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OUT OF THE BLUE

THE VALUE OF SEAGRASSES TO THE ENVIRONMENT AND TO PEOPLE

WORLD SEAGRASS ASSOCIATION

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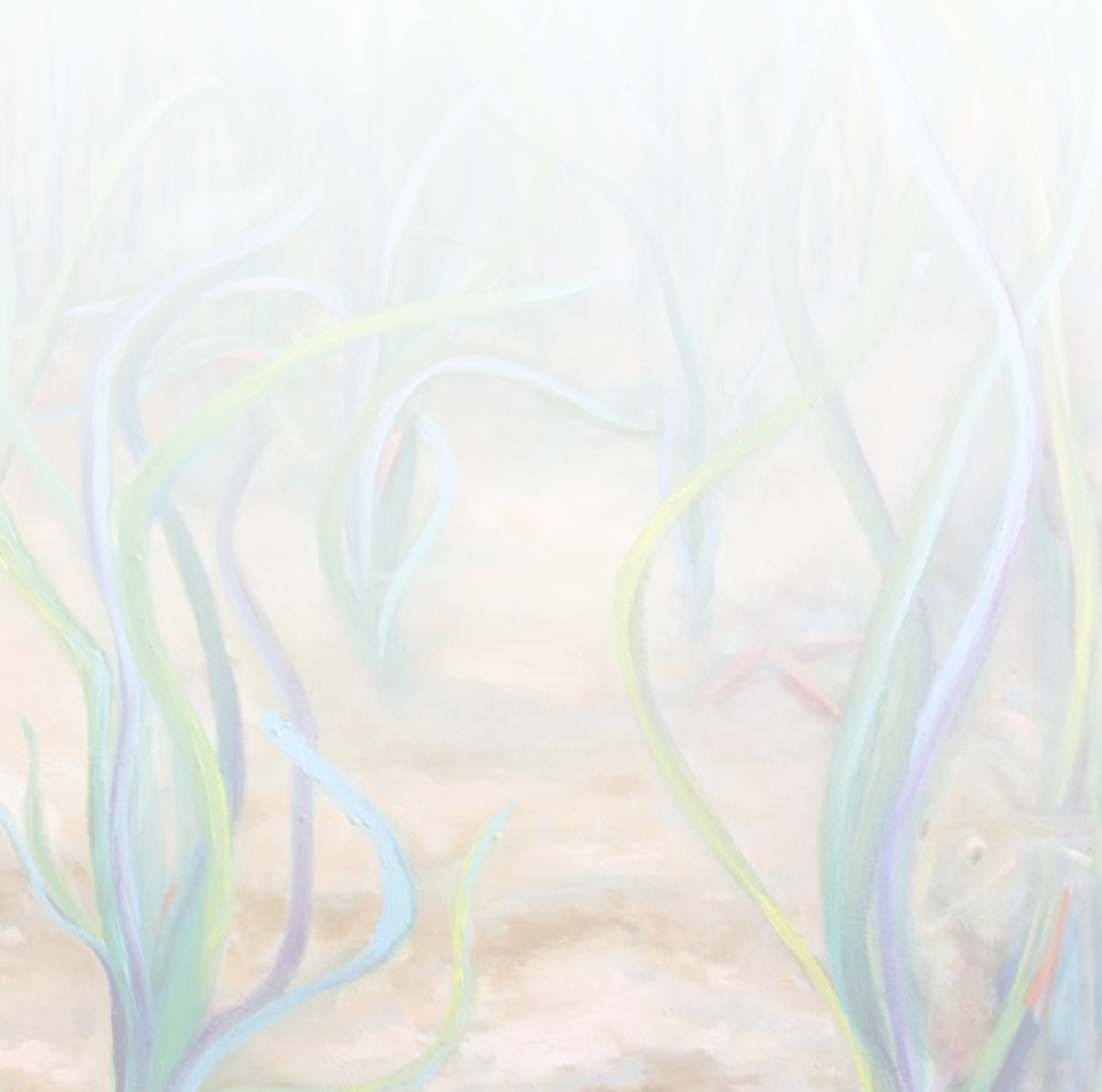
OUT OF THE BLUE

THE VALUE OF SEAGRASSES TO THE ENVIRONMENT AND TO PEOPLE



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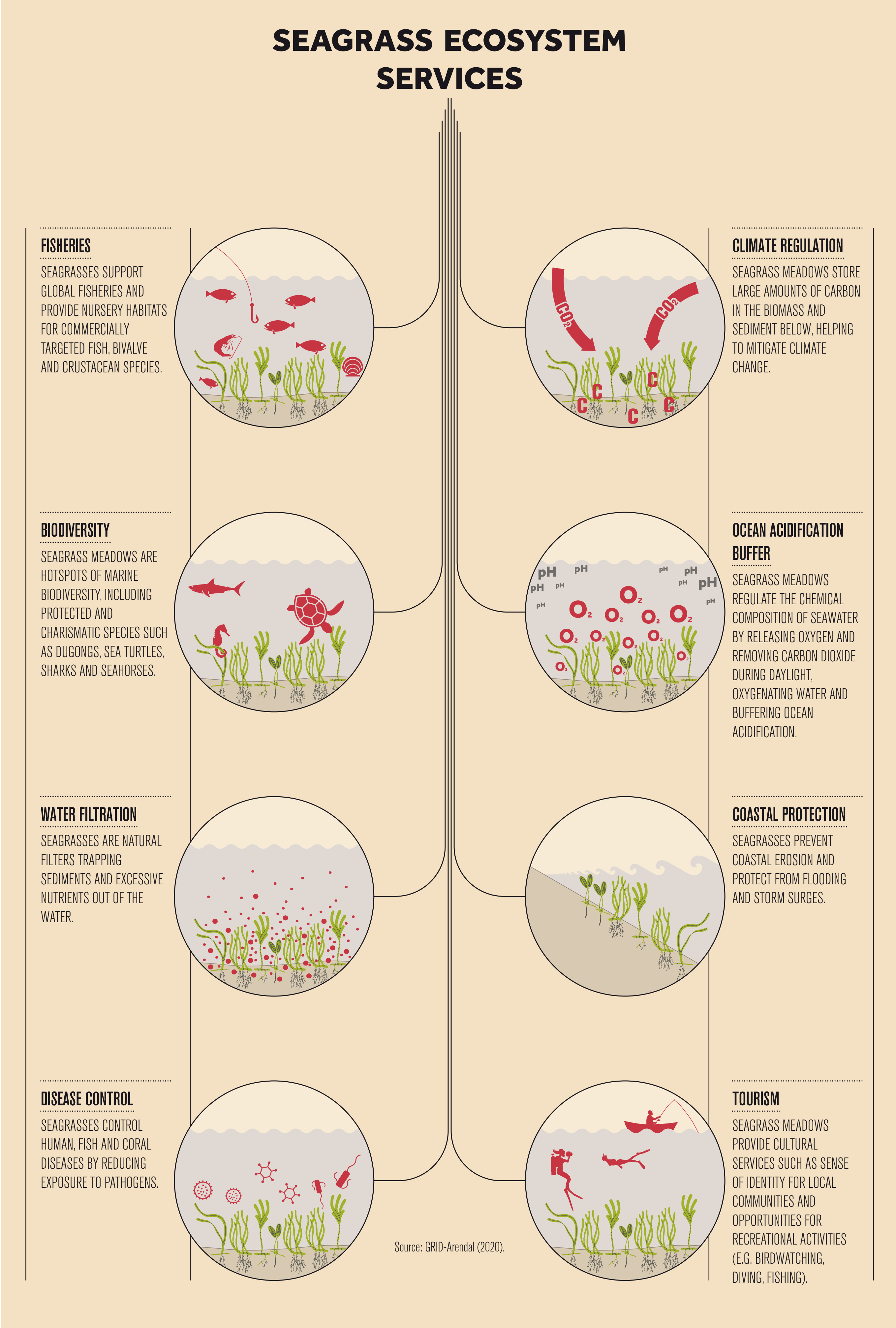
OUT OF THE BLUE

THE VALUE OF SEAGRASSES TO THE ENVIRONMENT AND TO PEOPLE

PART 1

SCIENTIFIC EVIDENCE

FIGURE 2



Source: GRID-Arendal (2020).

SEAGRASS ECOSYSTEM SERVICES: ASSESSMENT AND SCALE OF BENEFITS

Carmen B. de los Santos, Abbi Scott, Ariane Arias-Ortiz, Benjamin Jones, Hilary Kennedy, Inés Mazarrasa, Len McKenzie, Lina Mtwana Nordlund, Maricela de la Torre-Castro, Richard K.F. Unsworth, Rohani Ambo-Rappe

