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REVIEW

The planetary role of seagrass conservation

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Seagrasses are remarkable plants that have adapted to live in a marine environment. They form extensive meadows found globally that bioengineer their local environments and preserve the coastal seascape. With the increasing realization of the planetary emergency that we face, there is growing interest in using seagrasses as a nature-based solution for greenhouse gas mitigation. However, seagrass sensitivity to stressors is acute, and in many places, the risk of loss and degradation persists. If the ecological state of seagrasses remains compromised, then their ability to contribute to nature-based solutions for the climate emergency and biodiversity crisis remains in doubt. We examine the major ecological role that seagrasses play and how rethinking their conservation is critical to understanding their part in fighting our planetary emergency.

Though commonly called grasses, seagrasses are a unique group of submarine flowering plants that belong to the monocotyledon order Alismatales, comprising four families and 72 species. Although they occupy a broad range of niches and are derived from multiple evolutionary lineages (*1*), they all share a connection to marine environments and consistently exhibit features that separate them from all other angiosperms. Seagrasses have adapted to live underwater, where light is limited, where salt and nutrients can be problematic, and where soils can become highly toxic (*2*).

Seagrass diverged from other alismatid monocots ~105 million years ago, and work by Olsen *et al.* (*3*) supports hypotheses that modern seagrass biodiversity can be linked to the materialization of multiple habitats after the Cretaceous-Paleogene extinction event. In the past decade, the seagrass science community has grown (*4*) and revealed the uniqueness of these plants and the importance of the ecosystems that they create (Fig. 1). Seagrasses bioengineer their environment by slowing water flow, trapping particles, and improving the environment within a positive feedback mechanism to facilitate the creation of habitat (*5*). Just like terrestrial plants, their reproduction can be supported by a diverse range of pollinators, such as cumacean crustaceans (*6*), and seed dispersers, such as fish (*7*). Their reproduction is not always sexual—genetic evidence has revealed that vegetative growth has led to the establishment of one single clonal organism spanning >180 km of coastline (*8*). Nitrogen-fixing bacteria living within their roots allow them to colonize nitrogen-poor environments (*9*), and associations with clams (and their bacterial symbionts) have aided their ability to inhabit otherwise toxic sulphide-rich marine soils (*10*). There is also growing evidence of the presence of fungi associated with the roots and rhizomes of seagrasses, indicating that they may play essential roles similar to those of fungal associates of terrestrial plants (*11*).

Aside from their ecological uniqueness, seagrasses are of increasing interest in a sociopolitical context owing to their potential to help combat the current climate and biodiversity crises that our planet faces. Seagrass meadows also support human well-being by virtue of their role in supporting fisheries, coastal protection, and water filtration (*12*), and action for their conservation supports the fulfilment of the 17 Sustainable Development Goals (SDGs) proposed by the United Nations in 2015. Seagrasses also support many species of conservation concern, such as the dugong, green turtle, and manatee (*13*), and provide interacting ecological functioning throughout the coastal seascape (*14*).

> **“Compared with…terrestrial grasses and even seaweeds, the body of research within seagrass is magnitudes smaller…”**

To harness the power of seagrass as a nature-based solution to the climate emergency and the biodiversity crisis, seagrass systems must be in a resilient functioning state. Seagrass meadows remain globally threatened by diverse factors, including poor water quality, damage from boats and related activities, aquaculture, and coastal development (*15*). Even in areas where seagrass is protected, extreme climate drivers place seagrass at risk. For example, after a marine heatwave in 2010 to 2011, up to 699 km^2 of seagrass meadow in the Shark Bay Marine Park in Western Australia were lost or damaged, potentially releasing up to 9 Tg of CO_2 back into the atmosphere during the 3 years before regrowth occurred (*16*). Seagrass sensitivity to stressors is acute and may even extend to the effects of anthropogenic noise (*17*). In many places, the risk of seagrass loss and degradation persists (*15*), and its functional state is commonly compromised; unless this can be reversed, the potential for seagrass to contribute to the complex jigsaw of nature-based solutions remains in doubt. In this Review, we reflect on the status of seagrass ecosystems, the major ecological role that they play in the coastal environment, and how rethinking their conservation is critical to allowing them to play a role in reversing climate change.

