors affecting the functioning of the natural system (Granek et al., 2010). To assist with this latter barrier to EBM implementation, the 2016–2019 *Integrated Assessment of Qatari Coral Ecosystems: Towards an Ecosystem-based Approach for Management* project, funded by the Qatar National Research Fund was conducted. Data collection included both field and desktop studies on Qatar's coral reefs and seagrass beds, as well as interviews and focus group discussions with stakeholders, aimed at identifying a process for EBM that would specifically contribute to the sustainability these ecosystems.

The framework illustrated in Fig. 1 is based on the work of Granek et al. (2010) who draw on efforts to provide guidance on the participatory process needed to successfully implement EBM from a variety of researchers and practitioners in the field (Daily et al., 2009; Levin et al., 2009). This process has since been adopted by other researchers and practitioners (Kelble et al., 2013; Arkema et al., 2015), including those in the United Arab Emirates (Lamine et al., 2020; Mateos-Molina et al., 2020). It focuses on the need to link the services and as such, the benefits obtained from a given ecosystem to the functioning of that system (Table 1). The authors argue that by doing so, the trade-offs necessary to ensure the functioning of the ecosystem that provide the services valued to differing degrees by stakeholders can be more easily understood by both decision makers and affected stakeholders. Table 1 also demonstrates that multiple ecosystem services may be provided by the same ecosystem function (e.g. nutrient cycling allows for the benefits of fisheries, aquaculture and pollution buffering to be provided). Similarly, multiple functions may be needed to provide a single valued service (e.g. erosion control depends on both sediment trapping and wave attenuation). Hence there is a tight connection between ensuring the overall health of the ecosystem and its proper functioning to the provision of even just one service that might be valued by one or more stakeholders. This recognition of the need to maintain overall ecosystem health is particularly relevant to wealthy Gulf states where some stakeholders might discount the contribution of the goods-provisioning services provided by coral reefs and seagrasses yet value its cultural and regulating services such as aesthetics, recreation, erosion control or carbon sequestration.

3.1. Steps in the ecosystem services – EBM framework

3.1.1. Step 1 – system characterization

The process begins with an understanding of the functioning of the ecosystem based on scientific knowledge as well as soliciting local and traditional knowledge to supplement any data gaps that the natural scientists might have regarding the ecosystem. For coral reef and seagrass ecosystems, scientific knowledge can be obtained from both existing literature as well as field studies to assess the health of the system, its carrying capacity and areal extent, among other ecological and biophysical indicators (Flower et al., 2017). This is paralleled with gaining an understanding of the benefits derived by stakeholders who use the ecosystem, using social science methodologies to rigorously collect and analyse the data provided by these end users. This

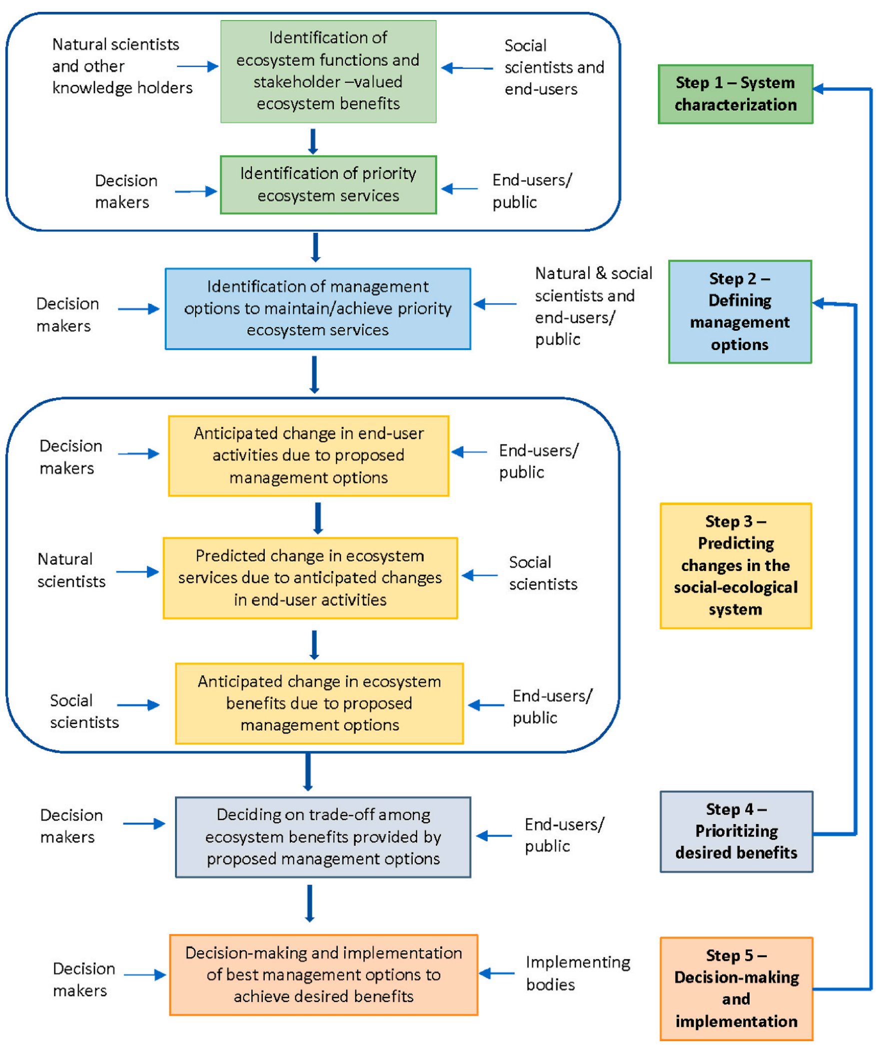

Fig. 1. Ecosystem services – EBM framework (adapted from Granek et al., 2010).

Table 1
Linkages between functioning of marine ecosystems and ecosystem services provided (Adapted from Granek et al., 2010).

Ecosystem functions	Examples of Ecosystem Services											
	Provisioning Services			Regulating Services					Supporting Services	Cultural Services		
	Fisheries production	Aquaculture production	Pharmaceuticals	Climate regulation	Pollution buffering	Erosion control	Carbon sequestration	Storm surges	Primary production	Tourism	Recreation	Aesthetic
Biodiversity	X		X						X	X	X	X
Carbon cycling				X			X					
Evapo-transpiration				X			X					
Habitat	X	X	X						X	X	X	X
Light attenuation	X			X								
Nursery areas	X									X		
Nutrient cycling	X	X			X				X			
Population dynamics	X		X						X	X	X	
Sediment trapping		X				X		X			X	X
Wave attenuation						X		X				

information on both the natural and social system is then shared with decision makers and end users to identify the main suite of ecosystem services generating the key benefits valued by end users.

3.1.2. Step 2 – Defining management options

Following agreement on the focal ecosystem services in Step 1, the next task is for decision makers, social and natural scientists to collectively identify existing and potential management options that could be used to ensure the provision of the priority ecosystem services. These options are then discussed with interested public and end users for their input and feedback. The options that appear to meet the stakeholder preferred uses of the ecosystem while potentially allowing for the ecosystem to generate these benefits are then carried forward into Step 3.

3.1.3. Step 3 – identifying changes in the social-ecological system

Step 3 is the most data intensive part of the Ecosystem Services-EBM framework. Consisting of three sequential components, it incorporates both modelling tools used by natural and social scientists and input from stakeholders and decision makers to predict changes. The intent of this step is to anticipate and respond to the consequences (both negative and positive) that might occur in both the natural and social system as a result of the implementation of each of the management options identified in Step 2.