All authors' affiliations are found on page 4

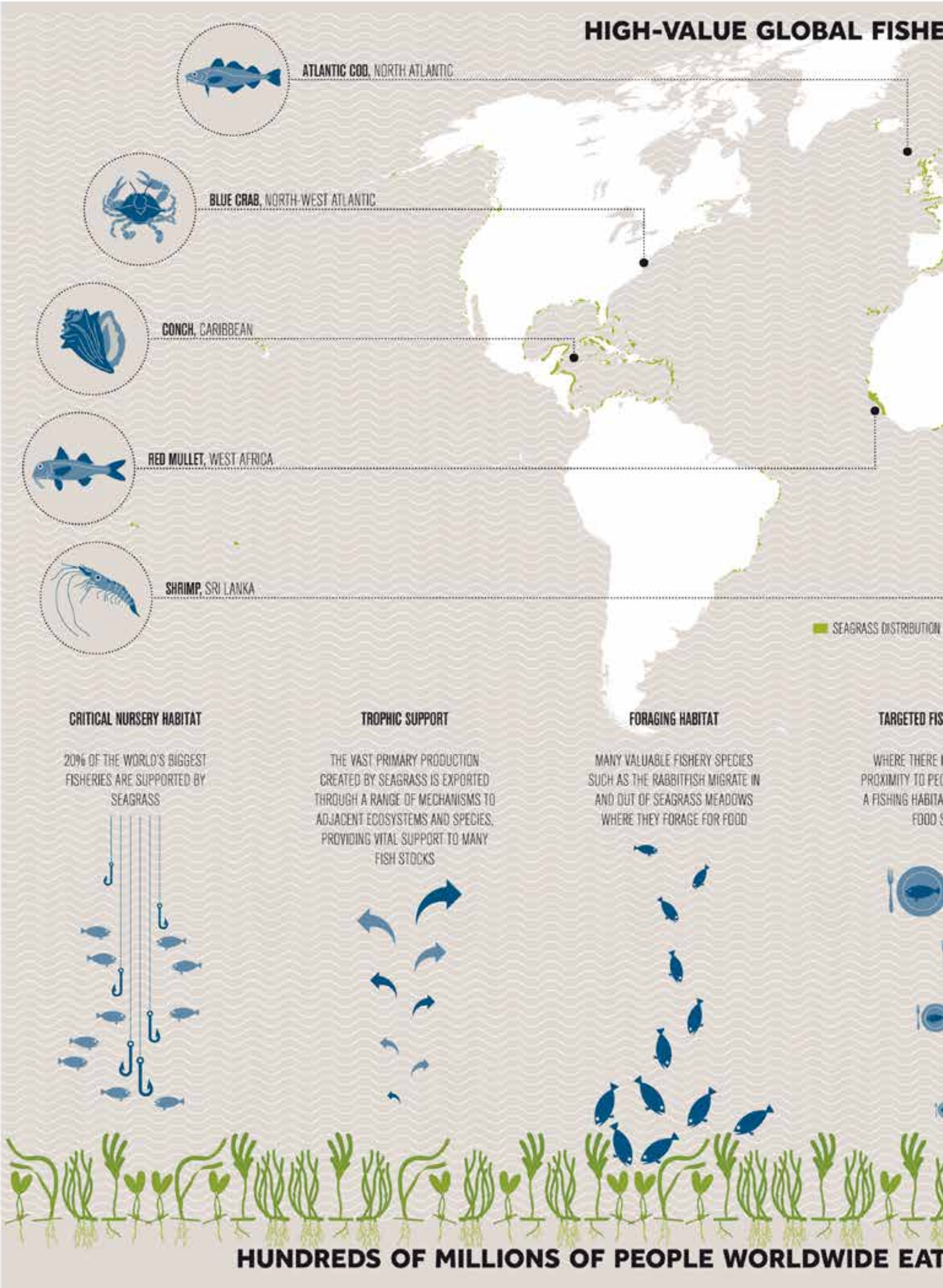
Seagrass ecosystems provide a wide variety of services that support human well-being around the world (Barbier et al. 2011). It is estimated that more than 1 billion people live within 100 km of a coast with seagrass meadows, thus potentially benefiting from their provisioning, regulating and cultural services. Seagrasses play a significant global role in supporting food security, mitigating climate change, enriching biodiversity, purifying water, protecting the coastline and controlling diseases (Figure 2). The integrity and provision of services by seagrass meadows are enhanced by their proximity and connectivity to other coastal ecosystems such as tidal marshes, coral reefs, mangrove and kelp forests, and oyster and mussel beds. The maintenance and regulation of these services is therefore essential to support human well-being and promote development in the future.

Seagrasses support world fisheries production

Seagrass meadows are of fundamental importance to world fisheries production of both vertebrates and invertebrates in various ways (Nordlund et al. 2018; Unsworth et al. 2019) (Figure 3). Seagrass meadows provide valuable nursery habitat to over one fifth of the world's largest 25 fisheries, including walleye pollock, the most landed species on the planet (Unsworth et al. 2019). Juveniles of high-value stocks, such the Atlantic cod, have improved growth rate and survival when living in seagrass and intentionally choose this habitat (Lilley and Unsworth 2014). Seagrass fisheries around the world have subsistence, commercial and recreational value, targeting anything that can be eaten, sold or used as bait worldwide. In cases where seagrass meadows are in close proximity to communities, they are often an important fishing habitat for local food supply (Nordlund et al. 2018). Invertebrate gleaning fisheries occurring within seagrass meadows are considered to be an accessible fishing activity mainly due to their shallow nearshore environment and the ease of collecting such fauna (Unsworth et al. 2019). In many parts of the Indo-Pacific region, these gleaning fisheries are vital for maintaining daily protein needs and alleviating poverty (Unsworth et al. 2014). In many cases, the beneficiaries of the fisheries supported by seagrass meadows are not co-located. Seagrasses provide 'extra-local' benefits to people that do not live next to the seagrass meadows or even in coastal areas, such as in the case of Atlantic cod (see case study 1). Seagrasses also have a range of indirect roles in enhancing fisheries, such as providing a trophic subsidy to offshore or deeper water fisheries or filtering terrestrial run-off.

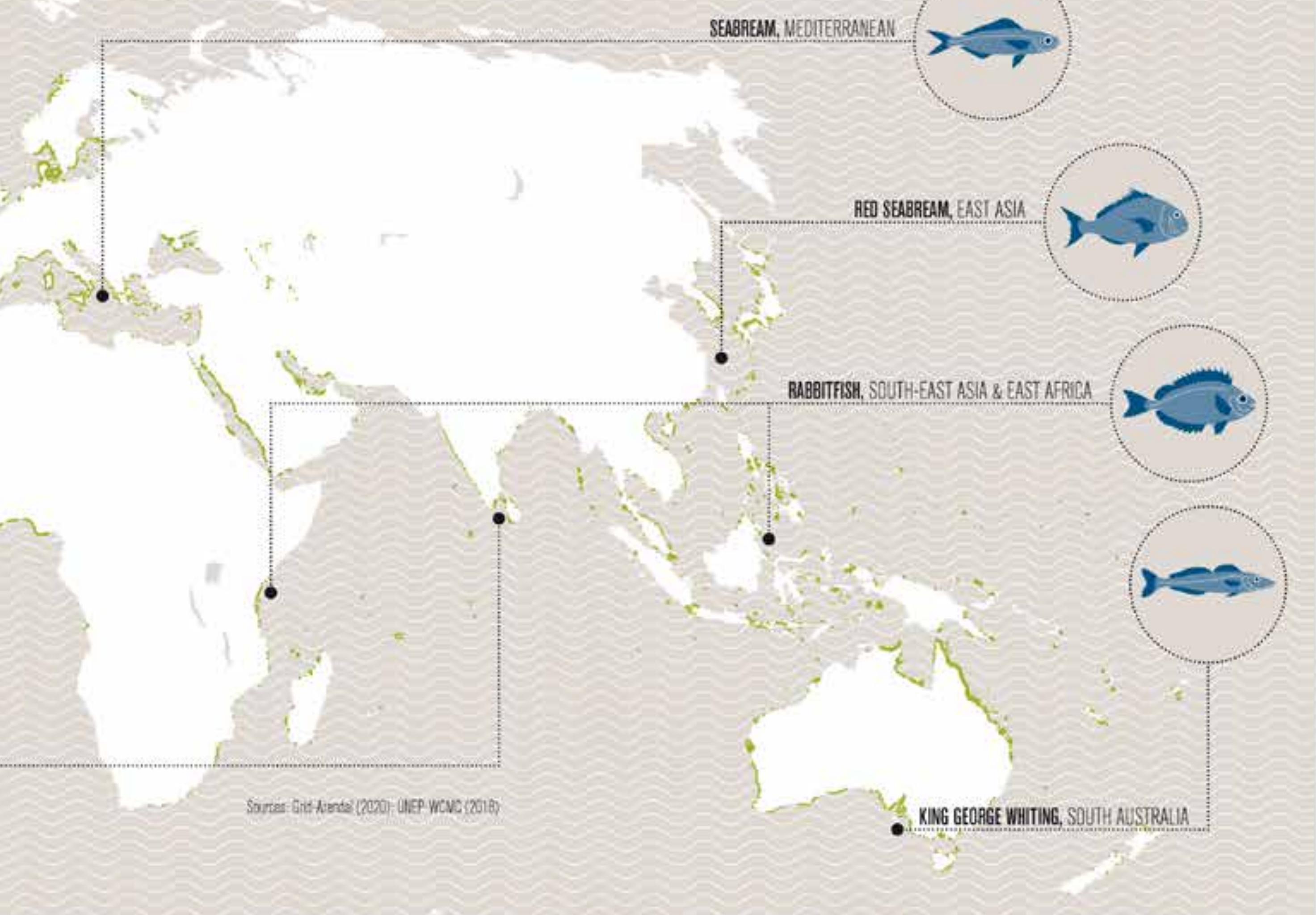
In the context of a changing global environment where many marine habitats such as coral reefs are increasingly becoming degraded, the need for fishers to compensate for this loss of fishing habitat by exploiting different habitats and locations is only likely to increase. As a habitat potentially less vulnerable to climate change, many seagrass meadows are likely to become more highly targeted for their fish assemblages, placing their sustainability in doubt (Unsworth et al. 2019). Although there is widespread recognition that seagrasses support fisheries, there is limited documented examples of the consequences of seagrass loss on associated fisheries. In many areas (for example, the United Kingdom) extensive seagrass loss has occurred outside the realm of recent recorded history, with the loss overshadowed by the wholesale overexploitation of fisheries. This 'shifting baseline' has led to the role of habitat in supporting fisheries being poorly recognized, causing biodiversity and habitat conservation in the coastal seascape to be disconnected from fisheries management (Sundblad et al. 2013). New methods and global databases of habitat trends and use of habitats by fishery species are required to properly attribute causes of decline in fisheries (Brown et al. 2018). It is crucial to look beyond stock production models and consider the role of habitat in fisheries production in order to improve the sustainable exploitation of fish stocks.

