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Leveraging the blue economy to transform marine forest restoration

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13 Leveraging the blue economy to transform marine forest restoration

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64 ABSTRACT.

65 The UN Decade of Ecosystem Restoration is a response to the urgent need to substantially
66 accelerate and upscale ecological restoration to secure Earth's sustainable future. Globally,
67 restoration commitments have focused overwhelmingly on terrestrial forests. In contrast, despite
68 a strong value proposition, efforts to restore seaweed forests lag far behind other major
69 ecosystems and continue to be dominated by small-scale, short-term academic experiments.
70 However, seaweed forest restoration can match the scale of damage and threat if moved from
71 academia into the hands of community groups, industry and restoration practitioners. Connecting
72 two rapidly growing sectors in the Blue Economy - seaweed cultivation and the restoration
73 industry - can transform marine forest restoration into a commercial-scale enterprise that can
74 make a significant contribution to global restoration efforts.

75

76 Keywords: seaweed, macroalgae, cultivation, upscaling, coastal habitat, industry

77

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

81

82

83 The UN Decade of Ecosystem Restoration (2021-2030) is a reaction to the urgent need to
84 massively accelerate global efforts to reverse centuries of ecosystem damage, and to address our
85 current climate and biodiversity crisis (UN 2020). While much of this effort is focused on
86 increasing forests on land (e.g., Bonn Challenge, IPCC 2018, Lewis et al. 2019), restoring
87 marine forests presents a unique – but underappreciated and underutilized – way to protect
88 biodiversity, enhance CO₂ drawdown and provide other benefits (Teagle et al. 2017, Ortega et al.

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89 2019, Feehan et al. 2021; Fig. 1). Growing awareness of marine forests as a source of climate,
90 environmental and socio-political solutions comes as part of the wave of ‘seaweed optimism’,
91 where seaweeds – and the underwater forests that they create – are heralded as overlooked
92 carbon sinks, important nutrient filters and focal points for high biodiversity, as well as an
93 untapped source of sustainable materials and source of opportunities to redress gender and
94 societal inequality (Duarte et al. 2017, Filbee-Dexter 2020, Seaweed Manifesto 2020, Mouritsen
95 et al. 2021). At the same time, increasing environmental protection laws, international
96 conventions and coastal development mandates to mitigate and offset damages to marine habitats
97 (e.g., EU Directives, OSPAR Convention, BEACH Act) are generating strong incentive and
98 additional resources for coastal habitat protection and restoration. Yet marine forests continue to
99 decline globally (Serisawa et al. 2004, Arafeh-Dalmau et al. 2019, Wernberg et al. 2019, Filbee-
100 Dexter et al. 2020, Gouraguine et al. 2021) and despite constituting the most extensive biogenic
101 coastal ecosystems (Duarte et al 2020), and substantial efforts and development of new
102 techniques, marine forests have the smallest restored areas of all coastal ecosystems (ca. 78% of
103 all projects are <1 ha and < 2 y, and only 3 projects to date have been greater than 100 ha; Eger
104 et al. 2021). Attention to their restoration is thus lagging substantially behind all other marine
105 systems (Feehan et al. 2021; Fig. 2). For every paper published on seaweed forest restoration, 11
106 are published on saltmarshes, 18 on seagrass and 22 on mangroves (Saunders et al. 2020). To
107 date, the largest successful seaweed forest restoration project covered only 870 hectares (Japan;
108 Eger et al. 2020b). For comparison, over 190,000 hectares of mangrove forests have been
109 restored globally (Saunders et al. 2020). This mismatch in scale and research effort is also
110 evident in international initiatives and financing options. Prominent international organizations
111 (WWF, IUCN, TNC) have created a Global Mangrove Alliance that aims to restore millions of
112 hectares to expand global mangrove cover by 20% and catalyze US \$10 billion in investments by
113 2030 (Worthington et al. 2020). Similarly, the recently launched Global Fund for Coral Reefs
114 (the first UN impact Fund dedicated to SDG 14- Life Below Water) aims to provide sustainable
115 financing of US \$500 million for coral reef protection and restoration
116 (globalfundcoralreefs.org/). In contrast, seaweed forests are not even mentioned in any of the
117 international restoration initiatives, and active interventions to regrow these marine forests are
118 not yet developed for many regions where extensive losses occur (Table 1). To match the
119 required restoration efforts with the scale of current declines and future threat, we must
120 overcome the key challenge of upscaling marine forest restoration from small-scale and short-

121 term experiments conducted by academic institutions to broad-scale community and industry-
122 driven initiatives funded through market-based incentives. These challenges include innovating
123 methods that can be applied at large scale and tools and technology that can be applied by local
124 stakeholders.