Global decline, net-zero loss, and achieving net gain

The role that seagrass can have in reversing or mitigating climate change requires consideration of their global biogeochemical contribution. For this, we first need a better understanding of whether seagrasses are currently in a state of net loss, stasis, or net gain globally, along with the parameters that drive their greenhouse gas balance (Fig. 1). The global coverage of seagrass is currently estimated to be 160,387 to 266,562 km^2 (*18*). This range reveals that we have very limited understanding of the actual extent of seagrass populations. We also do not fully understand the extent of the ecological goods and services that seagrass provides, including to biodiversity and coastal protection. Studies have sought to place estimates on seagrass loss at 1 to 7% per year (*19*, *20*) and create global carbon storage estimates of up to 19.9 Pg (*21*, *22*). However, if we do not know how much we have or have had, we cannot hypothesize very well on what has been lost or its associated ecological relevance.

The reported trajectory of seagrass coverage (*20*, *23*) indicates that it may be recovering in some areas; however, this analysis is limited because it only focuses on locations where seagrass is mapped, monitored, and likely affected by some level of conservation action, and it may represent only a fraction of potential and unknown seagrass area. Analyses are also limited by favoring data published in academic journals and excluding available data in the gray literature. A coordinated global effort is required to create meaningful global estimates of seagrass coverage and change that are validated with open data sharing between governments, academics, nongovernmental organizations, and commercial enterprises (*18*). In the UK, a technology-focused consortium is forming to fill the gaps in our knowledge to help drive understanding of the ecological role of seagrasses (*24*), and recommendations for a methodological pathway to improve the global seagrass map have recently been proposed (*18*, *25*).

Seagrass as a nature-based solution

The growing interest in nature-based solutions is necessitating deeper understanding of the ecological role that seagrass meadows play in the context of climate change. Seagrass meadows store and sequester carbon within their sediments over long periods of time at highly efficient rates; however, this role varies over space and time along with factors such as hydrodynamics and species composition influencing

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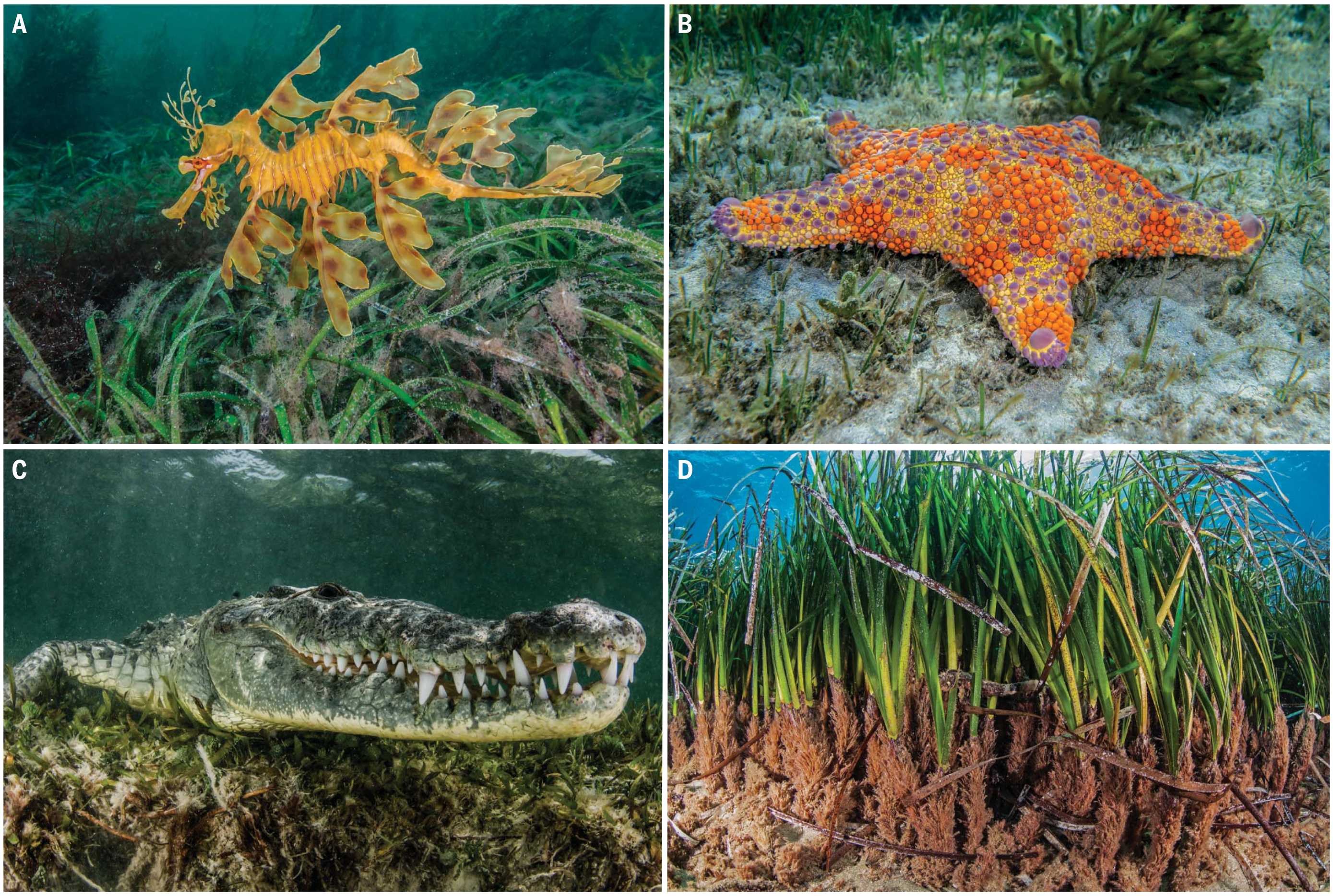