FIGURE 3



HIGH-VALUE GLOBAL FISHE
ATLANTIC COD, NORTH ATLANTIC
BLUE CRAB, NORTH-WEST ATLANTIC
CONCH, CARIBBEAN
RED MULLET, WEST AFRICA
SHRIMP, SRI LANKA
SEAGRASS DISTRIBUTION
CRITICAL NURSERY HABITAT
20% OF THE WORLD'S BIGGEST FISHERIES ARE SUPPORTED BY SEAGRASS
TROPHIC SUPPORT
THE VAST PRIMARY PRODUCTION CREATED BY SEAGRASS IS EXPORTED THROUGH A RANGE OF MECHANISMS TO ADJACENT ECOSYSTEMS AND SPECIES, PROVIDING VITAL SUPPORT TO MANY FISH STOCKS
FORAGING HABITAT
MANY VALUABLE FISHERY SPECIES SUCH AS THE RABBITFISH MIGRATE IN AND OUT OF SEAGRASS MEADOWS WHERE THEY FORAGE FOR FOOD
TARGETED FIS
WHERE THERE I
PROXIMITY TO PE
A FISHING HABITA
FOOD S
HUNDREDS OF MILLIONS OF PEOPLE WORLDWIDE EAT

ERIES LINKED TO SEAGRASS



HING HABITAT

S SEAGRASS IN
PLE IT IS ALWAYS
T IMPORTANT FOR
SUPPLY

REDUCED PATHOGENS IN FISH STOCKS

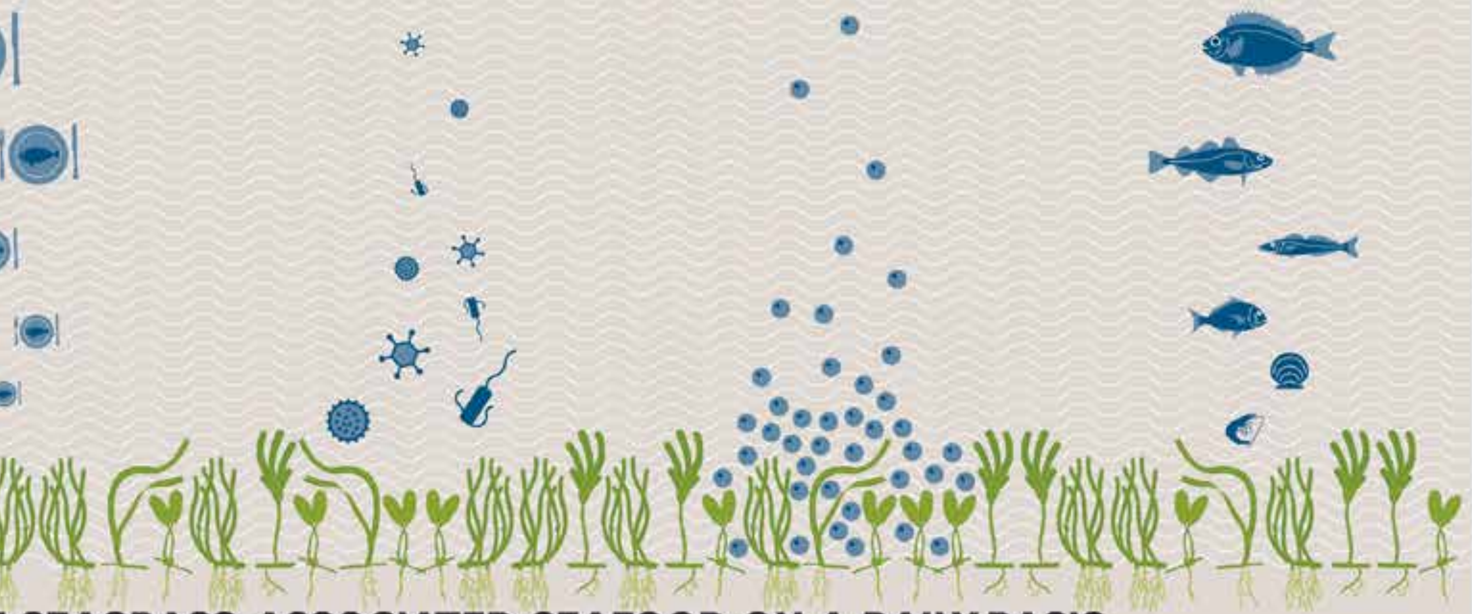
50% REDUCTION IN THE RELATIVE ABUNDANCE OF POTENTIAL BACTERIAL PATHOGENS CAPABLE OF CAUSING DISEASE IN HUMANS AND MARINE ORGANISMS

SPAWNING HABITAT

SEAGRASS MEADOWS PROVIDE AFFABLE ENVIRONMENTS WHERE FISH CAN SPAWN. THE PACIFIC HERRING COMMONLY LAYS EGGS ON SEAGRASS LEAVES

BIODIVERSITY SUPPORT

SEAGRASS MEADOWS SUPPORT AT LEAST 200 SPECIES OF FISH WORLDWIDE, MANY OF WHICH ARE IMPORTANT TO FOOD SUPPLY



T SEAGRASS-ASSOCIATED SEAFOOD ON A DAILY BASIS

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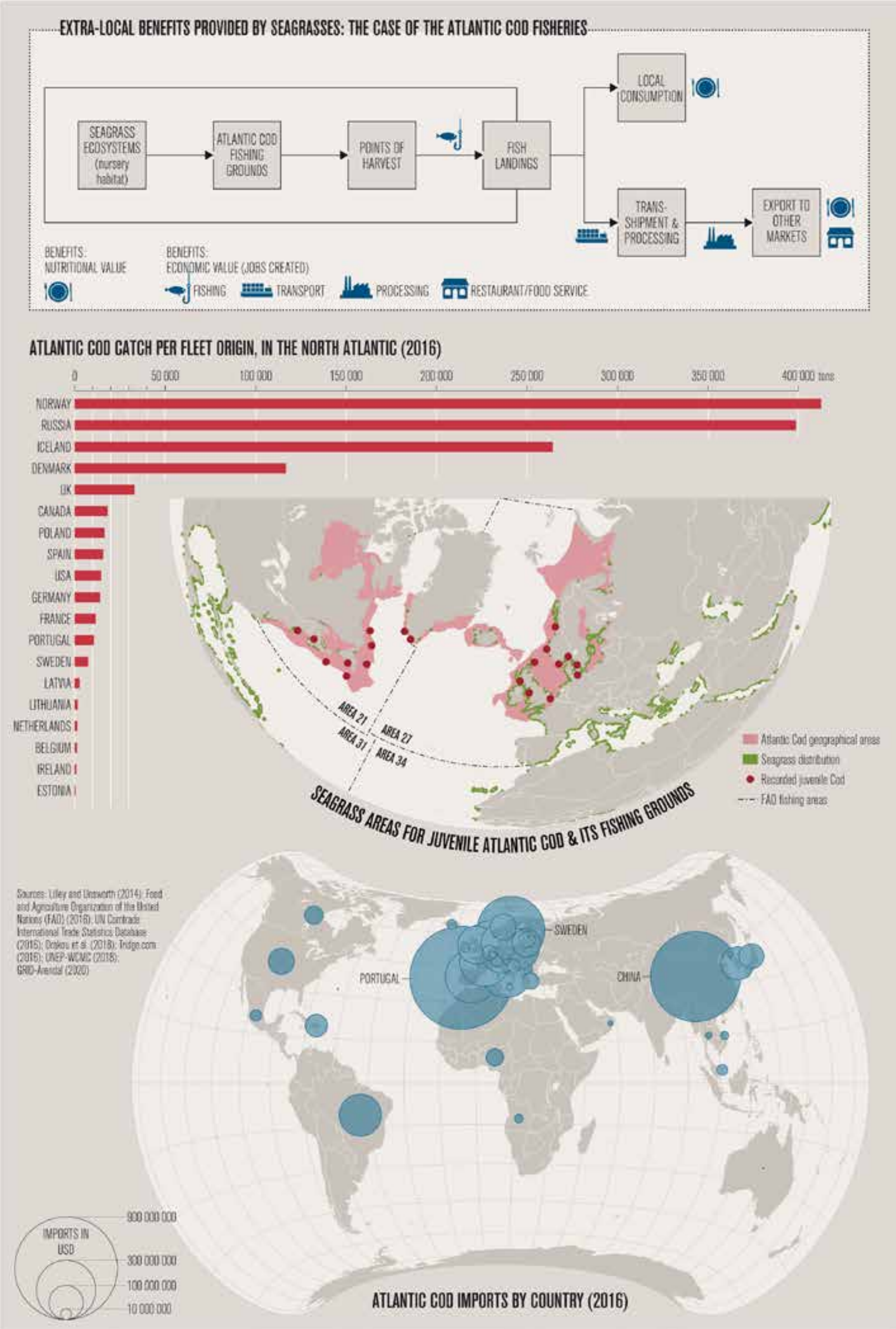
CASE STUDY 1

Extra-local benefits of seagrass meadows in supporting fisheries: Atlantic cod fisheries