3.1.4. Step 4 – Deciding on desired benefits

Based on the modelling outputs in Step 3, decision makers and stakeholders, with advice from natural and social scientists, would have the information showing how each of the proposed or existing management options potentially affect end user's activities, the state of the ecosystem and the resulting provision of benefits from the ecosystem, which stakeholders have indicated are of value to them. Given this, an increased understanding of which management options best meets the needs of the end users can be ascertained. Implementing this step of the framework can be expected to generate significant controversy as no single management option will likely achieve all of the benefits desired by all of the end users. However, increasing the awareness of linkages between ecosystem benefits that users expect and setting a standard for the healthy functioning of the ecosystem providing these benefits can lead to recognizing the need for trade-offs that allow for the best management alternative to the desired solution.

3.1.5. Step 5 – decision making and implementation

Having agreement on which set of management options best meets the needs of the end users and the ecosystem, decision makers can then implement the desired options with a level of confidence that reflects the legitimacy of the process. However, it would be idealistic to assume that all end users, despite involvement in the process, would be satisfied. This is because, if not managed carefully, the different steps in the framework can allow for the exercise of influence and power of differing end users and decision makers in the process (Granek et al., 2010). However, depending on the context for decision making, checks such as attention to fair allocation of benefits to current and future generations and attention to cultural and ethical norms can be used to mitigate these influences.

Lastly, it is worth noting that the use of the framework is not a one-time occurrence as both natural and social systems are dynamic. This is especially true in light of the uncertainty surrounding climate change impacts especially in marine ecosystems, leading to the need to revisit the system characterization in terms of both changes to the ecosystem and changes in the benefits the end users demand. For Qatar, this is exemplified in the recent shift within a few generations where end user demands for a marine system that allowed for pearl diving and fishing as key activities have been replaced with other priorities. Such changes, whether as a result of natural or anthropogenic market-based drivers, require ongoing monitoring and evaluation of the data collected over time. As such, decisions made as a result of one iteration of the process may no longer be relevant, necessitating adapting the plan by course correction.

4. Implementing the ecosystem services - EBM framework in Qatar

Primarily through the project led by Qatar University and funded by the Qatar National Research Fund, Qatar has taken steps to begin the process of determining how it might go about implementing an EBM approach to managing Qatar's coral reef and associated seagrass ecosystems (Burt et al., 2017; Ali et al., 2020). Here we highlight the current data available in Qatar to apply each step of the Ecosystem Services-EBM framework, the data gaps that still need to be filled in order for the process to be meaningfully applied and discuss possible strategies for moving forward.

4.1. Characterizing the coral reef and associated seagrass ecosystems of Qatar

The first step in the process requires input from natural scientists and local knowledge holders on the current knowledge of the level of ecosystem functions provided by the Qatari coral reef and sea grass ecosystems, coupled with input collected by social scientists from end users on the benefits derived from these ecosystems. This information can then to be used by decision makers and the public to prioritize the focal ecosystem services provided by coral reef and seagrass ecosystems.

4.1.1. Current status and functioning of Qatar's coral reefs

Despite the estimated 700 km^2 of hard-bottom habitat suitable for reef development within Qatar's EEZ (Ben-Hamadou, 2020), coral communities are currently restricted to the north-eastern tip of the peninsula and around offshore seamounts and islands (Burt et al., 2017). The most comprehensive and reliable studies are the sensitivity mapping of benthic communities along the eastern and western coasts of Qatar and at Halul Island, produced by Creocean for the Ministry of the Environment and published as atlases (MoE, 2010; SCENR, 2007). To gain updated data on Qatar's coral reefs, 16 reef sites were surveyed during this project (Appendix A). Within each site, 6 transects of 11 photoquadrats were assessed. Twelve additional coastal sites based on the historical distribution of corals in Qatar were also visited but found to be heavily degraded, so they were not included in the surveys (Fig. 2).

4.1.1.1. Coral reef functions. As a proxy for estimating the level of ecosystem functioning of the reefs, four benthic categories were chosen to describe reef health: hard coral, hard substrate, urchin, and crustose coralline algae. Additionally, four categories chosen to describe characteristics that may negatively impact the success of reef recovery or restoration were octocoral, algae, unstable substrate, and sponge (Ben-Hamadou, 2020). The negative characteristics were chosen as an indicator for habitat availability for coral recruitment and as a proxy for abundance of herbivorous fish as low algal cover could indicate high herbivore presence. In terms of the ecosystem functions provided by Qatari coral reefs, data from this study and the literature focused on biodiversity, habitat and nursery areas, population dynamics and light attenuating functions. Coral reef fishes were surveyed at nine coral reef sites, including: 2 shallow sites (Fasht Al-Huraibi, and Fasht Al-Udayd, 3–6 m depth), 2 Islands (Sheraoh and Al-Ashat, 3–6 m depth) and 5 offshore sites in the northeast of Qatar (Bulhambar and Ras Dhow, Umm Al Arshan, Mushroom Garden and Fasht East Halul, all at 10–20 m

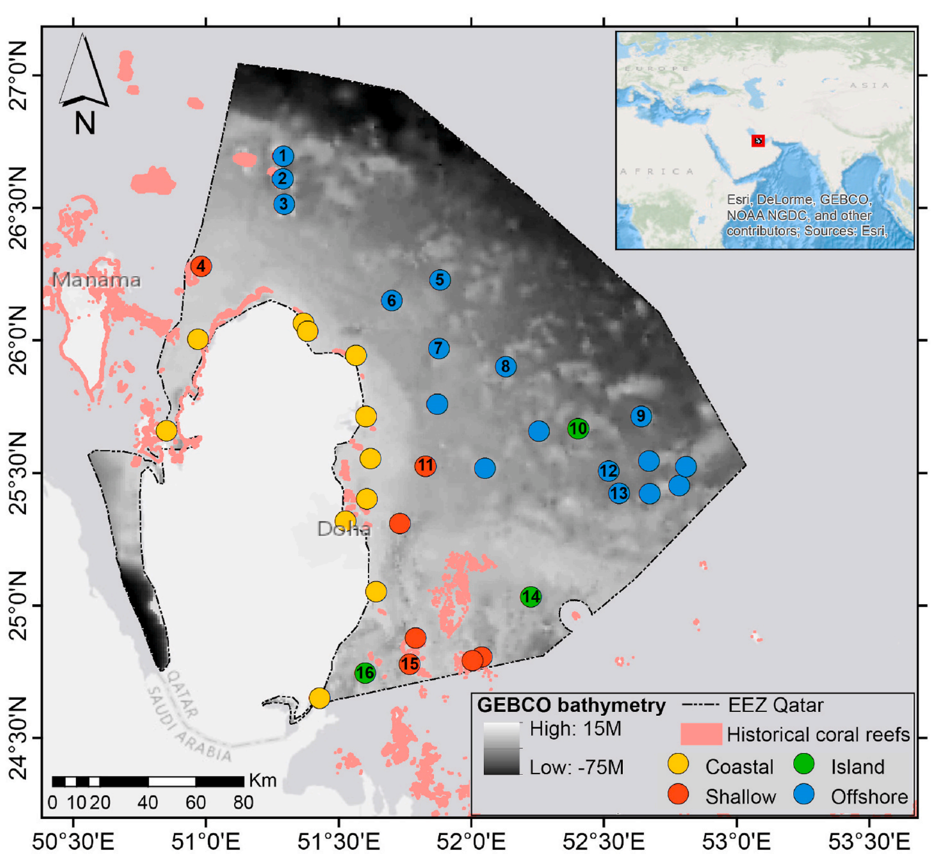

Fig. 2. Map of Coral Reefs within Qatar's Exclusive Economic Zone (EEZ), here delimited by the dotted line, combining data from this study and from published literature. Numbered markers denote the 16 sites surveyed for this study, including: 10 offshore sites (1 - North1, 2 - Binzayan, 3 - Um Al Arshan, 5 - Mushroom Garden, 6 - Um al Shaef, 7 - Balhambar, 8 - Ras Dhow, 9 - Fasht East Halul, 12 - Maydan Mahzam, 13 - Kharaze); 3 shallow sites (4 - Fasht al Dibal, 11 - Fasht al Hurabi, 15 - Fasht al Udayd) and 3 Islands (10 - Halul, 14 - Sheraoh and 16 - Al As'hat).

