



PERSPECTIVE


LEVERAGING THE BLUE ECONOMY TO TRANSFORM MARINE FOREST RESTORATION¹

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The UN Decade of Ecosystem Restoration is a response to the urgent need to substantially accelerate and upscale ecological restoration to secure Earth's sustainable future. Globally,

restoration commitments have focused overwhelmingly on terrestrial forests. In contrast, despite a strong value proposition, efforts to restore seaweed forests lag far behind other major ecosystems and continue to be dominated by small-scale, short-term academic experiments. However, seaweed forest restoration can match the scale of damage and threat if moved from academia into the hands of community groups, industry, and

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restoration practitioners. Connecting two rapidly growing sectors in the Blue Economy—seaweed cultivation and the restoration industry—can transform marine forest restoration into a commercial-scale enterprise that can make a significant contribution to global restoration efforts.

Key index words: coastal habitat; cultivation; industry; macroalgae; seaweed; upscaling

Abbreviations: EU, European Union; IUCN, International Union for Conservation of Nature; NGO, non-governmental organization; TNC, The Nature Conservancy; UN, United Nations; WWF, World Wildlife Fund

The UN Decade of Ecosystem Restoration (2021–2030) is a reaction to the urgent need to massively accelerate global efforts to reverse centuries of ecosystem damage, and to address our current climate and biodiversity crisis (UN General Assembly 2019). While much of this effort is focused on increasing forests on land (e.g., Bonn Challenge, IPCC 2019), restoring marine forests presents a unique—but underappreciated and underutilized—way to protect biodiversity, enhance CO₂ drawdown, and provide other benefits (Teagle et al. 2017, Ortega et al. 2019, Feehan et al. 2021; Fig. 1). Growing awareness of marine forests as a source of climate, environmental, and sociopolitical solutions comes as part of the wave of “seaweed optimism,” where seaweeds—and the underwater forests that they create—are heralded as overlooked carbon sinks, important nutrient filters, and focal points for high biodiversity, as well as an untapped source of sustainable materials and source of opportunities to redress gender and societal inequality (Duarte et al. 2017, Filbee-Dexter 2020, Seaweed Manifesto 2020, Mouritsen et al. 2021). At the same time, increasing environmental protection laws, international conventions, and coastal development mandates to mitigate and offset damages to marine habitats (e.g., EU Directives, OSPAR Convention, BEACH Act) are generating strong incentive and additional resources for coastal habitat protection and restoration. Yet marine forests continue to decline globally (Seri-sawa et al. 2004, Arafeh-Dalmau et al. 2019, Wernberg et al. 2019, Filbee-Dexter et al. 2020, Gouraguine et al. 2021) and despite constituting the most extensive biogenic coastal ecosystems (Filbee-Dexter 2020), and substantial efforts and development of new techniques, marine forests have the smallest restored areas of all coastal ecosystems (ca. 78% of all projects are <1 ha and < 2 y, and only three projects to date have been greater than 100 ha; Eger et al. 2021). Attention to their restoration is thus lagging substantially behind all other marine systems (Feehan et al. 2021; Fig. 2). For every paper published on seaweed forest restoration, 11 are published on saltmarshes, 18 on seagrass,

and 22 on mangroves (Saunders et al. 2020). To date, the largest successful seaweed forest restoration project covered only 870 hectares (Japan; Eger et al. 2020). For comparison, over 190,000 hectares of mangrove forests have been restored globally (Saunders et al. 2020). This mismatch in scale and research effort is also evident in international initiatives and financing options. Prominent international organizations (WWF, IUCN, TNC) have created a Global Mangrove Alliance that aims to restore millions of hectares to expand global mangrove cover by 20% and catalyze US \$10 billion in investments by 2030 (Worthington et al. 2020). Similarly, the recently launched Global Fund for Coral Reefs (the first UN impact Fund dedicated to SDG 14—Life Below Water) aims to provide sustainable financing of US \$500 million for coral reef protection and restoration (globalfundcoralreefs.org/). In contrast, seaweed forests are not even mentioned in any of the international restoration initiatives, and active interventions to regrow these marine forests are not yet developed for many regions where extensive losses occur (Table 1). To match the required restoration efforts with the scale of current declines and future threat, we must overcome the key challenge of upscaling marine forest restoration from small-scale and short-term experiments conducted by academic institutions to broad-scale community and industry-driven initiatives funded through market-based incentives. These challenges include innovating methods that can be applied at large scale and tools and technology that can be applied by local stakeholders.