Fig. 1. Seagrass and biodiversity. (**A** to **C**) Seagrass meadows contain biodiverse and enigmatic species assemblages, including the leafy sea dragon (A), sea stars (B), and predators such as crocodiles (C). (**D**) The biodiversity and productivity of seagrass meadows also lead to them storing and sequestering substantial amounts of carbon in their sediments. Seagrass meadows provide habitat in support of biodiversity [(A) to (C)] in coastal waters globally. When healthy and in a balanced state, seagrass can be a great source of many other ecosystem services, such as water filtration, carbon storage (D), and coastal defense. Anthropogenic factors, such as coastal development and poor water quality leading to eutrophication of coastal waters, are some of the principal drivers of seagrass decline.

IMAGE CREDIT: DIMITRIS POURSANIDIS, BENJAMIN JONES, AMANDA COTTON, JAYNE JENKINS VIA THE OCEAN AGENCY; AND RICHARD UNSWORTH

this function. Additionally, despite their more obvious role in the storage of organic carbon, seagrasses, like most vegetation, also produce the greenhouse gases methane (CH_4) and nitrous oxide (N_2O). The balance of these emissions relative to the storage of carbon is of principal importance in the context of their role in influencing climate. Limited understanding exists with respect to whole–seagrass ecosystem greenhouse gas balance (Fig. 2). Available data indicate that seagrasses have broadly lower greenhouse gas emissions of CH_4 and N_2O than comparative coastal and wetland habitats and that low salinity and anthropogenic stressors are major processes driving production (*26*). Similarly, comparison with habitats such as peatlands and mangroves shows seagrasses to be relatively low in CH_4 and N_2O (*27*). However, after seagrass meadow degradation and loss, there exists a potential for high emissions of CH_4 from underlying sediment (*28*). Eutrophication of seagrasses may also drive elevated N_2O emissions. Although scientific understanding in this field is increasing rapidly, our lack of understanding of the drivers of greenhouse gas emissions by plants, least of all by seagrasses (*21*, *27*), contributes to the uncertainties that surround the marketing of blue carbon (*29*).

Although its capacity for carbon storage is of high current interest, human appreciation for the ecological role of seagrasses has changed (*30*). An historic view of seagrasses from the Northern Hemisphere shows their importance in food production and as a raw material. For example, house roofs in Denmark were thatched with dried seagrass (some of which can still be seen), and seagrass detritus was used to fertilize crops (*30*). In the late 1800s, when Indian cotton crops failed, documented discussion by British cotton traders turned to the use of seagrass as an alternative fiber. In North America, companies existed that traded in seagrass as an insulation material, which was subsequently used in the US Capitol building. The Seri people of the Gulf of California collected seagrass seed to create a gruel (*31*). In the 21st century, in many parts of the world, seagrass meadows are a source of food from the gastropod and bivalve mollusks and sea cucumbers that they shelter (*32*). The importance of seagrass habitats as a source of seafood production is both direct and indirect at local and basin-wide scales, with 20% of the world's biggest finfish fisheries having some known association with seagrass (*33*).