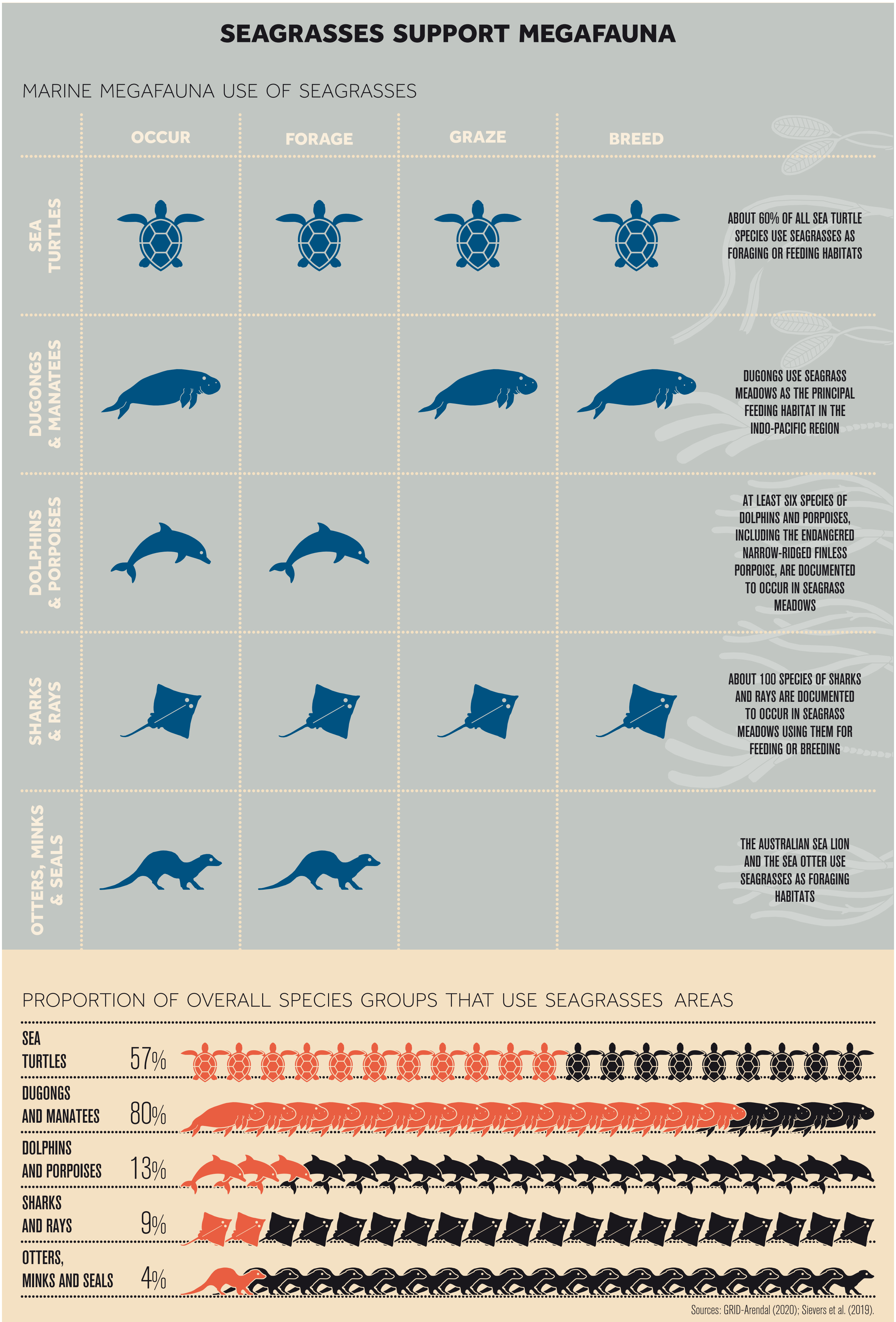
In the North Atlantic region, Zostera marina meadows are important contributors to stocks of Atlantic cod, one of the world's major commercial species (Lilley and Unsworth, 2014). Juvenile Atlantic cod are normally confined to shallow coastal areas, where seagrass meadows can occur. The juveniles are normally found in high density in locations with seagrasses, where their growth and survival can be enhanced, thereby increasing their chances of reaching the adult stage. Experimental evidence also indicates that these juvenile fish may actively choose seagrass as their habitat. In the North Atlantic, juvenile cod were recorded in shallow nearshore waters along eastern (England, Germany, Norway, Scotland, Sweden and Wales) and western (Canada, Greenland and the United States of America) coasts, as well as in deeper waters of the Grand Banks of Newfoundland. These waters comprise two major fishing areas (FAO 21 and 27), where fleets from local and foreign countries operate. Most of the catch (81 per cent) comes from Iceland, Norway and the Russian Federation, with some minor contributions from Canada, Denmark, the Faroe Islands, France, Germany, Greenland, Poland, Portugal, Spain and the United Kingdom. After the Atlantic cod is shipped and processed (for example, dried and salted), it is distributed to many countries throughout Europe, in particular the Netherlands, Portugal, Sweden and Spain, as well as China, Brazil and Nigeria, among others (Figure 4). This example illustrates how benefits of nature, specifically seagrass, can be distributed beyond the ecosystem location. The habitats that seagrasses provide for juvenile Atlantic cod generates nutritional (food for people) and economic (job creation) benefits. The beneficiaries are not only the people from the countries where seagrasses act as nursery habitat, but also from countries that import part of the Atlantic cod landings, such as the Netherlands, Portugal and Spain. Local management of Zostera marina in shallow coastal areas of the North Atlantic region should be considered not only for the maintenance of the Atlantic cod fisheries, but also for their impacts over the flow of ecosystem services and the extra-local benefits beyond local boundaries.

FIGURE 4



EXTRA-LOCAL BENEFITS PROVIDED BY SEAGRASSES: THE CASE OF THE ATLANTIC COD FISHERIES
SEAGRASS ECOSYSTEMS (nursery habitat)
ATLANTIC COD FISHING GROUNDS
POINTS OF HARVEST
FISH LANDINGS
LOCAL CONSUMPTION
TRANS-SHIPMENT & PROCESSING
EXPORT TO OTHER MARKETS
BENEFITS: NUTRITIONAL VALUE
BENEFITS: ECONOMIC VALUE (JOBS CREATED)
FISHING
TRANSPORT
PROCESSING
RESTAURANT/FOOD SERVICE
ATLANTIC COD CATCH PER FLEET ORIGIN, IN THE NORTH ATLANTIC (2016)
0
50 000
100 000
150 000
200 000
250 000
300 000
350 000
400 000 tons
NORWAY
RUSSIA
ICELAND
DENMARK
UK
CANADA
POLAND
SPAIN
USA
GERMANY
FRANCE
PORTUGAL
SWEDEN
LATVIA
LITHUANIA
NETHERLANDS
BELGIUM
IRELAND
ESTONIA
AREA 21
AREA 27
AREA 31
AREA 34
Atlantic Cod geographical areas
Seagrass distribution
Recorded juvenile Cod
FAO fishing areas
SEAGRASS AREAS FOR JUVENILE ATLANTIC COD & ITS FISHING GROUNDS
Sources: Lilley and Unsworth (2014); Food and Agriculture Organization of the United Nations (FAO) (2016); UN Comtrade International Trade Statistics Database (2016); Onjoku et al. (2018); Tridge.com (2016); UNEP-WCMC (2018); GRID-Arendal (2020)
SWEDEN
PORTUGAL
CHINA
IMPORTS IN USD
900 000 000
300 000 000
100 000 000
10 000 000
ATLANTIC COD IMPORTS BY COUNTRY (2016)

FIGURE 5


SEAGRASSES SUPPORT MEGAFAUNA
MARINE MEGAFAUNA USE OF SEAGRASSES
OCCUR
FORAGE
GRAZE
BREED
SEA TURTLES
ABOUT 60% OF ALL SEA TURTLE SPECIES USE SEAGRASSES AS FORAGING OR FEEDING HABITATS
DUGONGS & MANATEES
DUGONGS USE SEAGRASS MEADOWS AS THE PRINCIPAL FEEDING HABITAT IN THE INDO-PACIFIC REGION
DOLPHINS & PORPOISES
AT LEAST SIX SPECIES OF DOLPHINS AND PORPOISES, INCLUDING THE ENDANGERED NARROW-RIDGED FINLESS PORPOISE, ARE DOCUMENTED TO OCCUR IN SEAGRASS MEADOWS
SHARKS & RAYS
ABOUT 100 SPECIES OF SHARKS AND RAYS ARE DOCUMENTED TO OCCUR IN SEAGRASS MEADOWS USING THEM FOR FEEDING OR BREEDING
OTTERS, MINKS & SEALS
THE AUSTRALIAN SEA LION AND THE SEA OTTER USE SEAGRASSES AS FORAGING HABITATS
PROPORTION OF OVERALL SPECIES GROUPS THAT USE SEAGRASSES AREAS
SEA TURTLES 57%
DUGONGS AND MANATEES 80%
DOLPHINS AND PORPOISES 13%
SHARKS AND RAYS 9%
OTTERS, MINKS AND SEALS 4%
Sources: GRID-Arendal (2020); Sievers et al. (2019).

Seagrasses support diverse, unique and threatened marine biodiversity

The provision of shelter, feeding and nursery grounds are critical ecosystem services delivered by seagrasses worldwide, as evidenced by the high diversity and abundance of fauna within seagrass meadows. Many of these animals are of special interest and include threatened, endangered or charismatic species, in particular marine megafauna such as dugongs, sea turtles and sharks (Sievers et al. 2019) (Figure 5). Several marine species that use seagrasses as a nursery habitat are classified as Threatened, Endangered or Critically Endangered by the International Union for Conservation of Nature (IUCN) (Lefcheck et al. 2019), such as the case of the European eel (*Anguilla anguilla*). Dugongs and adult green turtles use seagrass meadows as principal foraging habitat in the Indo-Pacific region, as they eat up to 40 kg and 2 kg of seagrass a day respectively. Feeding on seagrass by these megafauna species is an important process, resulting in significant export of nutrients to nearby ecosystems such as coral reefs, as well as promoting carbon storage in seagrass meadow substrates (Scott et al. 2018). Seahorses spend most of their time attached with their tails to seagrasses where they hunt for food. About 30 per cent of seahorse species, which use seagrass meadows as their main habitat, are included in the IUCN Red List (Hughes et al. 2009). Seahorses are considered a flagship species for the conservation of seagrasses and the associated fauna (Shokri et al. 2008).