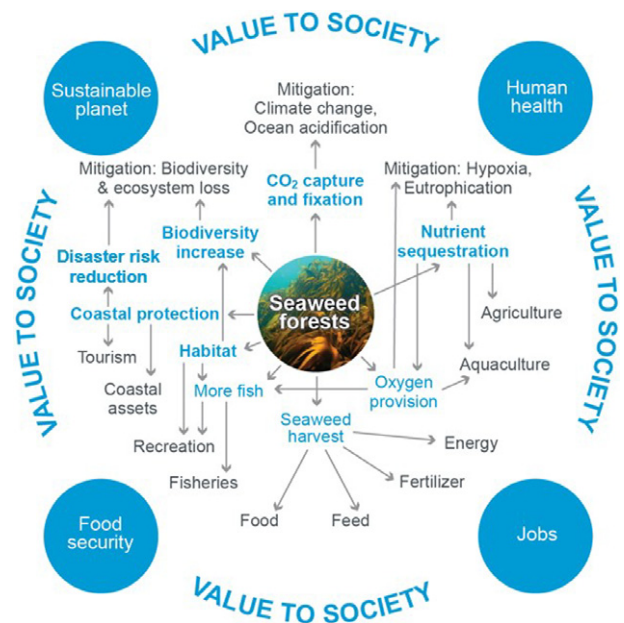


FIG. 1. Value proposition for marine forest restoration. Including some of the key direct ecosystem services and function provided by marine forests.

Cross-sectoral collaborations between scientists, industry, and community groups provide a key space to develop new technologies and innovative approaches, as well as generate the knowledge and social license required to scale up restoration to meet the challenges ahead (Mcafee et al. 2021). The rapidly expanding Blue Economy, and in particular the growing industries of seaweed cultivation (FAO 2018) and ecosystem restoration (Spalding 2016), can deliver powerful synergies with potential to transform the scale of marine forest restoration. The origin of the “Blue Economy” concept came from the 2012 United Nations Conference on Sustainable Development (Smith-Godfrey 2016) and today the term is closely associated with the UN’s Sustainable Development Goals (SDGs), specifically SDG 14: ‘Conserve and sustainably use the oceans, seas and marine resources for sustainable development’. Although there are many understandings of the Blue Economy, at its core, the concept captures the sustainable development of the oceans in a way

that both supports improved human well-being and builds resilient ecosystems. It includes a range of fields and enterprises, from sustainable fisheries, tourism, waste management, renewable energy, and restoration, monitoring, and conservation of marine ecosystems (Golden et al. 2017). Akin to the Green Economy, the Blue Economy necessitates that economic activities are balanced with conservation and sustainable management, which can often be at odds due to the growing economic expansion and development pressure in the coastal zone (Golden et al. 2017).

One sector of the Blue Economy of relevance for upscaling seaweed restoration is the growing seaweed sector, which is one of the more sustainable forms of farming in the world (Seaweed Manifesto 2020). The success of many large-scale restoration approaches depends on the ability to meet the demand for vast quantities of appropriately sourced seed (Breed et al. 2018). In much the same way as commercial shellfish hatcheries produce seed stock