Seagrasses also play a fundamental role in the filtration of coastal waters, trapping particles (including microplastics), cycling nutrients, and absorbing nitrogen from the water column (*34*). This filtration role also extends to the removal of bacteria and viruses (*35*–*37*), thus contributing to improved sanitation (*38*) and human health and well-being (*12*). In the Baltic Sea, seagrass meadows have been recorded to contain 63% fewer potentially harmful *Vibrio vulnificus* and *Vibrio cholerae* bacteria compared with nonvegetated areas (*37*).

Additionally, the role of seagrass in protecting coastlines from erosion is substantial and may grow in value with sea level rise and as storms become more frequent (*11*). The locally relevant role of seagrasses in ameliorating low pH from ocean acidification may also increase the value of these marine plants over time (*39*, *40*). Although the ecological roles that seagrasses play around the world shift with space and time, the constant across most of the world's seagrasses is that they remain at ecological risk and many are in a perilous state.

What is a pristine, healthy, or balanced seagrass ecosystem?

The extent and function of seagrass meadows are largely manifestations of current and previous human activity. We have limited capacity to appreciate the value of seagrass owing to the scale of alteration and unknown baselines for these systems (*41*, *42*). Evidence from ecological feedbacks indicates that seagrass meadows are driven by top-down and bottom-up processes (*43*, *44*). Although there is increasing appreciation for how seagrass might be influenced by excess nutrients and various pollutants in our coastal waters, we have limited appreciation for what extreme overexploitation of near-shore environments has done to seagrass meadows. We simply do not know what a so-called pristine meadow looks like, which creates a limited appreciation for the true ecological role of these poorly understood systems. A contributory factor to the poor understanding is the low relative research output on seagrasses [see (*45*)]. However, it is apparent that there has been a profound loss of predators from these systems, whereas numbers of consumers, secondary consumers, and grazers have also been affected (*46*)—in some cases, loss of predators has led to overgrazing (*47*, *48*).

In localities where associated biodiversity is high, functional redundancy may serve to protect seagrass meadows (*49*), but with decreasing diversity away from the tropics, such redundancy may be reduced. There is also a growing appreciation for seagrass as a foraging resource for seabirds; this is because they support abundant prey items, such as crustaceans, polychaetes, and fish (*50*). Given the parallel global decline of avifauna with global seagrass, we can only speculate as to what the functional role of loss of seagrass might have once been (*51*).

In recent decades, biodiversity and ecosystem functioning has evolved into a dynamic area of contemporary ecology with a rich body of research. Compared with research in terrestrial grasses and even seaweeds, the body of research within seagrass is magnitudes smaller and is fueled by a smaller community of scientists. We must understand the biodiversity associated with seagrass meadows to be able to develop management programs that secure their ecological functioning under further climate change. Global and regional studies are beginning to transform our knowledge (*44*, *52*, *53*), but tools such as sequencing environmental DNA need to be more widely applied. Reconstructions using molecular and historical evidence are needed to understand the true ecological potential of these ecosystems, to locate sites for rehabilitation and replanting, and to provide ambition to marine conservation.

Seagrass meadows and the SDGs

Improved protection and restoration of seagrasses require better recognition of the role that they play in supporting people and our planet; the state of seagrasses is symptomatic of the deteriorating state of the overall natural environment (*54*). The United Nations SDGs are a means of framing a response to this emergency by connecting the daily actions and needs of people, institutions, and communities to the sustainability of the planet and transforming these connections into measurable actions for positive environmental, social, and ecological outcomes. Articulating the ecological role of seagrass in terms of ecosystem services and natural capital promotes a scientific vision of what behavioral change might mean for seagrass, whereas the SDGs provide a framework for how change can be perceived by all people. We suggest that, of the 17 SDGs, action for seagrass conservation and restoration can make a meaningful contribution to 16 of these global goals (Fig. 3). We propose that the ecological role and value of seagrass can also be described in these terms to improve and catalyze action to halt and reverse seagrass loss.