depth). At each site, fish were visually censused using SCUBA, with all fish observed within 30 m × 1 m belt transects identified to species and enumerated.

Key findings on Qatar's coral reef ecosystem status and functioning based on our study include:

- Thirty-eight stony coral species, distributed within 12 coral families, were identified at the study sites
- Qatari coral reefs communities are now restricted to the north-eastern tip of the peninsula and around offshore seamounts and islands.
- Most of these reefs are severely understudied.
- Total coral species richness observed at each site ranged from 3 to 25 species, with the highest total richness occurring at the deep, offshore sites, where total richness nearly doubled that observed at shallow sites.
- Umm Al Arshan, an offshore seamount in the north of Qatar, has the highest coral species diversity recorded in Qatar (26 species) and one of the highest in the southern PAG, representing a third of the known coral diversity in this region.
- 46 species of fishes from 23 families were observed on coral reefs in this study.
- Mean density of fishes at the deep offshore reefs was 50% lower than at the shallow reef sites.
- The deep offshore seamounts in Qatar represent a unique blend of the diverse, planktivorous dominated reef fish communities of the northern Gulf, while the fish assemblages on shallow reefs are more representative of those across the environmentally extreme southern basin of the Gulf.
- These two divergent environments allow the persistence of quite distinct reef fish communities across a relatively narrow geographic area, enhancing Qatar's overall fish biodiversity.
- The surveys conducted revealed that most of the coastal and shallow (3–6 m) reefs in Qatar are dead or heavily degraded, sustaining only a residual stress-tolerant coral community.
- The reduction of shallow coral communities is paired with an abundant algal cover at those depths where algae easily outcompete corals for light and space.
- The presence of algae at every site is a strong indicator of the lack of herbivores, necessary to promote recovery in reefs affected by bleaching and/or mortality events
- This study has identified a number of intermediate (10–16 m) and deep offshore coral reefs (18–22 m) within the Qatar EEZ, hosting much higher cover and richness than shallower, coastal sites.
- These diverse and abundant intermediate and deep offshore coral ecosystems are believed to be of high importance in supporting coral-dependent fishes and as a source of coral larvae to seed reefs in surrounding nations, suggesting Qatar plays a pivotal role in terms of coral dynamics within the PAG.
- There are indications that change is underway in these offshore reef systems with the once dominant *Acropora* table coral which provides important three-dimensional complexity known to be important in supporting fishes is now a rare occurrence.
- The loss of this formerly-dominant *Acropora* table coral species is likely indirectly impacting the reef-associated fish assemblages.
- Recent analysis of Automatic Identification System (AIS) data,[1] a GPS-based boat tracking system, for the EEZ of Qatar revealed 9 major hotspots for fishing activity which coincided with known offshore coral reefs.
- Fasht East Halul, one of the largest and most diverse reefs in Qatar, was also the area with the highest intensity of fishing activity.
- The overlap of the major fishing hotspots with offshore coral sites is a clear indication of the importance of these habitats to the fisheries sector in Qatar, coupled with the risk posed to them from potential destructive fishing practices and/or gear entanglement.

4.1.2. Current status and functioning of Qatar's seagrass beds

While over 7000 km^2 of seagrass beds have been mapped in the PAG, representing approximately 5% of the global total seagrass area, only 30 km^2 of seagrass beds have been mapped in Qatar, although much larger areas are known to occur (Erftemeijer and Shuail, 2012). As such, seagrass beds likely occupy a significantly larger area than coral reefs, mangrove stands and other important coastal ecosystems in Qatar. To gain more data on Qatar's seagrass meadows, six sites across three locations (near Lusail, Wakra Beach and offshore northwestern Qatar) were monitored during this project (Fig. 3). At each site, 11 photo-quadrats were taken along each of six replicate belt transects (30 m long) (Appendix B). The results revealed significant differences in benthic cover among sites and among transects within each site (Ben-Hamadou, 2020).

4.1.2.1. Seagrass functions. Despite the broad recognition of the importance of seagrass beds to the ecology of the PAG, there have been no published studies that have examined the benthic and fish communities associated with these extensive ecosystems in the region. As such, there is little data on the actual level of seagrass ecosystem functioning associated with biodiversity, habitat and nursery areas, nutrient recycling, population dynamics and light attenuation. As a proxy for understanding the level of the seagrass function, fishes were surveyed at the study sites in June 2017, providing the first insights into fish assemblages associating with seagrass beds in the PAG. While not studied in this project, another proxy for the ecosystem function of seagrass meadows is the dugong ("bugarah al bahr" or "cow of the sea"). It has been estimated that Qatar is home to the world's second largest population of dugongs who use seagrass ecosystems for habitat and feeding. However, relatively little research has been conducted on the Qatari population (Al-Abdulrazzak and Pauly, 2017). In 2016, Warren et al. reported on a 2014-15 survey confirming some 508 individuals, including 51 cow-calf pairs using unmanned aerial vehicles (Warren et al., 2016b). The major activity observed was foraging upon a mixed stand of seagrasses in clear, shallow water. Today, dugongs are seen as a "symbol for conservation in a country that is trying to balance rapid modernization and coastal development with protection of marine biodiversity, as outlined in the Qatar National Vision 2030." (Warren et al., 2016b).

Key findings on seagrass ecosystem status and functioning based on our study include:

- Significant differences in benthic cover were observed among the surveyed sites and among transects within each site. This pattern was largely driven by the dominant species of seagrass *Halodule uninervis* and by 4 other categories: sand, turf algae, fleshy algae and bivalves.
- Among the three studied regions, the West Coast of Qatar has the overall highest density of seagrass.
- Crustose coralline algae (CCA) was only found at Wakra, possibly due to the presence and proximity of hard substrate that would have been built by a former, now dead coral reef.
- Sessile invertebrates were more frequently found at Wakra sites and were mostly represented by oyster spat that had recruited on the seagrass blades.
- A total of 14 species of fish were observed across the six seagrass survey sites. Of these, four species (*Cryptocentrus lutheri*; *Lethrinus nebulosus*; *Siganus luridus*; and *Terapon puta*) were observed across all sites. These four cosmopolitan species were also the most abundant fish overall and within individual sites, making up 92% of the total fish abundance observed across all seagrass sites.
- Despite this study being conducted across three geographically separate locations that are characterized by distinct environmental

[1] Extracted from globalfishingwatch.org.