Seagrasses purify water from nutrients, particles and contaminants

Seagrasses can improve water quality by filtering, cycling and storing nutrients and pollutants through uptake by their leaves and roots. For instance, seagrasses act as natural biofilters for the ammonium produced by intensive oyster farming (Sandoval-Gil et al. 2016). Seagrasses can also accumulate contaminants such as trace metals, which they can store in the sediment for millennia (for example, *Posidonia oceanica* in the Mediterranean Sea) (Serrano et al. 2011). However, when the concentration of pollutants is very high, this is not only harmful for the seagrass itself, but is also a threat to the seagrass-supported food web due to biomagnification processes. Thanks to their bioaccumulating capacity and sensitivity to environmental changes, seagrasses are used as bioindicators of water quality (Marbà et al. 2013). Their capacity for purifying water could potentially help in managing emerging contaminants, such as microplastics or chemicals that leach from plastics, though research on this topic is still in its infancy.

Seagrasses can control diseases by removing pathogens from the water

Seagrasses can remove microbiological contamination from the water, thus reducing exposure to bacterial pathogens for fish, humans and invertebrates. Seagrasses produce bioactive secondary metabolites with antibacterial and antifungal

activity. Extracts from three tropical seagrass species – *Halophila stipulacea*, *Cymodocea serrulata* and *Halodule pinifolia* – were active against *Staphylococcus aureus*, a bacterium that causes a range of illnesses in humans (Kannan et al. 2010). In small islands in central Indonesia, the levels of potentially pathogenic marine bacteria that cause diseases in humans, fish and invertebrates, can be reduced by 50 per cent if seagrass meadows are present compared with sites without seagrasses (Lamb et al. 2017). Coral reefs also benefit from seagrasses, with coral disease levels halved when seagrasses are adjacent to reefs (Lamb et al. 2017). Seagrass meadows can also control harmful algal blooms through algicidal and growth-inhabiting activities against the microalgae causing the blooms (Inaba et al. 2017).

Seagrasses help mitigate climate change by sequestering and storing carbon

Seagrass meadows are significant carbon sinks at the global scale with high capacity for taking and storing carbon in the sediment, which is also known as 'blue' carbon (Nellemann et al. 2009). Globally, seagrasses are estimated to store as much as 19.9 Pg in organic carbon (Fourqurean et al. 2012). For this service, seagrass ecosystems have great potential in combating climate change, with benefits for the whole planet (case study 2). Carbon is sequestered and stored as seagrass biomass (autochthonous Corg), and through the trapping of organic particles derived from adjacent ecosystems (allochthonous Corg). The anoxic conditions of seagrass sediments enhance the preservation of the sedimentary Corg (below-ground tissue and allochthonous Corg) leading in some cases to the formation of large carbon deposits in the sediment that can remain for millennia, if left undisturbed. The carbon stored in the above-ground living biomass (for example, leaves) is more prone to grazing, export or decomposition, and is considered a short-term carbon sink. Most of the carbon sequestered by seagrass meadows is stored in the sediment. The capacity of seagrasses to sequester carbon varies among seagrass species, meadow characteristics and environmental conditions. In general, the largest organic carbon deposits occur in permanently undisturbed meadows formed by large and persistent species with complex canopies and when located in sheltered, shallow, low-energy environments with low to medium nutrient inputs. Smaller seagrass species located in sheltered bays or lagoons with high mud content can also develop large soil carbon stocks, mainly through the accumulation of organic matter produced in other ecosystems. The loss of seagrass meadows leads to reduced carbon sequestration and storage capacity and to

CASE STUDY 2

Application of the extra-local ecosystem service framework to the climate regulation service of seagrasses in Gazi Bay, Kenya

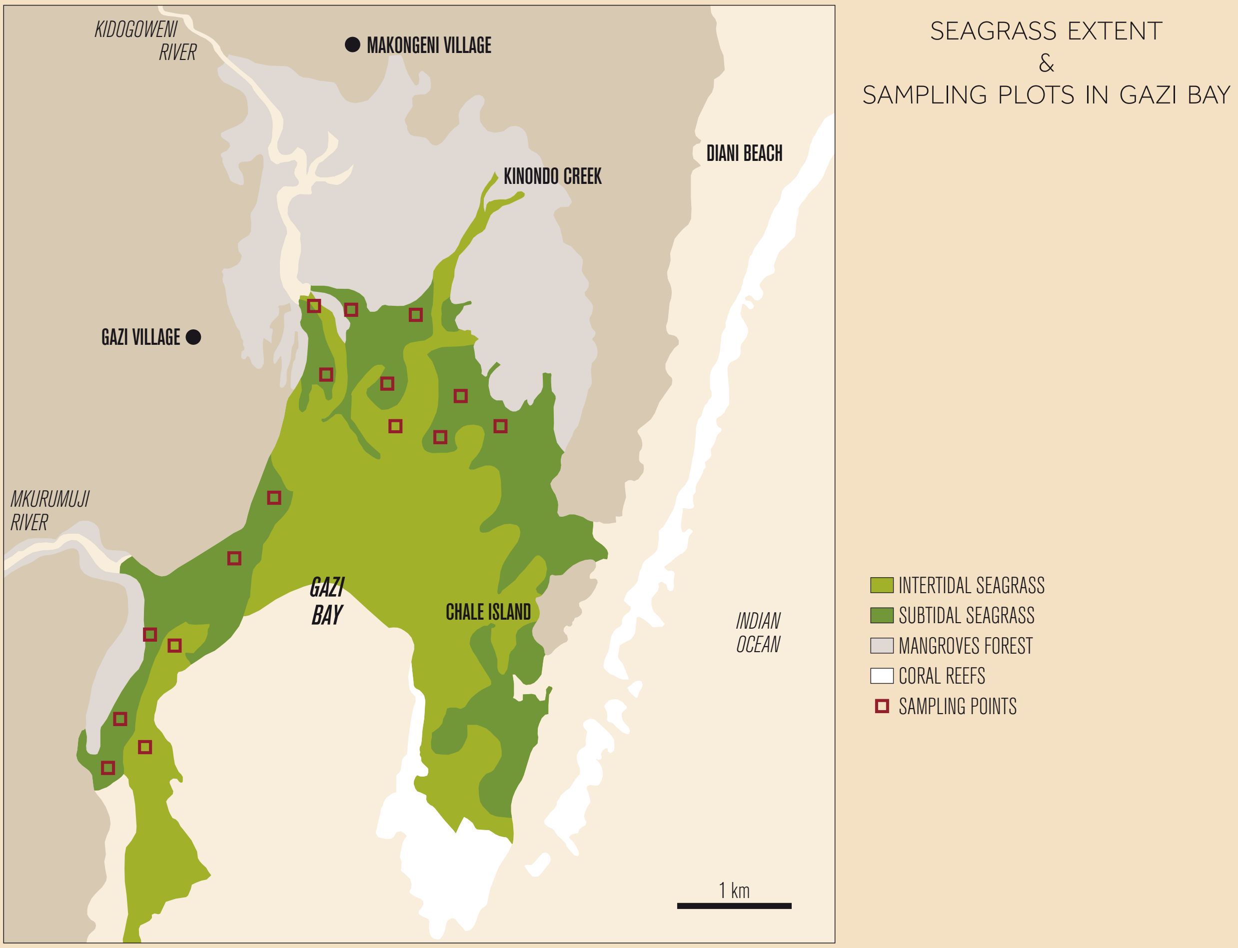
Although maps of carbon sequestration and storage capacity of seagrasses have increased considerably in recent years, the beneficiaries of this ecosystem service are often not specified or mapped. As a first approach, the beneficiaries of seagrass sequestration and storage of atmospheric carbon are the global population, given that regulating and mitigating climate change provide global benefits. To what extent people benefit from this service will likely vary among countries, with benefits depending on the population's vulnerability to climate change, countries' investment regimes and gross domestic product (GDP).

This example illustrates the global benefits of climate regulation provided by tropical seagrasses in Gazi Bay, Kenya. This bay is part of the Diani-Chale Marine National Reserve, located in the southern coast of Kenya. The bay has a mean depth of less than 5 m and a surface area of 17 km^2. Seagrasses are found at the centre of the bay, covering an area of 7 km^2, with *Thalassodendron ciliatum*, *Thalassia hemprichii*, *Enhalus acoroides* and *Syringodium isoetifolium* the dominant species. The total carbon stock of the seagrass meadows in Gazi Bay is around 620,000 Mg, including the living biomass (5.9 Mg C ha^{-1}) and the top 1-m sediment (235.6 Mg C ha^{-1}) (Githaiga et al. 2017).