Seagrass meadows form globally relevant habitats that support fisheries and associated economic goods; it is in this ecological role that seagrasses play a prominent role in SDGs. Thus, well-managed, sustainably exploited seagrass meadows that are in a state of ecological balance (*32*, *33*, *55*) will contribute to reducing poverty (*56*), reducing hunger (*32*), responsible consumption and production (*57*), and decent work and economic growth (*58*) (Fig. 3). Sustainably managed seagrass fisheries in many parts of the world also contribute toward gender equality and reducing other inequalities. For example, the role of women is underappreciated in intertidal and near-shore small-scale subsistence fisheries (*59*), of which seagrass meadows are a major component. Inclusion of women in these fisheries is well known to improve community adaptative capacity and resilience (*60*), leading to improved environmental outcomes (*59*).

A major ecological role of healthy seagrass systems is to make the wider environment more conducive for animal life (including humans) in both marine and coastal environments. Seagrass habitats enhance oxygenation in marine sediments; trap particles in the water column, improving water clarity; cycle and store nutrients; and reduce the bacterial and viral load in coastal waters. This creates a three-dimensional environment that harbors biodiversity, baffles wave energy to protect coastlines from erosion, and further enhances the whole coastal seascape for biodiversity (e.g., through the protection of adjacent habitats, such as coral reefs and mangroves).

The bioengineering effect that seagrasses have on their own environment also contributes to

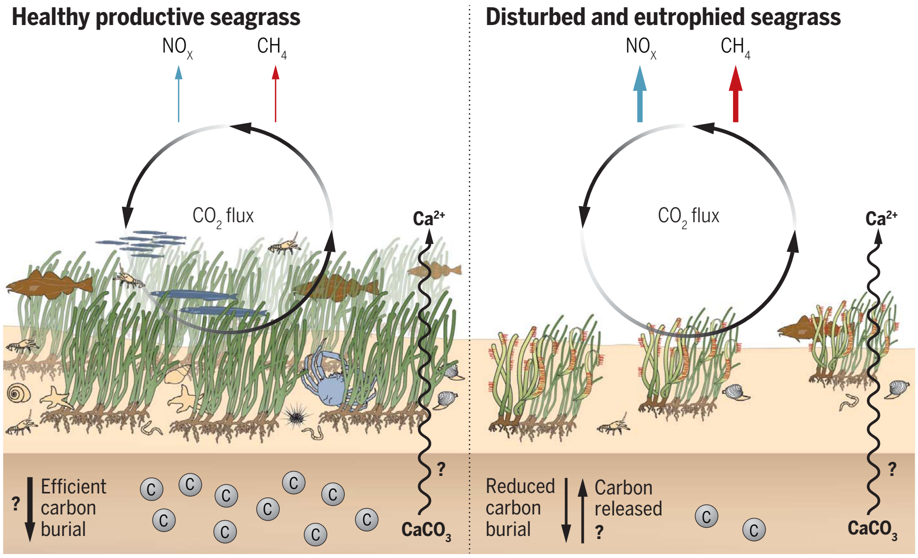

Fig. 2. The greenhouse gas balance of seagrass. There are many competing processes that result in seagrass meadows becoming net sources or sinks of greenhouse gases in our oceans. The left panel illustrates a healthy meadow where net photosynthetic productivity and dense seagrass is leading to rapid trapping and storage of carbon into the sediments. Although we lack a full understanding about greenhouse gas balance in seagrasses and the implications of disturbance, the right panel illustrates how meadow degradation and eutrophication can lead to the remobilization and loss of stored carbon and the potential increased production of CH_4 and N_2O. We also know little about the consequences of calcification by associated fauna within productive seagrass meadows on the overall carbon balance.

SDGs related to clean water and sanitation, good health, and well-being (*12*). Additionally, there is increasing appreciation of the value of seagrass for storing and sequestering carbon and the potential value of conserving seagrass meadows for climate mitigation (*61*). We understand that seagrasses enhance life below water, but less-well appreciated is that seagrass systems also enhance life on land by providing resources to shoreline habitats and populations, especially birds (*62*). The biodiversity present within seagrass meadows, the ecological processes and functions within them, and their relatively easy access also provide educational opportunities for human communities (*63*).

Without strong partnerships between communities, governments, nongovernmental organizations, and the private sector, seagrass conservation and restoration will not work effectively. The final SDG is about this bigger ambition. In the UK, the conservation charity Project Seagrass is bringing together private sector companies (e.g., CGI and Ocean Infinity), universities (e.g., Swansea and Heriot-Watt), institutes (e.g., NOC), and the government (e.g., the Hydrographic Agency) to map the UK's seagrass meadows. Similar initiatives are happening globally in places such as the Seychelles, Australia, and Indonesia.