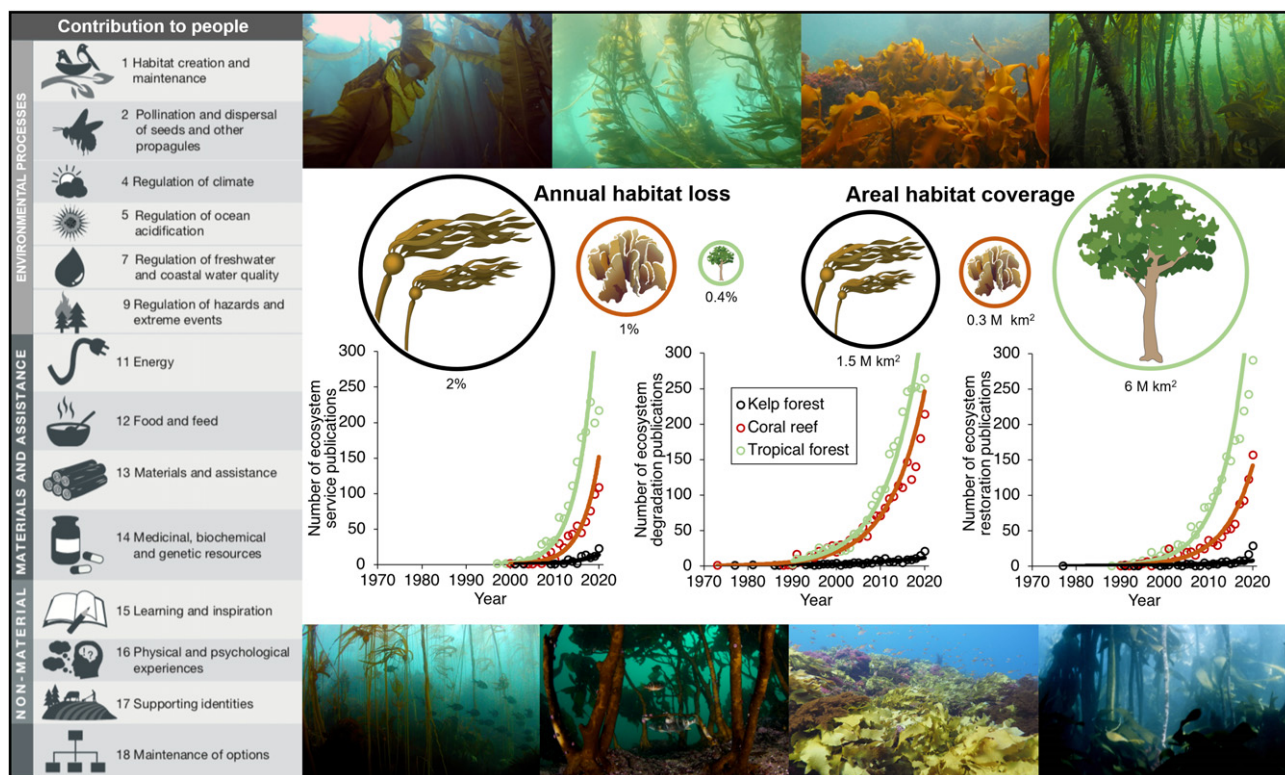


Fig. 2. Kelp forests are overlooked ecosystems for restoration. Kelp forests provide extensive benefits to humans, including 14 of the 18 contributions of nature to people identified by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Scientific interest in kelp forest ecosystem services, degradation, and restoration has increased within the past decade, but lags decades behind coral reefs and tropical rainforests. This is despite kelp forests declining at an annual rate two times that of coral reefs and more than four times that of rainforests and covering an ocean area five times greater than all coral reefs and a quarter the size of the Amazon rainforest (Feehan et al. 2021). Photographs (top left to bottom right; photo credits in parentheses): *Eualaria fistulosa*, Gulf of Alaska (Pike Spencer); *Macrocystis pyrifera*, western Canada (Jenn Burt); *Saccharina latissima*, Atlantic Canada (Kira Krumhansl); *Laminaria hyperborea*, northern Norway (Thomas Wernberg); *Nereocystis luetkeana*, western USA (Jared Figurski); *Lessonia trabeculata*, Chile (Alejandro Pérez Matus); *Ecklonia radiata*, western Australia; *Ecklonia maxima*, South Africa (both Thomas Wernberg). Plots: Web of Science topic searches for keywords: (kelp*, coral*, or ["tropical forest*" not kelp]) in combination with (restoration, degradation, or "ecosystem service*"). Lines are exponential fits. Left-hand panel is reproduced from IPBES (2019).

TABLE 1. Scale of loss of marine forests and scale of restoration success to date for select countries and regions with available data. Restoring includes all active efforts to increase natural seaweed habitats, including reducing stressors, transplants, or herbivore removals. Natural recovery is not included (e.g., disease outbreaks of herbivores) nor is addition of artificial reefs outside of natural habitat.