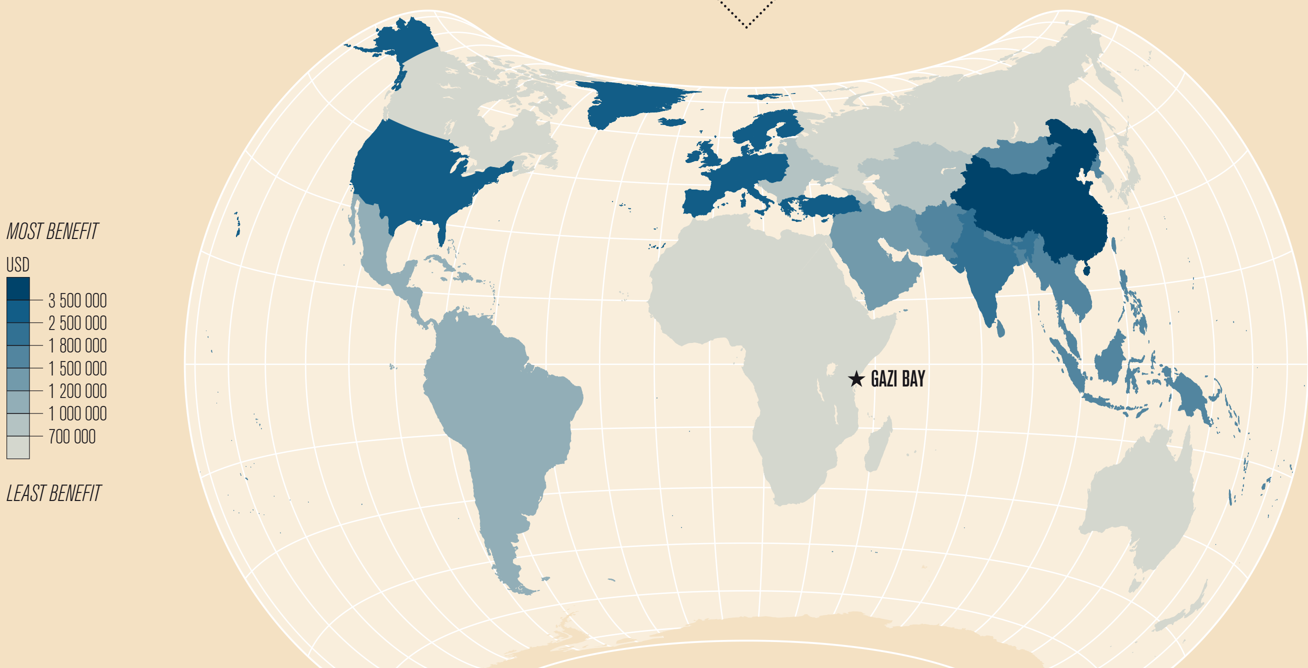
The beneficiaries of this service provided by seagrasses can be assessed following the extra-local approach (Drakou et al. 2017; Ganguly et al. 2018), based on the social cost of carbon (SCC) for different regions across the world. SCC denotes the value of avoided damages as a result of a unit reduction of CO_2 or its equivalent emissions. Based on the revised DICE-2016R model (Dynamic Integrated model of Climate and the Economy), the monetary value of the total carbon stored in the Gazi Bay seagrass meadows is estimated to be $19 million at a global scale. This value is unevenly shared across the globe as illustrated in Figure 6, with China, Europe and the United States of America as the main beneficiaries. Although this analysis is heavily influenced by regional SCC estimates, the major goal of this approach was to show that while Kenyan seagrass ecosystems may be an important supplier of this service, Kenyan people are not the only beneficiaries. This is an excellent example of how the climate regulation benefits provided by seagrass meadows in a specific part of the world, have extra-local benefits for people in geographically disconnected regions.

FIGURE 6

THE CLIMATE REGULATION VALUE PROVIDED BY SEAGRASSES IN GAZI BAY, KENYA TO DIFFERENT REGIONS ACROSS THE GLOBE



CARBON STORAGE × TOTAL SEAGRASS AREA × SOCIAL CARBON COST = CLIMATE REGULATION BENEFIT
(SOIL AND SEAGRASS BIOMASS)



CLIMATE REGULATION
BENEFIT PER REGION

Sources: Githaiga et al (2017); GRID-Arendal (2020).

more CO_2 emissions derived from the remineralization of the soil Corg deposits. With present rates of loss, seagrasses are estimated to release up to 299 Tg carbon per year (Fourqurean et al. 2012). Similar to what happens with the degradation of terrestrial carbon sinks, the loss of seagrass ecosystems may significantly contribute to anthropogenic CO_2 emissions and to the acceleration of climate change.

Despite the significant role that seagrass meadows play as carbon sinks and the risk of CO_2 emissions following degradation, they have been traditionally overlooked in greenhouse gas emission accounting inventories, and subsequently in the development of climate change mitigation strategies, all of which tend to focus on terrestrial ecosystems (for example, the United Nations Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+)). The publication of two seminal reports by Nellemann et al. (2009) and Laffoley and Grimsditch (2009), pointed to the potential that restoring and conserving seagrass meadows (along with mangroves and saltmarshes) has as a climate change mitigation approach within a novel framework termed blue carbon strategies. Since these reports, significant advances in science and policy have been made towards implementing blue carbon strategies. The development of guidelines by the Intergovernmental Panel on Climate Change (IPCC) supports the reporting of greenhouse gas emissions or sequestration derived from the conversion and restoration of seagrass meadows within countries' national inventories (IPCC 2013). Also, carbon standards have been developed so that restoration projects can benefit from carbon credits (for example, the Verified Carbon Standard) (Needelman et al. 2018). However, there are still some challenges that prevent the widespread implementation of these strategies, such as the lack of Corg sequestration rates and stocks for some regions, the lack of accurate seagrass maps, the spatial variability in greenhouse gas emissions derived from seagrass degradation and the uncertainties related to legal aspects such as land tenure, tidal boundaries or legal responsibilities (Herr et al. 2017; Needelman et al. 2018; Lovelock and Duarte 2019). Although no projects have used seagrass as a tool for emissions reduction to date, the markets and methods are currently being developed and it is likely that they will be tested and applied soon (see chapter on financial incentives).

Seagrasses can mitigate the effect of ocean acidification

The high productivity of seagrasses affects the carbonate chemistry of the surrounding seawater due to the large quantities of dissolved inorganic carbon taken up during photosynthesis. As a result, seagrasses tend to increase seawater pH during the daytime, potentially offsetting the deleterious effects of the increasing anthropogenic CO_2 in the seawater. Marine organisms, particularly calcifying organisms, such as corals (Manzello et al. 2012) and shellfish (Wahl et al. 2017) living within or adjacent to seagrasses, may benefit from this service, since they can find a local refugium from ocean acidification. Although their role in buffering ocean acidification depends on environmental conditions (Koweek et al. 2018), healthy seagrass meadows can contribute to enhancing the resilience of the most vulnerable species to ocean acidification in the short-term (Wahl et al. 2017).

Seagrasses provide coastal protection and contribute to climate change adaptation

Seagrass meadows play an important role in protecting coastal areas from erosion, flooding and storm surges (Duarte et al. 2013; Ondiviela et al. 2014). Their leaves reduce flow velocity and decrease wave energy favouring sedimentation and, along with roots and rhizomes, prevent erosion and stabilize the sediment. In addition, seagrass litter that accumulates on the beach contributes to stable dunes. In the particular case of large seagrass species, such as Posidonia, the thick piles of beach-cast seagrass material, called banquettes, can reach up to 3 m in height, protecting the shoreline from erosion. Seagrass meadows also enhance vertical accretion of sediments and seabed elevation (Potouroglou et al. 2017) through the accumulation of below-ground biomass and particles trapped from the water column. The coastal protection service that seagrass meadows provide is particularly important in the context of climate change, considering that the frequency and strength of waves and storm surges are expected to increase. Seagrass meadows may adapt to sea level rise through soil elevation or inland migration, if they are not hindered by any coastal infrastructure (Duarte et al. 2013). Traditional engineering solutions are based on building so-called 'grey' infrastructures (for examples, dykes, seawalls), though these solutions may involve direct loss of coastal habitats. Such infrastructures also need to be maintained and upgraded to assure their efficiency in future climate change scenarios, making them economically unsustainable (Morris et al. 2018). In contrast, natural barriers from ecosystems such as seagrasses have the capacity of self-repair and adapt to sea level rise while also providing other multiple ecosystem services. In tropical areas, seagrasses together with sediment-producing calcifying algae have been shown to be an effective natural solution for nourishing beaches, offering a self-sustainable alternative to traditional engineering solutions and increasing the resilience of coastal areas to climate change (James et al. 2019). This highlights seagrasses as one of the best ecosystems for eco-engineering, nature-based solutions.

Seagrass meadows provide various cultural services

Seagrass meadows have cultural benefits worldwide, from providing tourism and recreation opportunities to being of spiritual and religious importance. Such cultural services are rarely included in ecosystem accounts at the national, regional or global levels, as their quantification is not as straightforward

Source: GRID-Arendal (2020).

as for other services. Language is considered an indicator of cultural diversity and can be used to identify where seagrass is valued culturally. For example, if seagrasses have specific names in a local language, then there is some perceived value of the resources they provide (in other words, people know what they are and value them as specific plants for certain reasons). Numerous languages denote the distinct value of seagrass as a biological entity. This is shown by the specific names given to seagrass in local languages, such as Lamun in Indonesian and Nyasi bahari in Swahili. Some local names also relate to the ecology of such species in providing important services, as in the case of the Monken tribes from the Myeik Archipelago (Myanmar), who refer to seagrass as Leik-Sar-Phat-Myet or 'the food of marine turtles' (Jones et al. 2018), as well as to reproductive ecology, with, for example, Seri in Mexico referring to the month of April as xnoois ihaat iizax or 'the month when the seagrass flowers' (Felger and Moser 1973).

The value of seagrasses for tourism and recreation is often not acknowledged, despite the vast indirect income they provide to such industries. For example, the Quintana Roo region in Mexico is famous for its sport fish populations of tarpon, bonefish, snook and permit, yet much of the recreational fishing activity occurs in the seagrass lagoons of the peninsula. Similarly, many tourists flock to seagrass areas in Akumal in Mexico to swim with green turtles, and to Marsa Alam in Egypt to snorkel and dive with dugongs. In temperate areas, brant geese, as well as numerous other birds, attract birdwatchers to locations with seagrass meadows such as the Solent in the United Kingdom and Puget Sound in the United States of America (Plummer et al. 2013).