Many aspects of the SDGs focus on the human planet, where the role that seagrasses play is changing with respect to a changing climate. With an expanding need to harness the energy of our oceans through wind, waves, and tide, there is increasing potential for new infrastructure to come into conflict with seagrass ecosystems. At the same time, this could lead to improved outcomes for seagrass, especially at a time when there is increasing global recognition of the need to develop strong criteria and indicators for pathways toward nature-positive outcomes. One such mechanism is that adopted in Australia, where marine biodiversity offsetting is accepted as a component of development consent to achieve an ambition of no net loss of biodiversity. A failed push toward tidal lagoon power in the UK provided impetus for seagrass restoration, and there is a growing focus on using seagrass restoration as a means of enhancing fish habitat as an offset to the effect of offshore wind power installations on marine biodiversity. The decline and reduced use of major historic urban coastal infrastructure, such as disused docklands, fisheries ponds, and mill ponds, are typical of many areas of the temperate Northern Hemisphere. The large empty docklands of South Wales provide an exemplary opportunity for seagrass restoration, and in southern Spain, entrepreneurial restaurateurs are bringing disused salt ponds back to life with seagrass for the growth of food products (*64*).

Charting a pathway to the net recovery of seagrass

Solutions for seagrass conservation and restoration have never been more urgent given the ongoing risks they face (*15*) and their potential role in helping mitigate climate change and the biodiversity crisis (*21*). Given the real and immediate threat of runaway climate change that places the future of humanity at risk, we need to rapidly move toward a conservation and restoration model that focuses on achieving global net recovery of seagrass (Fig. 4). Although financial mechanisms are emerging that begin to place monetary value onto seagrass carbon stores and carbon sequestration potential that will enable greater conservation and restorative action, concern exists about the potential for perverse and unintended consequences of such mechanisms (including international ownership of local resources), particularly around their role in supporting livelihoods (*56*).

It has been argued that avoiding a climate catastrophe requires at least three global transformations that are unprecedented in both magnitude and speed (*54*). One of these is a transformation of our relationship with nature to one that conserves, restores, and enhances its benefits for people and the planet (*54*). The SDGs could provide a valuable lens for securing the wider ecological role of seagrass meadows beyond carbon sequestration.

Seagrass habitats are global; estimates of loss are widespread and varied, but there is general agreement that the loss is vast. However, this does mean that there is huge potential for nature-based solutions focused on seagrass restoration. A restored seagrass meadow may take many years and be high cost in terms of

Seagrass conservation supports 16 of the 17 Sustainable Development Goals

1 No poverty
Seagrass ecosystem services for poverty alleviation (substrate for living, subsistence, and livelihoods)

2 Zero hunger
Seagrass subsistence fisheries support zero hunger

3 Good health and well-being
Seagrass bioengineers its environment, making it more affable and increasing the nutritional value of fish

4 Quality education
Seagrass ecosystems provide a means of teaching children core scientific principles (e.g., photosynthesis and environmental values)

5 Gender equality
Empowering women in seagrass fisheries (access to food and income for women)

6 Clean water and sanitation
Healthy seagrass filters and cleans water

7 Affordable and clean energy
Seagrass restoration can be embedded in marine renewable energy

8 Decent work and economic growth
Sustainable seagrass fisheries and green restoration jobs promote seagrass

9 Industry, innovation, and infrastructure
Opportunity for using seagrass as a trailblazer for the uptake of net gain within industrial marine biodiversity loss

10 Reduced inequalities
Management of seagrasses and their fisheries supports the underappreciated role of women in these activities

11 Sustainable cities and communities
Old coastal urban heritage infrastructure (e.g., ports) creates opportunities for seagrass restoration

12 Responsible consumption and production
Seagrass conservation requires sustainable management of associated resources

13 Climate action
Seagrass meadows store and sequester carbon

14 Life below water
Seagrasses bioengineer the seabed, enhancing life and biodiversity underwater

15 Life on land
Seagrasses support coastal defense, provide trophic subsidy to the coast, and support coastal avifauna

16 Peace, justice, and strong institutions
No major role

17 Partnerships for the goals
Improved seagrass conservation and restoration activity requires strong cross-sectoral partnerships

PHOTO BY BENJAMIN-L-JONES ON UNSPLASH

Fig. 3. Seagrass and sustainable development. Conservation and restoration of seagrass meadows and their ecological role can be communicated through the lens of the SDGs, of which seagrasses contribute to 16 of the 17 goals. A major part of this contribution is through the roles that they have as bioengineers and in supporting fisheries.