Region	Dominant species	Area (ha) of damage	Predominant driver	Year	Area restored (ha)	Percent restored (%)	Source
New Zealand	<i>Durvillaea</i> spp.	6	Marine heatwave	2016–2018	0	0	Thomsen et al. 2019, M. Thompson pers. comm.
New South Wales (Australia)	<i>Phyllospora comosa</i>	31	Pollution	~1960s	0.4	1	Coleman et al. 2008, Vergés et al. 2020
Tasmania (Australia)	<i>Ecklonia radiata</i>	4861	Warming-driven overgrazing	2000s–present	<0.01	0	Ling and Keane 2018
Western Australia	<i>Ecklonia radiata</i>	97,438	Marine heatwave	2011	0	0	Wernberg et al. 2016
Japan	<i>Ecklonia</i> spp., <i>Sargassum</i> spp.	75,000 ^a	Coastal development, temperature, extreme events	1999–2018	870		Eger et al. 2020
Korea	<i>Ecklonia</i> , <i>Sargassum</i> spp.	10,000	Coastal development and pollution	1900s	20,000 ^c		Sondak and Chung 2015, Eger et al. 2021
NW Spain	<i>Laminaria ochroleuca</i>	1183 ^b	Overgrazing	2020	0	0	C. Piñeiro-Corbeira and R. Barriero unpub. data
NW–SW France	<i>Laminaria hyperborea</i> , <i>Laminaria digitata</i> , <i>Saccharina latissima</i>	1000–3000 ^d	Water quality, invasive species, warming	1980s–present	0	0	Cosson 1999, de Bettignies et al. 2021, T. de Bettignies unpub. data
Denmark	<i>Saccharina latissima</i> , <i>Laminaria digitata</i>	5500	Excavation for coastal development	1800s	11.3	0.2	Støttrup et al. 2014, Helmig et al. 2020, P. Staer pers. comm.
Southern Norway	<i>Saccharina latissima</i>	780,000	Warming, eutrophication	2002	0.001	0	Gundersen et al. 2017, Filbee-Dexter et al. 2020, Fredriksen et al. 2020
Northern Norway	<i>Laminaria hyperborea</i>	200,000	overgrazing	1970s	110	0.055	Norderhaug and Christie 2009, Gundersen et al. 2017, Eger et al. 2020
Nova Scotia (Canada)	<i>Saccharina latissima</i> , <i>Laminaria digitata</i>	2530 ^e	Warming, invasive epiphyte	2000s	0	0	Filbee-Dexter et al. 2016
Long Island Sound (USA)	<i>Saccharina latissima</i> , <i>Laminaria digitata</i>	2300 ^e	Warming	2000s	0	0	Feehan et al. 2019
Chile	<i>Lessonia</i> , <i>Macrocystis pyrifera</i>	382,153 ^f	Overgrazing, urbanization	unknown	0.012	0	Stotz et al. 2016, Campos et al. 2020
Southern California (USA)	<i>Macrocystis pyrifera</i>		Overharvesting and water quality	Early 1900s	10s		Eger et al. 2021
Northern California (USA)	<i>Nerocystis luetkeana</i>	665–4800	Marine heatwave overgrazing	2014	0	0	Rogers-Bennett and Catton 2019

^aincludes both seaweed and seagrass forests.

^bValue corresponds to one of several rias in NW Spain.

^cRestored area is mainly addition of artificial reefs and does not directly correspond to the area of natural reef lost.

^dCoarse estimate of km of coastline with loss based on seaweed forest extending 0.1–0.2 km from shore multiplied by the km of degraded rocky coastline (~100–150 km).

^eCoarse estimate of area based on the average kelp forest margin of 0.23 km from shore (Filbee-Dexter and Scheibling 2017) multiplied by the km of coastline loss.

^fEstimated from portion of transects in barrens state along 600 km of coastline between 5 and 15 m depth.

for oyster reef restoration, and commercial nurseries produce tree seedlings for terrestrial forest and mangrove restoration (Nguyen et al. 2016, Faruqi et al. 2018), commercial seaweed culture banks and hatchery facilities can expand restoration capacity for seaweeds through large-scale production of seaweed seed stock to restore natural rocky reefs. This approach would build on existing seaweed cultivation methods recently adapted to restoration, such as deployment of seeded substrates and lines (Glenn et al. 1996, Chung et al. 2013, Verdura et al. 2018, Fredriksen et al. 2020). These substrates (e.g., small rocks, biodegradable seaweed cultivation lines, or other artificial structures) can be seeded with seaweeds in hatcheries, cultivated for a period of time (weeks), and then outplanted to damaged reefs, where they can establish full canopies and eventually seed adjacent damaged areas through natural reproduction (Fig. 3). These seeded substrates can often be spread over large areas of seafloor without the use of highly specialized equipment or trained personnel such as scuba divers. Benefiting from the scale and technological advances in commercial aquaculture and seeding practices, this approach can overcome many of the barriers currently limiting seaweed forest restoration, including the small scales of transplantations and the cost-prohibitive approaches that require commercial divers.