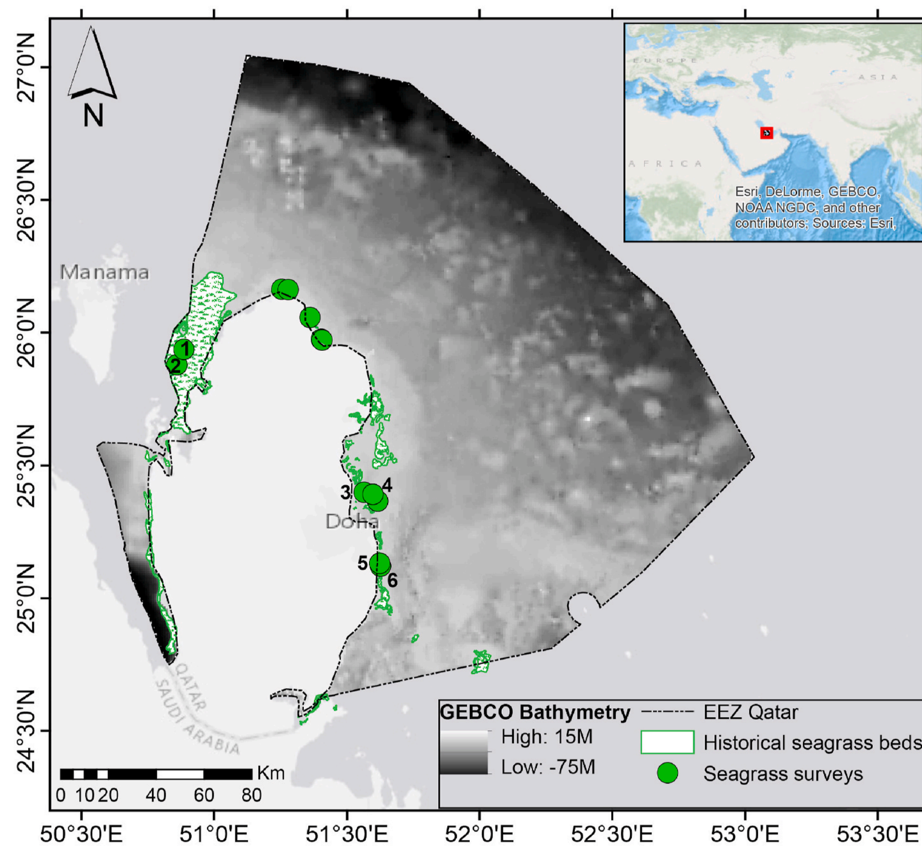

Fig. 3. Map of known seagrass beds within Qatar's Exclusive Economic Zone (EEZ), here delimited by the grey line, combining data from this study and from published literature (MoE, 2010; SCENR, 2007). Numbered markers denote the 6 sites surveyed for this study, including: two sites in the North West coast (1 and 2) and four sites in the East coast, two near Lusail (3 and 4) and two off Wakra beach (5 and 6).

conditions, there is broad similarity in fish communities in seagrass beds, with densities, species richness and overall community structure comparable among all six sites.

- Several of the most abundant and broadly distributed species (e.g. *Lethrinus nebulosus* and *Siganus luridus*) are commercially important species in Qatar. All observed individuals of these species were juveniles, indicating the seagrass ecosystem functioning as important nursery habitat that supports a major economic sector in Qatar.
- These seagrass communities hosted a number of species of fish that are rare or non-existent in other important subtidal habitats in the PAG such as coral reefs, indicating biodiversity functioning of the seagrass ecosystem that is not available at other subtidal habitats, thereby enhancing the overall diversity of fish species present in Qatar.
- Based on the average density of fish observed during the survey, the 30 km^2 of mapped seagrass beds in Qatar is estimated to support in excess of 10.7 million individual fishes. Given that larger unmapped areas are known to occur, this likely represents a very conservative estimate of the total number of fish being supported by seagrass beds in Qatar.

4.1.3. Identification of ecosystem benefits of value to Qatari stakeholders

To gain some perspective on the benefits that stakeholders in Qatar appear to value from coral reef and seagrass meadows, interviews were conducted with a diversity of stakeholders over the period 2017–2019. These included 17 individual interviews with stakeholders spanning sectors that included government, academia, coastal development, fisheries industry and civil society (NGOs, recreational users, private citizens, etc.). A group interview comprising four recreational divers and lasting 90 min was also held as well as a focus group comprising six representatives from the recreational, eco-business, industrial, government and academic sectors which also lasted approximately 90 min. Detailed analysis of these interviews are discussed in an upcoming paper by Al Naimi et al. (unpublished data).

Based on the integrated analysis of the three different forms of interviews, information was obtained on the participants' shared vision for Qatar's marine environment, opportunities for achieving the vision, principles for guiding decisions affecting the marine environment as well as insights into stakeholder derived benefits from coral reef and seagrass ecosystems. Participants vision for Qatar's marine environment can be summarized as follows: ***a healthy marine environment, identified as a place showing a balance in the abundance and diversity of species and habitat, a place where the environment was incredible for recreation, having more access to beaches, and having healthy water quality for both the ecosystem and people. Corals will have the chance to grow and fishes will have the chance to reproduce.*** Participants agreed that tools to implement this vision could include no-take marine protected areas, coupled with building awareness of the marine environment in Qatar. Principles identified by participants to achieve this vision included transparency, accountability, inclusivity and the adoption of the principle of conservation using protected areas as a tool for implementation.

Key findings from the stakeholder analysis include:

- Participants noted that the wording in Qatar's National strategy supports the implementation of an ecosystem-based approach to managing Qatar's coral reef and seagrass ecosystems.

- Qataris need to embrace the slogan “Qatar deserves the best” as the rallying call for implementing the Ecosystem Services – EBM framework.
- Raise awareness among all levels of society and sectors of the wealth and beauty of Qatar’s marine heritage, leading to increased investments in social capital such as capacity building.
- Implement mechanisms to assess the economic value contributed by these ecosystems and understand the trade-off that need to be made so that decisions are based on how to develop in a sustainable manner.
- Increase monitoring and enforcement efforts that are in keeping with existing laws and regulations.
- The most consistent input from all the social collection samples (Interviews, group Interview, and Focus group) was the influential role of political leaders in Qatar to shape EBM implementation and success.
- The upcoming FIFA World Cup 2022 event was seen as a strong driver for implementing Qatar’s 2030 strategic vision and to demonstrate Qatar’s leadership in supporting EBM. The accompanying tourism opportunities were stressed as an opportunity to promote sustainable ecotourism (e.g. whale shark tours) and raise awareness of the need for marine conservation.
- Poor communication with stakeholders limits awareness of existing environmental management efforts that may already be in place.
- Regarding communication, social media was highly recommended as the medium for communication amongst stakeholders and general public.
- Collaboration across sectors, including government agencies, academia, private sector and civil society, was noted as essential.

4.1.4. Identification of focal ecosystem services

This final stage in Step 1 of the Ecosystem Services – EBM framework (Fig. 1), draws on the outputs of the natural and social analysis regarding coral reef and seagrass ecosystems to determine which ecosystem services should be prioritized. This is generally undertaken based on a joint discussion with the stakeholders benefiting from these services and the decision makers. This stage of the process has not yet been undertaken in Qatar and the following guidance is provided only as an example based on the information obtained from the social analysis and the characterization of the natural system.