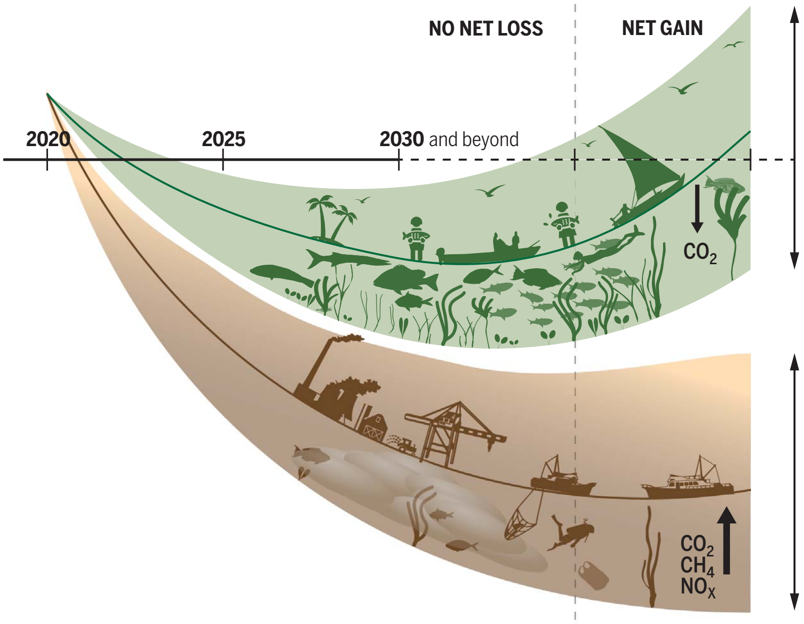

Fig. 4. A trajectory of seagrass recovery. Business as usual: Although seagrass meadows provide extensive ecosystem services and offer a major global opportunity as nature-based solutions, without intervention, they remain on a trajectory of global decline throughout the next century. Pathway to net gain: If major conservation action is taken to halt and reverse seagrass loss and degradation, then seagrasses can provide major contributions to fulfilling the aims of 16 of the 17 SDGs and for providing a major nature-based solution to climate change. Net gain of biodiversity requires avoidance of damage (e.g., legal instruments to halt bottom trawling) or minimization of effects that cannot be avoided, restoration to enhance or recreate habitats after damage (e.g., advanced mooring systems to allow recovery from boat damage), compensation, and recovery to enhance or recreate habitats known to have been historically lost or degraded (e.g., by active replanting). Image uses silhouettes created using symbols from the IAN Library, UMCES, University of Maryland.

labor and infrastructure to become ecologically functional (*65*, *66*). The opportunity provided by seagrass restoration should not detract from the urgent need to protect what we already have. As seagrass meadows become degraded, they not only begin to become net emitters of carbon, but they also release large amounts of nitrogen and sediments into the coastal ecosystem (*34*), together with any potential contaminants trapped within (e.g., heavy metals or plastics) (*67*). Achieving no net loss (and ultimately global net gain) of seagrasses requires scientific vision and political will (Fig. 3). This will not be easy, but we know that cumulative and connected conservation of seagrass over large scales can have major economic and environmental benefits (*65*). In general, plant conservation lags behind the conservation of animals (*68*), but seagrass could provide a model for how to overcome this so-called plant blindness, especially in the context of nature-based solutions (*69*).

Seagrasses have previously been described as the "ugly duckling" of marine conservation (*70*), but their star has risen with increasing interest in their potential to contribute to nature-based solutions to climate change and sustainable development. However, there are substantial ecological, social, and regulatory barriers and bottlenecks to seagrass restoration and conservation because of the scale of the interventions required. We must work inclusively at a local scale but in a globally connected network. Advances in marine robotics, molecular ecology, remote sensing, and artificial intelligence offer new opportunities to solve conservation problems in difficult environments at unprecedented global scales.

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