Effectively upscaling seaweed forest restoration has potential to leverage more than the seaweed farming sector alone. The restoration sector aims to restore biodiverse and functional ecosystems at unprecedented scales (Verdone and Seidl 2017, Per-ring et al. 2018). This could be an increasingly important sector as policy-driven financial incentives for restoration and natural based solutions become more common. Although much of the focus has been on restoring terrestrial ecosystems, this growing industry could also generate the impetus, resources, and capacity to initiate and manage more

seaweed forest projects that cover larger areas (Bendor et al. 2015). In some situations, targeted conservation as well as catchment and fisheries management could further play a role in helping to mitigate stressors that suppress recovery or hinder restoration. For example, through the establishment of marine reserves which increase large fish (Babcock et al. 2010, Coleman et al. 2015) and reduce grazing pressure on seaweeds, or through targeted fishing of over abundant sea urchins (Steneck et al. 2013), which can threaten these habitats (Norderhaug and Christie 2009, Filbee-Dexter and Scheibling 2014, Jeon et al. 2015, Edwards et al. 2020). Collaboration between restoration practitioners and local fishers or seaweed cultivators will also help diversify the income stream for these small businesses, increasing financial resilience, and building important supply chains for the various actors. This multisector approach to restoration would reduce individual costs per group and draw on different areas of expertise (Gann et al. 2019). Cross-sectoral partnerships between local stakeholders, industry, and scientists can create strong local buy-in and social license, and ensure the best available techniques and facilities are used in restoration activities (France 2016, Eger et al. 2020).

The use of commercial seaweed farming technology by the restoration industry will also support innovation and advances in our capacity to cultivate seaweeds, which can grow the seaweed sector and further contribute to grow the blue economy. Seaweed farms produce food and sustainable materials with a small carbon and environmental footprint, requiring no feed, freshwater, or fertilizer (Seaweed Manifesto 2020). Contributing to 13 of the UN Sustainable Development Goals, farmed seaweeds are increasingly identified as providing numerous untapped solutions to our current environmental and social challenges (Seaweed Manifesto 2020). There is also an expanding seaweed biotech

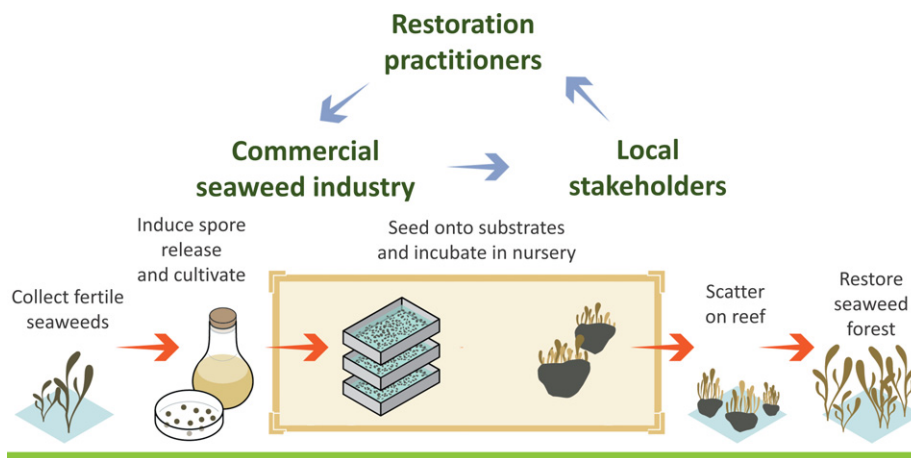


FIG. 3. Cross-sectoral approach to seaweed forest restoration showing use of commercial scale and quality seaweed rearing facilities to local restoration projects. In this example, restoration practitioners pay commercial seaweed hatcheries to produce seed stock that are sent to local stakeholders to restore seaweed forests.

industry that is capturing investments in carbon capture and sustainable production methods (e.g., biodegradable plastics), and which also uses seaweed culturing and outplanting techniques (Mouritsen et al. 2021). Commercial seaweed production is a 4 billion USD industry annually, and considerable investment is needed to grow the industry outside of Asia (FAO 2018). Although small-scale farms are increasing in North America, South America, Africa, Europe, and Oceania, key hurdles for developing a sustainable seaweed industry include lack of trained personnel, market development and supply chains, seed banks, and social license (Buschmann et al. 2017, Wade et al. 2020). In this regard, any effort devoted to creating a demand for seed supply for native species, developing technology for more efficient seaweed cultivation, or other actions that drive job growth and training in this sector will augment the transition to a more green, circular, and carbon neutral economy. At the same time, the increased scale of production will generate research and development into seaweed culturing that expands the technical capacity required to grow the restoration sector and upscale current techniques.