Key ecosystem benefits that were identified by the diversity of stakeholders interviewed center around the following three ecosystem services:

- *Provisioning*, in the form of fishery production and the potential for aquaculture;
- *Cultural*, in the form of recreational use of the ecosystems (e.g. diving and recreational fishing), aesthetics (clean water and unpolluted marine environment), protection of iconic species (e.g. dugongs and whale sharks) and national pride (e.g. “Qatar deserves the best”);
- *Regulating*, in the form of pollution buffering and climate change.

In terms of provisioning relative to fishery production and from a food security perspective, unlike neighbouring countries, Qatar currently meets most of the fish demands of its residents. Annual production of approximately 15,000 tonnes is harvested by some 624 boats serving the ports of Shamal, Al Khor, Doha and Al Wakra (Ministry of Development Planning and Statistics, 2017). However, in light of its growing population and to minimize relying on imports, maintaining the benefits derived from coral reef and seagrass ecosystems in the form of fish production is critical. How long this can be sustained with existing management is questionable as current advice suggests that the level of production is more than double the maximum sustainable yield, leading to over-exploitation of a number of the commercially important species (Al-Abdulrazzak, 2013). Additionally, the overlap between the coral reef habitats and the fishing resources as well as demersal fishing on the highly productive offshore but shallow hairãt’ habitats, threaten the biodiversity of these areas. Furthermore, illegal fishing is considered a growing problem for Qatar, threatening the ongoing provisioning of fishery resources and the economic importance of the industry despite its small scale. Illegal fishing (e.g. using driftnets) is common due in part to the lack of clarity and poor dissemination of regulations and because enforcement agencies are unable to ensure compliance with regulations (De Young, 2006).

In terms of cultural services, recreational use of the marine environment, particularly around coral reefs, is noted as highly valued. However, there can be additional pressures exerted on the provisioning service with the increase in growth and uncontrolled nature of the recreational fishing sector. This sector was estimated to deploy over 1000 crafts in 2006 resulting in significant quantities of undocumented fish catch (De Young, 2006). Given the country’s rapidly growing population, a corresponding increase in recreational fishing is expected, thus the potential for conflicting focal ecosystem services will need to be addressed.

While not specifically mentioned by the interviewed stakeholders, the supporting service of primary production is linked nonetheless to the value stakeholders placed on fishery production. Likewise, the maintenance of regulating services provided by seagrass beds such as pollution buffering and carbon sequestration as well the dissipation of wave energy by coral reefs are linked to the value placed on these services by stakeholders. The level of priority that is assigned to these ecosystem services by the relevant Qatari decision makers and the public will determine which among them become the focal ecosystem services that need to be maintained through the identification of relevant management actions (Step 2, Fig. 1).

4.2. Identification of management options to maintain focal ecosystem services

As identified in the Ecosystem Services- EBM framework, this step in the framework requires input from natural and social scientists, interested publics and decision makers. While the project was able to obtain input from natural and social scientists and a diversity of stakeholders, decision makers have not had the opportunity to comment on the proposed actions. As such, the following integrated goals, strategies and actions (Table 2) identified by stakeholders from all three interview types (individual, group and focus group) and discussed with natural and social scientists involved with the project are provided only as potential recommended actions.

4.3. Identifying changes in the social-ecological system

Step 3 in the Ecosystem Services – EBM framework explores potential changes that might arise in the social-ecological system based on the management options identified in Step 2. These changes relate to the behaviour of the users, the changes that arise in the natural systems due to these behavioural changes and the consequential impact these changes would have on the availability of the focal ecosystem services in providing the benefits that end users value. Data for this step in the framework are primarily obtained through modelling and the use of scenarios. Since this step in the framework has not been undertaken during the project, a hypothetical example based on the Goal 2, *Contextualizing and drafting legislations, regulations and policies* and the suggested management action aimed at *expanding the establishment of marine protected areas (MPAs)* (Table 2) is presented here to illustrate how this action might affect changes in the social-ecological system.

First, the creation of MPAs is deemed worthy of consideration as a management action as it responds directly to the three identified focal ecosystem services of provisioning, cultural and regulating. This addresses end user benefits of fishery production as both coral reefs and seagrass beds serve as important habitat and nursery areas for fish. It also addresses the maintenance of cultural values associated with

Table 2
Integrated goals, objectives and strategies from stakeholder interviews (individual, group and focus group).

GOALS	STRATEGIES	ACTIONS
•1. Scientific planning and valuation of marine environment	Include scientific knowledge and experience to inform the development of management and monitoring plans	Set up an information framework for Qatar's marine environment that cover various aspects of scientific, social, cultural and economic knowledge
	Align research in Qatar with knowledge gaps and marine management objectives	Design a clear plan to manage the marine environment, supported by scientific research at Qatar University
	Promote the role of education in Qatar in the development and conservation of marine environment	Establish training sessions to develop capacities of fishery workers with good practices of fishing
•2. Contextualizing and drafting legislations, regulations and policies	Coordination and integration between the various ministries and bodies related to the marine environment	Integrate the marine Ecosystem Services -EBM framework into decision-making processes, including regulatory processes and policy-making
	Use current scientific evidence on health of reefs and seagrass areas to declare areas to be protected.	Expand the establishment of marine protected areas (MPAs) Define coastal protected areas, which require complementary marine planning near the beach, on the beach, and within the Gulf waters
	Expand marine ecotourism opportunities	Clarify rule governing marine ecotourism and support expansion in holding events and marine competitions
	Ensure laws for fish, coral, and the marine environment in general are in accordance with goals for protecting the marine environment	Formulating/revising Fisheries and Mining (oil and gas) regulations to reflect newly developed protective strategies
3. Monitoring and enforcement	Take the necessary measures to stop the deterioration of the marine environment immediately and without any delay	Activate existing policies and legislation and put them into effect
	Support participatory monitoring of activities that damage the marine environment	Protect the coral sites from damage by fishing gears such as the gargoors and manshal
	Foster continuous integrated management and monitoring between different government agencies	Develop and implement a process for sharing of information across government departments
	Implement strict control of coastal protected areas	Rigorous monitoring of oil and gas companies and coastal infrastructure activities that pollute the marine environment
	Address illegal fishing and poor gear practice such as ghost fishing as dumping of garbage	Immediately apply deterrent penalties for illegal fishing and for dumping garbage of all kinds on the beaches and at sea
4. Promote public engagement	Mapping out coral reef and seagrass habitat to show potential human use overlap	Disseminate information on the benefits of protecting coral reefs and seagrass ecosystems
	Employ social media in a way that makes planning and management information for the marine environment timely available and understandable to the public	Communicate the penalties that individuals or organizations may be exposed to if they pollute the marine environment through various media
	Promote environmental education in schools and among the public	Building an aquarium to inform people what organisms that should not be hunted and provide them with more attractive information about the marine environment Clean beaches periodically through volunteer work

protecting marine megafauna such as dugongs and allows for benefits associated with aesthetics, recreation and national pride. At the same time, the location of the proposed areas for protection needs to be based on both scientific evidence, (such as the finding of healthy reefs further offshore) and economic impact on the fishing sector as the research conducted for this project found significant overlap between fishing pressure and offshore reefs.