125 Cross sectoral collaborations between scientists, industry and community groups provide
126 a key space to develop new technologies and innovative approaches, as well as generate the
127 knowledge and social license required to scale up restoration to meet the challenges ahead
128 (Mcafee et al. 2021). The rapidly expanding Blue Economy, and in particular the growing
129 industries of seaweed cultivation (FAO 2018) and ecosystem restoration (Spalding 2016), can
130 deliver powerful synergies with potential to transform the scale of marine forest restoration. The
131 origin of the 'Blue Economy' concept came from the 2012 United Nations Conference on
132 Sustainable Development (Smith-Godfrey 2016) and today the term is closely associated with
133 the UN's Sustainable Development Goals (SDGs), specifically SDG 14: "Conserve and
134 sustainably use the oceans, seas and marine resources for sustainable development". Although
135 there are many understandings of the Blue Economy, at its core the concept captures the
136 sustainable development of the oceans in a way that both supports improved human well-being
137 and builds resilient ecosystems. It includes a range of fields and enterprises, from sustainable
138 fisheries, tourism, waste management, renewable energy, and restoration, monitoring and
139 conservation of marine ecosystems (Golden et al. 2017). Akin to the Green Economy, the Blue
140 Economy necessitates that economic activities are balanced with conservation and sustainable
141 management, which can often be at odds due to the growing economic expansion and
142 development pressure in the coastal zone (Golden et al. 2017).

143 One sector of the Blue Economy of relevance for upscaling seaweed restoration is the
144 growing seaweed sector, which is one of the more sustainable forms of farming in the world
145 (Seaweed Manifesto 2020). The success of many large-scale restoration approaches depends on
146 the ability to meet the demand for vast quantities of appropriately provenanced seed (Breed et al.
147 2018). In much the same way as commercial shellfish hatcheries produce seed stock for oyster
148 reef restoration, and commercial nurseries produce tree seedlings for terrestrial forest and
149 mangrove restoration (Nguyen et al. 2016, Faruqi et al. 2018), commercial seaweed culture
150 banks and hatchery facilities can expand restoration capacity for seaweeds through large-scale
151 production of seaweed seed stock to restore natural rocky reefs. This approach would build on

152 existing seaweed cultivation methods recently adapted to restoration, such as deployment of
153 seeded substrates and lines (Glenn et al. 1996, Chung et al. 2013, Verdura et al. 2018, Fredriksen
154 et al. 2020). These substrates (e.g., small rocks, biodegradable seaweed cultivation lines or other
155 artificial structures) can be seeded with seaweeds in hatcheries, cultivated for a period of time
156 (weeks), and then out-planted to damaged reefs, where they can establish full canopies and
157 eventually seed adjacent damaged areas through natural reproduction (Fig. 3). These seeded
158 substrates can often be spread over large areas of seafloor without the use of highly specialized
159 equipment or trained personnel such as scuba divers. Benefiting from the scale and technological
160 advances in commercial aquaculture and seeding practices, this approach can overcome many of
161 the barriers currently limiting seaweed forest restoration, including the small scales of
162 transplantations and the cost-prohibitive approaches that require commercial divers.

163 Effectively upscaling seaweed forest restoration has potential to leverage more than the
164 seaweed farming sector alone. The restoration sector aims to restore biodiverse and functional
165 ecosystems at unprecedented scales (Verdone and Seidl 2017, Perring et al. 2018). This could be
166 an increasingly important sector as policy-driven financial incentives for restoration and natural
167 based solutions become more common. Although much of the focus has been on restoring
168 terrestrial ecosystems, this growing industry could also generate the impetus, resources and
169 capacity to initiate and manage more seaweed forest projects that cover larger areas (Bendor et
170 al. 2015). In some situations, targeted conservation as well as catchment and fisheries
171 management could further play a role in helping to mitigate stressors that suppress recovery or
172 hinder restoration. For example, through the establishment of marine reserves which increase
173 large fish (Babcock et al. 2010, Coleman et al. 2015) and reduce grazing pressure on seaweeds,
174 or through targeted fishing of over abundant sea urchins (Steneck et al. 2013), which can
175 threaten these habitats (Norderhaug and Christie 2009, Filbee-Dexter and Scheibling 2014, Jeon
176 et al. 2015, Edwards et al. 2020). Collaboration between restoration practitioners and local
177 fishers or seaweed cultivators will also help diversify the income stream for these small
178 businesses, increasing financial resilience and building important supply chains for the various
179 actors. This multi-sector approach to restoration would reduce individual costs per group and
180 draw on different areas of expertise (Gann et al. 2019). Cross-sectoral partnerships between local
181 stakeholders, industry and scientists can create strong local buy-in and social license, and ensure
182 the best available techniques and facilities are used in restoration activities (France 2016, Eger et
183 al. 2020a).