The need for a broad suite of solutions is well established for restoring forests. Natural forest regrowth (passive restoration after removal of degraded factors) that relies on spontaneous increase in trees without direct reintroduction can work well for some sites with nearby donor seed sources and limited past damage. However, actively planting trees is often a more effective approach for heavily damaged urban land (Chazdon et al. 2020). These lessons from forests also apply to seaweed forest restoration, with seeding seaweeds being analogous to planting tree seedlings/saplings. Afforestation using artificial reefs seeded with seaweeds (although they function differently than natural reefs) could work well in areas with a limited supply of propagules, on heavily modified urban coasts with infill, artificial structures, and no natural reefs or on wind turbines or other infrastructure being added to the coastal zone (e.g., green/gray infrastructure; Kuwae and Crooks 2021). In areas where stressors like pollution are reduced, but the degraded system persists, active restoration can help overcome negative ecological feedbacks that prevent natural recruitment (Vergés et al. 2020). Importantly, without such interventions, the potential gain in ecosystem function from management actions to reduce stressors such as pollution, fishing, or eutrophication could be greatly delayed or lost. Restoring small patches of habitats in more natural systems could also speed up natural regrowth of the entire area (Campbell et al. 2014). Increased seaweed may also further improve water quality by taking up excess nutrients and organic pollutants (Neveux et al. 2018, Bews et al. 2021). In this way, the ecological footprint of a restored area is much larger than its area of seafloor because it is donating

propagules, providing spillover of associated species, and changing environmental conditions on the surrounding reefs through CO₂ and nutrient uptake and improved water clarity.

There are challenges to overcome before large-scale cross-sectoral marine forest restoration can be realized. Solutions need to align with the priorities of the seaweed industry and ecosystem management/conservation sectors. These could differ, with the seaweed industry and biotech focusing on enhancing productivity, marketable species, and carbon capture, whereas restoration could focus on biodiversity, long-lived species, and other functions. There is also a challenge of regulations, policies, and legislation, which are not in place to support large-scale seaweed restoration, but are an essential step for a shift toward large-scale restoration actions (France 2016). This likely represents a massively overlooked hurdle that both the restoration sector and the seaweed farming industry face. Yet, collaborations among local governments, stakeholders, scientists, and industry partners could prepare the groundwork for this. Mitigation or removal of stressors driving decline in seaweeds is essential for restoration success (Layton et al. 2020), and must be addressed before, or in parallel with seeding efforts. Ongoing changes in environmental conditions driven by climate change and human population growth are challenging to alleviate (Hobbs 2013). Along with necessary approaches to reduce stressors, broadcast seeding of seaweed forests provides pathways to propagate climate-tolerant genotypes that can “future proof” these habitats (Coleman and Gould 2019, Coleman et al. 2020). There is great potential to target resilient donor plants, increase their quantity with commercial cultivation, and then propagate strong genotypes on seeded substrates spread onto degraded reefs to increase resilience of seaweed forests to climate change and other threats (Alsuwaiyan et al. 2021, Wood et al. 2021). As such, a cross-sectoral approach that leverages the knowledge of restoration scientists, the socioeconomic motivation of local stakeholders, and the financial incentives of the commercial seaweed and restoration industries could provide a restoration solution that can succeed in the face of increasing degradation and altered ocean conditions.