Second, following such an assessment, if a decision is made to consider putting in place an MPA or network of MPAs offshore, it is reasonable to expect a decrease in the availability of the protected area for commercial fishing activity. Assuming monitoring and enforcement policies are implemented along with the creation of the MPA, this will generate a behavioral change resulting in a decrease in the pressure exerted on the reefs and an expected increase in the status of the biodiversity associated with the reefs. Additionally, this action could potentially protect the health of the reefs, at least from local anthropogenic impacts. Taken together, it is reasonable to hypothesize that these changes in both behaviour and the improved status of the ecosystem in terms of health and biodiversity would result in the ongoing provision of benefits that end users value.

4.4. Deciding on desired benefits

To implement step 4 of the framework, all affected stakeholders and decision makers are recommended to be involved in the discussions on which management options should be pursued. The aim is to acknowledge and identify the trade-offs needed as not all stakeholders' expectations could be met simultaneously. In such a situation, the recommended action focusing on the expansion of MPAs may require agreeing on alternative fishing areas and/or providing alternative livelihood opportunities. The modelling and scientific expertise of natural and social scientists, including economists, is required for informed selection amongst management options. This allows the costs and benefits, to both the end users and focal ecosystem services, to be assessed for each option. While this has not been done during our study, it is an essential part of informed decision-making.

4.5. Decision making and implementation

This final step in the framework rests with the decision makers who are mandated to design policy on behalf of the people of Qatar. Our study has identified the implementation of the Ecosystem Services – EBM framework as a mechanism for supporting the sustainability of Qatar's coral reef and associated seagrass bed ecosystems. However, the quality of information provided to assist with such decisions depends on the availability of knowledge required to effectively conduct each step in the framework. Our study has contributed significant new knowledge on the status of Qatar's coral reef and seagrass ecosystems and for the first time, has solicited end user values of ecosystem benefits. This provides the basis to initiate the remaining steps of the framework, starting with joint deliberations of the study findings with decision makers, end-users and interested members of the public, supported by relevant natural and social science expertise. As highlighted in Table 2, decision makers in Qatar have the opportunity to start to implement some of these actions with the existing level of knowledge and to use these initiatives to advance an adaptive 'learning by doing' approach.

5. Conclusion

Through the project entitled *Integrated Assessment of Qatari Coral Ecosystems: Towards an Ecosystem-based Approach for Management, NPRP No.: NPRP8-952-1-186*, led by Qatar University and funded by the Qatar National Research Fund, Qatar has begun the process of acquiring the data needed to begin applying the Ecosystem Services – EBM framework. The work undertaken has led to valuable insights regarding both the natural environment as well as the value that different stakeholders are placing on the coral reef and seagrass ecosystems. Most significantly, it has resulted in the identification of a number of goals, strategies and actions that potentially may be assessed further by Qatari policy- and decision-makers and the public for implementation.

The work undertaken in this project has increased the current level of knowledge regarding coral reef and seagrass ecosystems and the benefits derived from them by a subset of the population. With the number of anthropogenic and natural threats facing these ecosystems, this increase in knowledge provides the opportunity to establish priority actions that specifically respond to the benefits valued by Qataris. As identified from this study, key among these are maintaining fish production and ensuring the recreational, cultural and aesthetic benefits provided by coral reef and seagrass ecosystems. The opportunity now exists to take a prioritized, precautionary, "learning by doing" approach that is uniquely Qatari to ensure the risks to the maintenance of these benefits are understood and addressed. As an example, both climate change impacts and overfishing have been shown to be mitigated by establishing marine protected areas and depending on their locations and allowable activities, can also preserve cultural, recreational and aesthetic values (Green et al., 2014). Similarly, while coastal engineering has served as a threat to coastal and marine environments, recent examples of ecological engineering have been used to mitigate against further degradation (Burt and Bartholomew, 2019). Acquiring additional natural scientific knowledge on these ecosystems is continuing with the support of funding from the Qatar National Research Fund. However, a number of challenges exist in order to use this newly acquired knowledge to influence stakeholders' behaviour and to ensure the implementation of informed decisions in Qatar. Nonetheless, as identified in the findings from the social analysis, the opportunities exist within Qatar to successfully overcome these challenges. Key opportunities for a way forward are reiterated here, given their potential to make Qatar a leader in advancing EBM, not only among Gulf states, but globally:

- The need to increase awareness of the importance of Qatar's natural marine environment to the ongoing provision of benefits that the population value. Sustainable management of the environment relies heavily upon the capacity of all stakeholders and the wider community of Qatar. This approach is already reflected in the government's objective of "Incorporating ownership into institutional plans with improved monitoring and reporting mechanisms" (Planning Statistics Authority, 2018).
- Stakeholders were unanimous in suggesting that a transition towards sustainable marine resource management could be navigated by embedding EBM objectives into the timelines of Mega-Events (such as the FIFA World Cup 2022) and the national strategies and targets (National Development Strategy, 2018–2022 and Vision 2030).
- Approaching high profile leadership, and influential institutions, such as Qatar Museums, increasing the social responsibility for natural heritage, and bridging the ecosystem generational gap to minimize the "shifting baseline syndrome" (where the current generation use only what they can see as their frame of reference rather than what was and could be again). This was seen as an essential way to generate progress in EBM. Additionally, stakeholders recommended the need for the Supreme Council for Legacy to communicate and fulfill some of the necessary steps such as utilizing Qatar's natural marine wealth for ecotourism and highlighting the cultural heritage of its coral reefs and seagrasses.
- Extensive reporting of existing efforts and regulations by the Ministry of Municipality and Environment would increase access to information, and boost public confidence in the regulators, and their commitment to enforcing environmental legislation. These steps would address the goals of raising awareness and the profile of Qatar's reputation as environmentally progressive in the region.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Data Collection, Analysis and Results of 16 Coral Reefs in Qatar

(Source: Ben-Hamadou, R. 2020. *Integrated assessment of Qatari coral ecosystems. Towards an Ecosystem-based Approach for Management*. NPRP8-952-1-186. Final Technical Report, April 2020. Qatar National Research Foundation).

Sixteen reef sites were surveyed, including 5 deep offshore sites (North-1, Binzayan, Um Al Arshan, Mushroom Garden, Fasht East Halul), 5 intermediate offshore sites (Bulhambar, Um al Shaer, Ras Dhow, Kharaze, Maydan Mahzam), 3 shallow sites (Fasht al Dibal, Fasht al Hurabi and Fasht al Udayd) and 3 Islands (Halul, Sheraoh and Al As'hat). Within each site, 6 transects of 11 photoquadrats were assessed. Four benthic categories chosen to describe reef health were: hard coral, hard substrate, urchin, and crustose coralline algae, and the four categories chosen to describe characteristics that may negatively impact the success of reef recovery or restoration were octocoral, algae, unstable substrate, and sponge. The negative characteristics were chosen as an indicator for habitat availability for coral recruitment and as a proxy for abundance of herbivorous fish (low algal cover could indicate high herbivore presence). Coral reef fishes were surveyed at nine coral reef sites, including: 2 shallow sites (Fasht Al-Huraibi, and Fasht Al-Udayd), 2 Islands (Sheraoh and Al-Ashat), 2 intermediate offshore sites (Bulhambar and Ras Dhow) and 3 deep offshore sites in the northeast of Qatar (Umm Al Arshan, Mushroom Garden and Fasht East Halul). At each site, fish were visually censused using SCUBA, with all fish observed within 30 m $\times$ 1 m belt transects identified to species and enumerated.

Table A.1
Scleractinian (hard) coral species presence, distribution, and site species diversity and mean cover at each coral reef investigated in this study.