184 The use of commercial seaweed farming technology by the restoration industry will also
185 support innovation and advances in our capacity to cultivate seaweeds, which can grow the
186 seaweed sector and further contribute to grow the blue economy. Seaweed farms produce food
187 and sustainable materials with a small carbon and environmental footprint, requiring no feed,
188 freshwater, or fertilizer (Seaweed Manifesto 2020). Contributing to 13 of the UN Sustainable
189 Development Goals, farmed seaweeds are increasingly identified as providing numerous
190 untapped solutions to our current environmental and social challenges (Seaweed Manifesto
191 2020). There is also an expanding seaweed biotech industry that is capturing investments in
192 carbon capture and sustainable production methods (e.g., biodegradable plastics), and which also
193 uses seaweed culturing and out-planting techniques (Mouritsen et al. 2021). Commercial
194 seaweed production is a 4 billion USD industry annually, and considerable investment is needed
195 to grow the industry outside of Asia (FAO 2018). Although small scale farms are increasing in
196 North America, South America, Africa, Europe and Oceania, key hurdles for developing a
197 sustainable seaweed industry include lack of trained personnel, market development and supply
198 chains, seed banks and social license (Buschmann et al. 2017, Wade et al. 2020). In this regard,
199 any effort devoted to creating a demand for seed supply for native species, developing
200 technology for more efficient seaweed cultivation, or other actions that drive job growth and
201 training in this sector, will augment the transition to a more green, circular and carbon neutral
202 economy. At the same time, the increased scale of production will generate research and
203 development into seaweed culturing that expands the technical capacity required to grow the
204 restoration sector and upscale current techniques.

205 The need for a broad suite of solutions is well established for restoring forests. Natural
206 forest regrowth (passive restoration after removal of degraded factors) that relies on spontaneous
207 increase in trees without direct reintroduction, can work well for some sites with nearby donor
208 seed sources and limited past damage. However, actively planting trees is often a more effective
209 approach for heavily damaged urban land (Chazdon et al. 2020). These lessons from forests also
210 apply to seaweed forest restoration, with seeding seaweeds being analogous to planting tree
211 seedlings/saplings. Afforestation using artificial reefs seeded with seaweeds (although they
212 function differently than natural reefs) could work well in areas with a limited supply of
213 propagules, on heavily modified urban coasts with infill, artificial structures and no natural reefs
214 or on wind turbines or other infrastructure being added to the coastal zone (e.g., green/gray
215 infrastructure; Kuwae and Crooks 2021). In areas where stressors like pollution are reduced, but

216 the degraded system persists, active restoration can help overcome negative ecological feedbacks
217 that prevent natural recruitment (Vergés et al. 2020). Importantly, without such interventions the
218 potential gain in ecosystem function from management actions to reduce stressors such as
219 pollution, fishing, or eutrophication could be greatly delayed or lost. Restoring small patches of
220 habitats in more natural systems could also speed up natural regrowth of the entire area
221 (Campbell et al. 2014). Increased seaweed may also further improve water quality by taking up
222 excess nutrients and organic pollutants (Neveux et al. 2018, Bews et al. 2021). In this way the
223 ecological footprint of a restored area is much larger than its area of seafloor because it is
224 donating propagules, providing spillover of associated species, and changing environmental
225 conditions on the surrounding reefs through CO₂ and nutrient uptake and improved water clarity.