In many regions of the world, seagrass meadows also represent a traditional way of life and identity for fishers and communities, as they are directly associated with food and livelihoods, as well as spiritual fulfilment (de la Torre-Castro and Rönnbäck 2004). For instance, in Zanzibar, Tanzania, seagrasses are believed to be sent from God as a decoration of the sea (de la Torre-Castro and Rönnbäck 2004), while in Roviana Lagoon, Solomon Islands, fishers twist seagrass leaves together and shout "Kuli pa Kovi!" (seagrass of Kaovi!) as a call to seagrass spirits to increase their luck (Lauer and Aswani 2010). From a religious perspective, the opercula of molluscs collected in seagrass meadows have been used to produce ceremonial incense. Seagrass deposits play a key role in preserving valuable underwater archaeological and historical heritage across the world, such as Roman and Phoenician shipwrecks, prehistoric settlement sites and submerged ancient cities, and also constitute historical archives of human cultural development over time (Krause-Jensen et al. 2019). Therefore, better understanding and integration of cultural services in this framework will require the use of socioecological tools to link the seagrass structure and functions with the cultural values and benefits.

Seagrass and its direct uses

Seagrass in the fermentation industry

Research in bioethanol production has been on the rise since 2000, with researchers studying freshwater species such as water hyacinth, and marine macroalgae such as Saccharina japonica and Ulva spp. In 2014, scientists from Japan studied the possibility of using Zostera marina seeds to obtain fermented products that contained ethanol at high concentrations (Uchida et al. 2014). They processed eelgrass seeds following a similar method used in the manufacture of Japanese sake or rice wine. This allowed the production of 16.5 per cent ethanol, which is stronger than most wines. As Zostera marina is a widespread plant in the northern hemisphere, it has the potential to be utilized not only for biofuel, but also by food and beverage industries in the future. It could also potentially be harvested as a crop, which would allow for the development of a new marine fermentation industry.

Seagrass as biochar

Seagrass wrack (washed up seagrass on coastal areas) can be beneficial for both terrestrial and marine ecosystems, as well as for humans. Biocharrring is the process of converting biomass through thermochemical processes in an oxygen-limited environment to create a solid material with high carbon content. It has recently gained recognition as a tool to enhance the sequestration of atmospheric carbon, thereby helping to mitigate climate change. Seagrasses were found to have high conversion efficiency, which was comparable to high-quality terrestrial biochar products (Macreadie et al. 2017).

Seagrass in medicine

Despite promising achievements in pharmaceutical biotechnology and the development of new drugs, cancer and infectious diseases are still the main causes of mortality and morbidity in the world. Green synthesis has been introduced as a simple, economically viable and environmentally friendly alternative approach for the synthesis of nanoparticles. In a typical green synthesis, biological compounds (such as plant extracts) act as both a reducing agent and a stabilizing agent, leading to the production of desirable nanoparticles with predefined features. The seagrass Cymodocea serrulata is a valuable bioresource to generate rapid and eco-friendly bioactive nanoparticles for lung cancer therapy (Palaniappan et al. 2015).

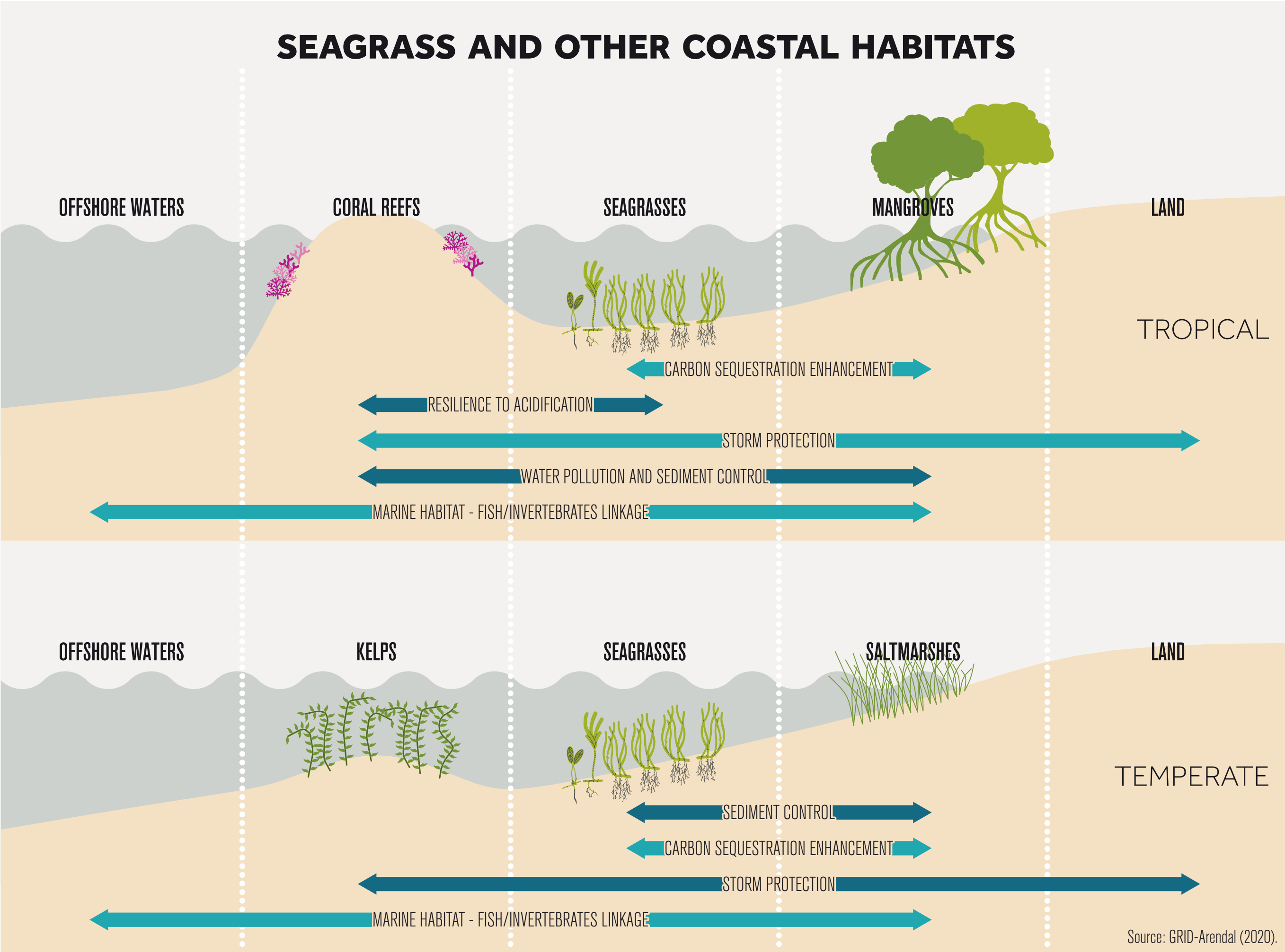
Seascape connectivity and ecosystem services provision

Seagrass ecosystems do not occur in isolation and are instead interconnected across a continuous land–sea interface, known as a seascape. In the tropics, seagrass meadows typically exist in close proximity to mangroves and coral reefs, whereas in temperate locations, seagrasses are often connected to saltmarshes, estuaries, kelp forests or bivalve reefs (Figure 7). The connectivity of ecosystems across the seascape suggests a direct transfer of carbon, nutrients and sediments (Gillis et al. 2013; Huxham et al. 2018), and is also important for the ontogenetic and foraging movements of marine fauna across habitats within seascapes (Campbell et al. 2011). There are several examples of how such interconnected ecosystems enhance the services they provide (Figure 7). In the tropics, seagrasses and coral reefs moderate the impact of waves and storms, enhancing the coastal protection service provided by mangroves (Huxham et al. 2018). In turn, mangroves can buffer seagrass ecosystems from excess nutrient and sediment run-off from land sources (Gillis et al. 2014). The seascape connectivity may be particularly important in the face of climate change, since the association of habitats can improve their resilience and thus maintain the flow of services they provide. For example, the existence of seagrass meadows in shallow tropical marine areas depends on the degree to which coral reefs reduce wave energy, an interdependency that could be altered by sea level rise. Under moderate scenarios of future sea level rise, rates of coral accretion at 3 mm yr^{-1} could buffer the negative effects of deepening water on seagrass habitat suitability until 2050, although this facilitation process will not be supported under severe sea level rise trajectories or for longer periods of time (Saunders et al. 2014). There is still a lack of understanding of how seascape connectivity affects the different services that seagrasses provide. Research is therefore needed to determine which services are most influenced by connectivity and how connectivity influences the way people access and benefit from ecosystem services.

Mapping seagrass ecosystem services

Mapping the services provided by seagrass ecosystems is key to tracking their changes over time and space. In addition, the presentation of the services and their beneficiaries in a spatially explicit way is an effective approach to inform policy- and decision-making processes. Mapping ecosystem services is also one of the steps in ecosystem accounts, which aim to track changes in ecosystem assets and to link this information to economic and other human activities (UNEP-WCMC 2017). Despite advances to assess seagrass ecosystem services and map their extent, there are still many data gaps that hinder the acquisition of comprehensive maps of the services. For instance, seagrass distribution maps are still poorly resolved in many areas, making habitat mapping a key priority for

FIGURE 7



seagrass ecosystem services assessments. In addition, better understanding of the relationships between seagrass extent, status and service provision, as well as defined indicators of the services and their benefits, are key to mapping ecosystem services at different temporal and spatial scales.