	Al Ashat	Binzayan	Bulhambar	Fasht Al Dibal	Fasht Al Hurabi	Fasht Al Udayd	Fasht East Halul	Halul	Kharaze	Maydan Mahzam	Mushroom Garden	North-3	Ras Dow	Sheraoh	Umm Al Arshan	Umm Al Shaer	Total
Acanthastrea echinata							×								×	×	3
Acropora clathrata		×															1
Acropora downingi		×						×						×		×	4
Acropora tortuosa							×										1
Alveopora tizardi							×										1
Anomastraea irregularis		×	×								×	×	×		×	×	7
Coscinaraea monilis								×	×			×	×		×		5
Cycloseris curvata											×		×				2
Cyphastrea microphthalma	×	×		×	×	×	×	×	×	×				×			10
Cyphastrea serailia				×				×									2
Dipsastraea favus		×	×				×	×	×	×	×	×	×		×	×	11
Dipsastraea pallida	×	×	×				×	×	×	×	×	×	×	×	×	×	13
Dipsastraea speciosa	×		×				×		×	×	×	×	×	×	×	×	11
Echinophyllia aspera		×															1
Favites acuticolis		×	×				×	×	×	×	×	×	×		×	×	11
Favites pentagona		×	×				×		×	×	×	×	×	×	×	×	11
Goniopora lobata		×	×				×		×		×	×			×		7
Hydnophora pilosa							×										1
Leptastrea purpurea		×							×	×	×				×		5
Leptastrea transversa	×	×			×		×		×	×		×	×			×	9
Pavona cactus											×						1
Pavona decussata		×					×	×			×	×			×	×	7
Pavona ccf explanulata							×				×		×		×		4
Platygyra crosslandi		×															1
Platygyra daedalea	×	×	×	×	×	×	×	×	×	×	×	×		×	×	×	15
Platygyra lamellina		×	×				×		×		×				×	×	7
Platygyra sinensis		×															1
Plesiastrea versipora		×	×				×		×		×	×	×		×	×	9
Porites harrisoni	×			×		×		×						×			5
Porites lobata		×			×												2
Porites lutea	×	×	×	×			×	×	×	×	×	×	×		×	×	13
Psammocora albopicta		×	×				×		×		×	×	×		×	×	9
Psammocora profundacella		×	×				×	×		×						×	6
Psammocora stellata	×	×	×				×	×	×	×	×		×		×	×	11
Sclerophyllia maxima							×										1
Siderastrea savignyana												×			×		2
Turbinaria peltata		×	×							×	×	×	×		×	×	8
Turbinaria reniformis		×									×	×			×		4
Species Diversity	8	25	14	5	4	3	22	13	16	13	20	17	15	7	21	18	
Stony Coral Cover (%)	*8*	*37*	*14*	*19*	*8*	*9*	*39*	*9*	*3*	*9*	*27*	*5*	*5*	*13*	*31*	*17*	

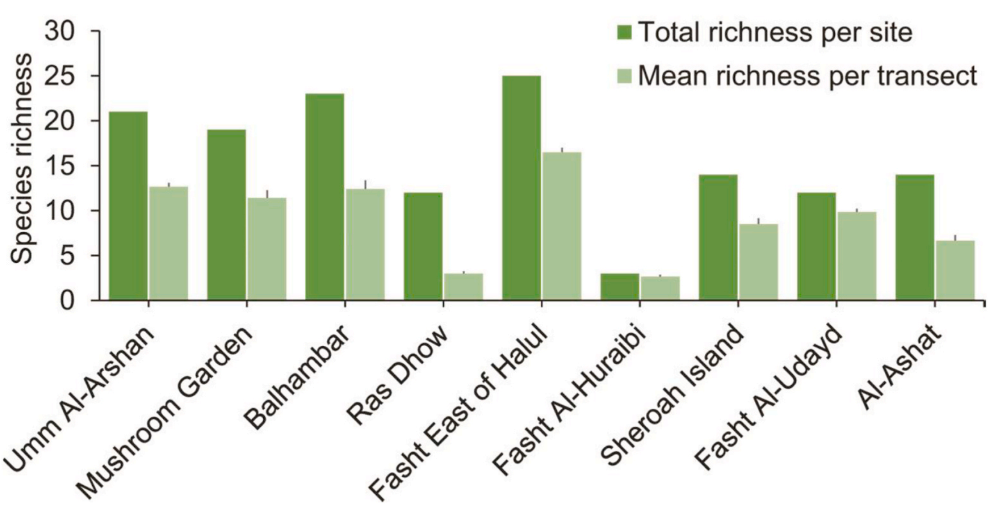

Fig. A.1. Total species richness per site and mean species richness per transect (±SE) of fishes observed at nine coral reef sites in Qatar.

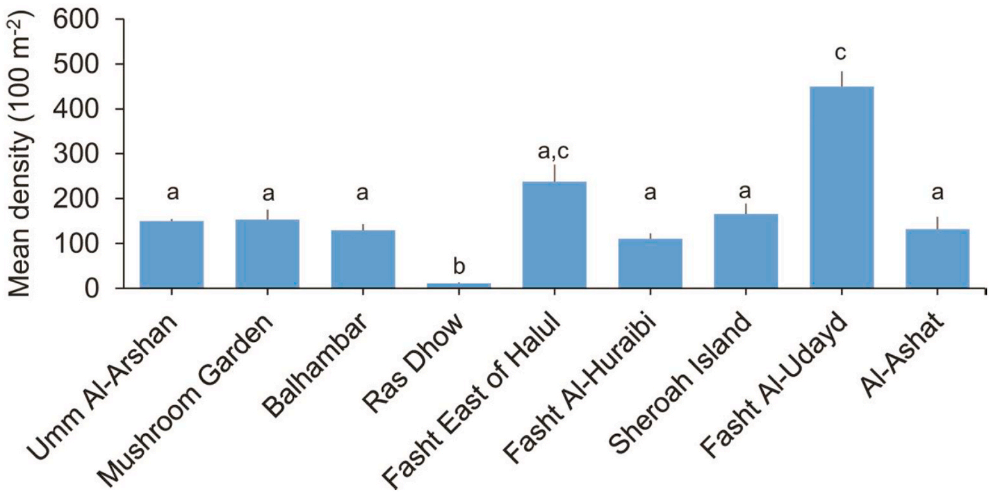

Fig. A.2. Mean density of fishes (±SE 100 m-2) at nine coral reef sites in Qatar. Different letters indicate a significant difference (Tukey's unequal-N test, $p < 0.05$).

Appendix B. Data Collection, Analysis and Results of Six Seagrass meadows in Qatar

(Source: Ben-Hamadou, R. 2020. *Integrated assessment of Qatari coral ecosystems. Towards an Ecosystem-based Approach for Management*. NPRP8-952-1-186. Final Technical Report, April 2020. Qatar National Research Foundation).

In this study, a total of 396 seagrass photoquadrats (0.25 m^2) were collected from six sites across three locations, including two sites adjacent to Wakra Beach, two sites near Lusail, and two sites offshore from northwestern Qatar. At each site, 11 photoquadrats were taken along each of six replicate belt transects (30 m long), amounting to 66 photoquadrats per site, covering a total area of 16.5 m^2. Subsequent identification and quantification of was done using the 19 categories listed in Table 1, including the 3 species of seagrass: *Halophila stipulacea, Halodule uninervis* and *Halophila ovalis*. Visual surveys of fish were performed using SCUBA. At each site, fish were censused within six replicate 30 m × 1 m belt transects that were spaced approximately 5 m apart, with all fish observed within transects identified to species and enumerated to estimate total abundance.