To better illustrate the geographic scale of the challenge, marine forests of large brown seaweeds (kelp forests) cover an area roughly the size of Mexico (160 million hectares), with a total annual production of 0.9 PgC (Duarte et al. 2022). Over the past few decades, marine forests have declined globally (Filbee-Dexter and Wernberg 2018, Wernberg et al. 2019, Smale 2020). While there are many unmonitored forests with unclear status, the most recent estimate of 1.8% instantaneous loss each year (Krumhansl et al. 2016) implies that 3 million hectares of marine forests need to be restored in 2021

just to keep pace with current declines. At a typical project scale of 100 m² over 2 y (Eger et al. 2020), this would require 288 million new seaweed restoration projects. Even using metrics from the largest ever documented successful seaweed forest restoration project (Japan 870 ha, 8 y, US \$5.2 million; Eger et al. 2020), this would require 3310 projects of this scale to be initiated, costing a total of US \$17 billion. While this is obviously a crude calculation, and only a fraction of these regions are suitable for active restoration action, it does highlight the incredible magnitude of disparity between current efforts and the scale of loss.

As the UN Decade of Restoration catalyzes efforts to upscale restoration, initiatives must remain aware of local needs and context. Ecosystem restoration is, by nature, on the ground local response to a global challenge. While there is a rush to go to scale, we still also need time to trial techniques, adapt approaches to local contexts and learn from smaller efforts. The ‘Greening the Blue Front Yard’ approach represents a strong value proposition and model for community-based engagement in marine restoration: In the same way as communities and municipalities maintain and restore nature areas on land (parks, green spaces; the green backyard), a healthy and well-maintained “blue front yard” provides substantial benefits to local communities and can be financed by policy-driven incentives and offset schemes. For example, the Wetlands Reserve Program in the USA (Gray 2005) and the Water Framework Directive in the EU (Directive 2000/60) provide financial incentives or legislation to restore, or improve, wildlife habitats. Similar programs could be used to maintain key services (coastal protection by wave dampening, nutrient filtering, nursery habitats) by marine forests, but this hinges on recognition of the value of the services these habitats provide (Eger et al. 2021). The commercial seaweed sector can propel the transition away from academic-driven activities by supplying propagule cultures or seeded substrates directly to restoration practitioners, community groups, NGOs, or local governments, removing technological barriers and increasing accessibility of restoration. This path for future actions to enhance marine forest resilience and recovery can be used as part of a broader management strategy to combat global decline in marine forest health and to help ensure these ecosystems continue to support income, livelihoods, and overall well-being of the local and global citizens that benefit from their goods and services.

These ideas were developed by the SEAFORCE consortium through discussions with Seaweed Solutions, Algal Plus, C-weed Aquaculture, and other seaweed cultivators. Illustrations in Figure 2 are courtesy of Andrea Dingeldein (thelocalnaturalist.com) and Tracey Saxby and Dieter Trace of the Integration and Application Network (ian.umces.edu/media-library).

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K. Filbee-Dexter: Conceptualization (lead); Data curation (lead); Funding acquisition (lead); Investigation (lead); Methodology (lead); Project administration (equal); Resources (equal); Software (equal); Validation (equal); Visualization (equal); Writing – original draft (lead); Writing – review & editing (lead). **T. Wernberg:** Conceptualization (lead); Data curation (supporting); Formal analysis (equal); Funding acquisition (lead); Investigation (lead); Methodology (lead); Project administration (lead); Resources (lead); Supervision (equal); Validation (equal); Visualization (supporting); Writing – original draft (lead); Writing – review & editing (lead). **R. Barreiro:** Conceptualization (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **M. A. Coleman:** Conceptualization (lead); Funding acquisition (lead); Writing – original draft (supporting); Writing – review & editing (supporting). **T. de Bettignies:** Conceptualization (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **C. Feehan:** Data curation (equal); Visualization (equal); Writing – review & editing (supporting). **J. N. Franco:** Conceptualization (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **B. Hasler:** Conceptualization (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **I. Louro:** Conceptualization (supporting); Funding acquisition (supporting); Project administration (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **K. Norderhaug:** Conceptualization (supporting); Funding acquisition (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **P. A. Staehr:** Conceptualization (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **F. Tuya:** Conceptualization (supporting); Writing – original draft (supporting); Writing – review & editing (supporting).

COMPETING INTERESTS

Ines Louro and Jan Verbeek work for SeaForester, a for profit seaweed restoration company. www.seaforester.org.

Alsuwaiyan, N. A., Vranken, S., Filbee-Dexter, K., Cambridge, M., Coleman, M. A. & Wernberg, T. 2021. Genotypic variation in response to extreme events may facilitate kelp adaptation under future climates. *Mar. Ecol. Prog. Ser.* 672:111–21.

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