Degradation and loss of seagrass ecosystem services

Ecosystem services that support human well-being have been degraded as a consequence of human activities, especially during the past half century when changes have occurred more rapidly and extensively than in previous times. Seagrass ecosystems are being subjected to impacts from coastal development and water pollution, as well as other coastal uses that can cause their decline or degradation. As a consequence, the ecological functions that seagrasses provide can be impaired, thereby affecting their services and benefits, which will eventually lead to negative economic and social repercussions. Losses in seagrass ecosystem services are reported in many locations around the globe. These losses are resulting in declines of seagrass-associated animals, such as dugongs, seahorses and commercially-targeted species (Scott et al. 2018; Sievers et al. 2019). The loss of seagrass capacity to sequester and store carbon is also of high concern, since seagrass loss eventually leads to significant emissions of CO2 into the atmosphere (Arias-Ortiz et al. 2018). For instance, Shark Bay (Australia), one of the largest seagrass meadows in the world, was damaged following a marine heatwave in 2010/2011, causing an estimated 2–9 million tons of CO2 to be released into the atmosphere and leading to the decline of seagrass-associated species, many of them of conservation concern or commercially targeted (see case study 4 and chapter on threats and resilience). In Chesapeake Bay in the United States of America, a decline of 29 per cent in the eelgrass area between 1991 and 2006 resulted in severe ecological and economic consequences. The estimated loss of 693,000–1,859,000 tons of carbon after the seagrass decline implied an economic loss of $96.5–259 million. The seagrass loss also led to an estimated loss of 523–1,403 million juvenile blue crabs and 47,800–80,200 tons of silver perch, which represents, in economical values, 1–2 and 10–20 years of their fisheries respectively (Lefcheck et al. 2017).

Restoring seagrass ecosystem services

Restoration of degraded seagrass ecosystems, whether by planting or natural recolonization, can be effective in reversing biodiversity loss and recovering ecosystem services. For instance, seagrass-associated faunal communities can recover following natural meadow recolonization, as observed in a *Zostera muelleri* meadow in a New Zealand urban estuary (Lundquist et al. 2018). Over a 15-year period, the benthic macrofaunal diversity and abundance had increased, which also enhanced

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the nutrient and carbon cycling. Other long-term studies have also shown the effectiveness of seagrass restoration in the re-establishment of seagrass services; for example, the successful restoration projects in Oyster Harbour, Western Australia (case study 3), and in the Coastal Bays of Virginia, United States of America. In the latter, re-seeding of Zostera marina led to a distinct change in nitrogen removal and carbon storage (Reynolds et al. 2016). The restored meadow removed 4,100 tons of nitrogen through plant uptake and sediment storage, and had carbon stocks and carbon accumulation rates similar to those of natural meadows, with an estimated 15,000 tons of carbon being sequestered. The recovery of these services was estimated as having an economic value of $8 million per year. These high economic and environmental benefits of the restored services highlight the importance and necessity to invest in resources to restore seagrass. Even more valuable is the facilitation of natural restoration by controlling water quality through nutrient pollution, which has, for example, successfully

Assessing seagrass ecosystem services: quantification and mapping

Assessing ecosystem services requires the use of indicators in relation to the capacity, the flow or the benefits of the service in question (Liquete et al. 2013). For example, studies assessing the seagrass service of fisheries support normally use the fish biomass of commercially targeted species associated to seagrass meadows along with indicators of flow, such as annual fish catch, and indicators of benefits, such as the fish market price. This approach yields estimations of the annual revenues of the fish catch associated to seagrasses. In the case of the Cymodocea nodosa seagrass meadows in Gran Canaria (Tuya et al. 2014), the fisheries support service was estimated at 895 kg ha^{-1} of commercially-targeted fish based on fish visual census. This service was translated into economic benefits of 866 € ha^{-1}, or ca. 600,000 € yr^{-1} when accounting for the total seagrass area extent in the island. Another approach to assess the fisheries support service is the use of the seagrass residency index for economically important species to estimate the proportion of commercial fishery landing values and recreation fisheries total expenditure that can be attributed to seagrass. Using this approach, it has been estimated that the Mediterranean seagrass Posidonia oceanica has a direct annual contribution of 4 per cent to the total value of landings of commercial fisheries and 6 per cent to the total expenditure of recreational fisheries, despite covering < 2 per cent of the marine area (Jackson et al. 2015). Seagrass fisheries support assessments normally lack the spatial or temporal component, which are essential to improve understanding of the dynamics of the ecosystem services provision and demand, as well as to inform managers and policymakers. Assessments of other ecosystem services provided by seagrasses, such as water purification or coastal protection, rarely include indicators of the benefits. Quantification of the water purification service provided by seagrasses normally includes indicators of the flow, such as the nitrogen removal rate or uptake rate (Asmala et al. 2019), but rarely indicators of the benefits or the associated value. Mapping ecosystem services requires data with a degree of detail that vary with the selection of the spatial scale, from local to global, and the purpose of the maps (Burkhard and Maes 2017). Basic data requirements include the ecosystem extent and condition, and more advanced maps in order to visualize the associated service flow in biophysical units, and the benefits and values in socio-economic units. Local assessments normally require high-resolution extent maps and a deep understanding of the ecological processes underlying the service provision, which may involve costly in situ measurements of the service indicators. On the other hand, global assessments may use lower resolution maps and scaling-up estimations from local or regional quantification of the service. The lack of the required data fitting the desired scale is one of the identified constraints to map seagrass ecosystem services. Some countries and regions are more data-rich, which allows a robust assessment of seagrass ecosystem services. Such is the case of the recent assessment of Australia's blue carbon resources (Serrano et al. 2019), which includes scientific data from 637 seagrass meadows on soil and biomass carbon stocks and sequestration rates, compiled by over 40 researchers. This is an example on how data sharing can open the way towards more comprehensive maps of seagrass services at national or regional levels. In data-poor areas, mapping seagrass habitats should be the priority, so services could be roughly mapped and estimated using ranges of ecologically meaningful indicators from available data for services assessed in similar locations.

THREATS TO SEAGRASSES AND ECOSYSTEM RESILIENCE

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Seagrasses are a key marine habitat that has been globally declining since the 1930s (Orth et al. 2006), with the most recent census estimating that 7 per cent of seagrass is being lost worldwide per year, which is equivalent to a football field of seagrass every 30 minutes (Waycott et al. 2009). Seagrass meadows are threatened by natural and anthropogenic stressors attributed to a variety of physical factors (for example, increased temperatures, salinity changes, hypoxia, extreme weather events, sedimentation and altered wave and current dynamics) and biological factors (for example, invasive species, algal blooms, eutrophication, altered grazing patterns, competition and disease) (Short and Wyllie-Echeverria 1996). These impacts are magnified throughout the ecosystem because seagrasses engineer their environment and provide a foundation for entire communities. Global losses of seagrass cover have major implications for humans due to the numerous ecosystem services they provide.

Seagrasses are flowering plants that produce seeds, which also grow through substrate by extension of their underground rhizomes and production of new leaves as bundles called shoots. Several biophysical parameters determine whether seagrass can grow and reproduce, including temperature, salinity, hydrodynamics, depth, substrate and light availability (Unsworth et al. 2011). The specific levels of each need vary among the 72 different seagrass species occurring globally (Erftemeijer and Robin Lewis III 2006). These needs can be grouped into three classes:

1. habitat suitability – depth, sediment substrate, temperature and water movement
2. water quality – adequate light for photosynthesis, salinity, absence of toxicants
3. grazing and recruitment processes – suitable assemblages of grazing animals, water movement to transport seeds and vegetation fragments.

Evaluating the threats to and resilience of seagrass is critical in order to identify management strategies. The highest impact threats to seagrass are urban/industrial run-off, urban/port infrastructure development, agricultural run-off and dredging (Grech et al. 2012). The greatest climate-related threat is perceived to be from increased frequency and intensity of tropical storms, with more uncertainty about the impact of increasing temperatures and sea level rise. For example, turbulent seas during cyclones can directly uproot seagrass plants, while extreme rainfall events associated with cyclones can increase contaminant loads, resulting in poor water clarity and light availability. Fishing activities, anchoring, trampling and dredging (Erftemeijer and Robin Lewis III 2006) also pose major threats to seagrass.

Though not always considered, it is essential to understand and acknowledge the different spatial and temporal scales and intensities of threats. The impacts of multiple activities occurring together can interact, increasing or decreasing the effects of individual activities (Grech et al. 2011). At this stage, there is little quantitative understanding of these interactions and management plans do not account for them (Griffiths et al. 2019). The sensitivity of seagrasses to some threats can vary seasonally, meaning the timing of threatening activities can be critical. For example, many species are most at risk during their growing and reproductive phases. During these phases, threats that affect the production of a seedbank within a single year can be catastrophic for future generations (van Katwijk et al. 2010). Slow-growing perennial seagrasses are able to resist threats for longer periods, but this slower growth strategy also means that loss can take decades to repair, even for relatively small-scale impacts, such as seismic surveys, which can cause patches in an otherwise continuous *Posidonia australis* meadows (Meehan and West 2017). Beyond seasonal effects, the frequency of threats can also be problematic, especially if threatening processes recur faster than seagrass is able to recover (O'Brien et al. 2017; Wu et al. 2017). Threats can be land-based, sea-based or climate-related (Figure 8), all of which can affect seagrasses either directly or indirectly.

Land-based threats

Seagrasses are predominantly found in shallow coastal waters (although there are some exceptions) (Coles et al. 2009) and are therefore in proximity to areas most heavily used by humans. Several widespread threats originate from land-based sources, such as run-off from agricultural, urban and industrial regions that carries contaminants, including excessive sediments, nutrients, pulses of reduced salinity and toxicants (for example, herbicides) into seagrass habitats (Grech et al. 2012). Land-based run-off can also indirectly impact seagrass meadows by affecting multiple core habitat needs through a process known as eutrophication, which is a state of excessive plant and algal growth caused by

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