Table B.1
List of the 19 benthic categories applied in the classification of seagrass photoquadrats.

Short Code	Functional Group	Name
ANUN	Other Invertebrates	Anemone, unidentified
Brz	Other Invertebrates	Bryozoan
Bvv	Other Invertebrates	Bivalve
CCA	Algae	CCA
DeadSG	Seagrass	Dead seagrass
FALG	Algae	Fleshy algae
HalStipula	Seagrass	*Halophila stipulacea*
HalUni	Seagrass	*Halodule uninervis*
HOV	Seagrass	*Halophila ovalis*
Other	Other	All other
RckPav	Hard Substrate	Rock_Pavement
Rubble	Hard Substrate	Broken coral rubble
Sand	Soft Substrate	Sand
SHAD	Other	Shadow
ShellHash	Soft Substrate	Shell hash/Gravel
Sponge	Other Invertebrates	Sponges
Trans	Other	Transect hardware
Turf	Algae	Turf
Unc	Other	Unclear

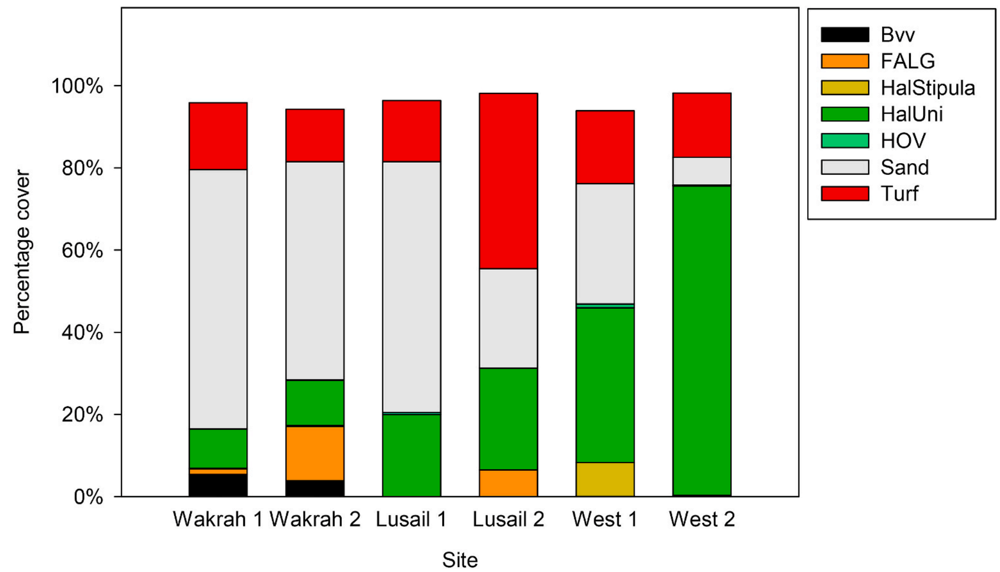

Fig. B.1. Percentage cover of the dominant benthic categories at each of the six seagrass meadows surveyed in Qatar; staked bars represent the average cover of each category in the six transects sampled in each site.

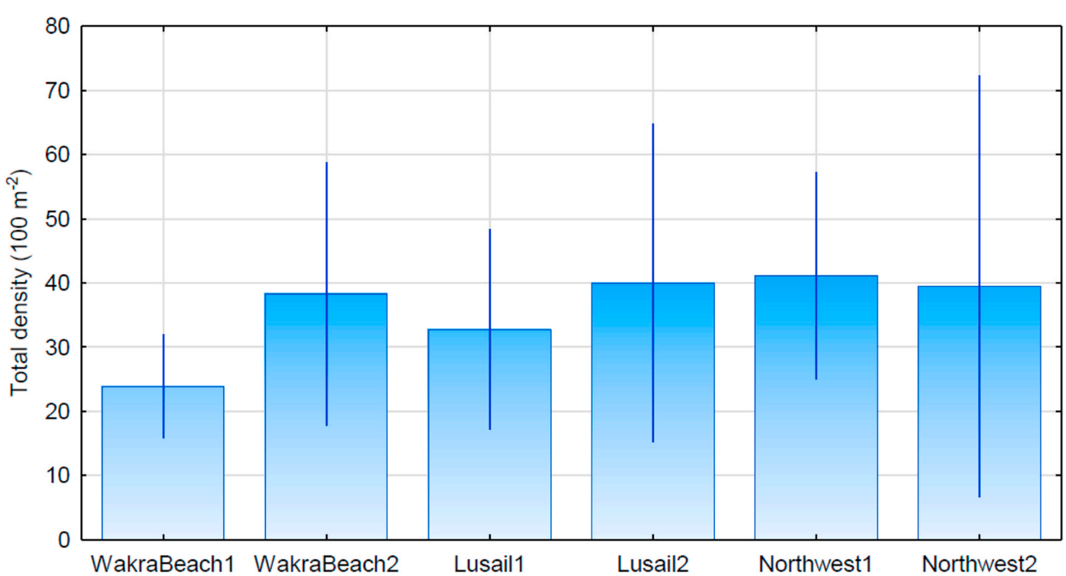

Fig. B.2. Mean density (±SE) of fishes (100 m-2) at each of the seagrass sites in Qatar

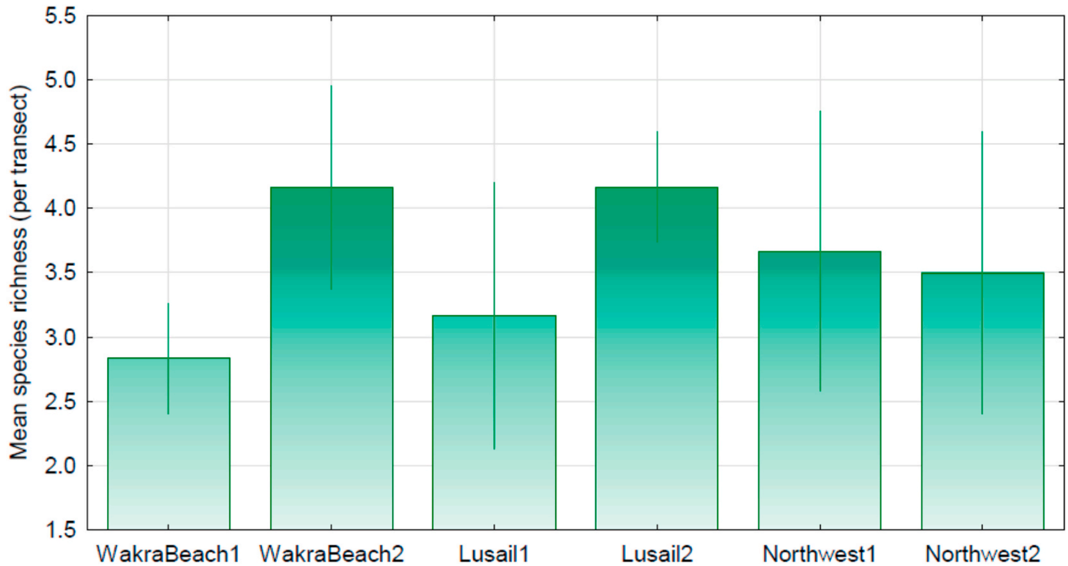

Fig. B.3. Mean species richness (±SE) of fishes (per transect) at each of the seagrass sites in Qatar

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