226 There are challenges to overcome before large-scale cross-sectoral marine forest
227 restoration can be realized. Solutions need to align with the priorities of the seaweed industry and
228 ecosystem management/conservation sectors. These could differ, with the seaweed industry and
229 biotech focusing on enhancing productivity, marketable species and carbon capture, whereas
230 restoration could focus on biodiversity, long-lived species and other functions. There is also a
231 challenge of regulations, policies and legislation, which are not in place to support large-scale
232 seaweed restoration, but are an essential step for a shift towards large-scale restoration actions
233 (France 2016). This likely represents a massively overlooked hurdle that both the restoration
234 sector and the seaweed farming industry face. Yet, collaborations among local governments,
235 stakeholders, scientists and industry partners could prepare the groundwork for this. Mitigation
236 or removal of stressors driving decline in seaweeds is essential for restoration success (Layton et
237 al. 2020), and must be addressed before, or in parallel with seeding efforts. Yet, ongoing changes
238 in environmental conditions driven by climate change and human population growth are
239 challenging to alleviate (Hobbs 2013). Along with necessary approaches to reduce stressors,
240 broadcast seeding of seaweed forests provides pathways to propagate climate-tolerant genotypes
241 that can ‘future proof’ these habitats (Coleman and Gould 2019, Coleman et al. 2020). There is
242 great potential to target resilient donor plants, increase their quantity with commercial
243 cultivation, and then propagate strong genotypes on seeded substrates spread onto degraded reefs
244 to increase resilience of seaweed forests to climate change and other threats (Alsuwaiyan et al.
245 2021, Wood et al. 2021). As such, a cross-sectoral approach that leverages the knowledge of
246 restoration scientists, the socio-economic motivation of local stake-holders and the financial

247 incentives of the commercial seaweed and restoration industries could provide a restoration
248 solution that can succeed in the face of increasing degradation and altered ocean conditions.

249 To better illustrate the geographic scale of the challenge, marine forests of large brown
250 seaweeds (kelp forests) cover an area roughly the size of Mexico (150 million hectares), with a
251 total standing stock of 3 PgC (Duarte et al. 2021). Over the past few decades, marine forests have
252 declined globally (Filbee-Dexter and Wernberg 2018, Wernberg et al. 2019, Smale 2020). While
253 there are many unmonitored forests with unclear status, the most recent estimate of 1.8%
254 instantaneous loss each year (Krumhansl et al. 2016) implies that 3 million hectares of marine
255 forests need to be restored in 2021 just to keep pace with current declines. At a typical project
256 scale of 100 m² over 2 y (Eger et al. 2020b) this would require 300 million new seaweed
257 restoration projects. Even using metrics from the largest ever documented successful seaweed
258 forest restoration project (Japan 870 ha, 8 y, US \$5.2 million; Eger et al. 2020), this would
259 require 3450 projects of this scale to be initiated, costing a total of US \$18 billion. While this is
260 obviously a crude calculation, and only a fraction of these regions are suitable for active
261 restoration action, it does highlight the incredible magnitude of disparity between current efforts
262 and the scale of loss.

263 As the UN Decade of Restoration catalyzes efforts to upscale restoration, initiatives must
264 remain aware of local needs and context. Ecosystem restoration is, by nature, an on the ground
265 local response to a global challenge. While there is a rush to go to scale, we still also need time
266 to trial techniques, adapt approaches to local contexts and learn from smaller efforts. The
267 ‘Greening the Blue Front Yard’ approach represents a strong value proposition and model for
268 community-based engagement in marine restoration: in the same way as communities and
269 municipalities maintain and restore nature areas on land (parks, green spaces; The Green
270 Backyard), a healthy and well-maintained ‘blue front yard’ provides substantial benefits to local
271 communities and can be financed by policy-driven incentives and offset schemes. For example,
272 the Wetlands Reserve Program in the USA (EPA 2005) and the Water Framework Directive in
273 the EU (Directive 2000/60) provide financial incentives or legislation to restore, or improve,
274 wildlife habitats. Similar programs could be used to maintain key services (coastal protection by
275 wave dampening, nutrient filtering, nursery habitats) by marine forests, but this hinges on
276 recognition of the value of the services these habitats provide (Eger et al. 2021). The commercial
277 seaweed sector can propel the transition away from academic-driven activities by supplying

278 propagule cultures or seeded substrates directly to restoration practitioners, community groups,
279 NGOs or local governments, removing technological barriers and increasing accessibility of
280 restoration. This path for future actions to enhance marine forest resilience and recovery can be
281 used as part of a broader management strategy to combat global decline in marine forest health
282 and to help ensure these ecosystems continue to support income, livelihoods and overall well-
283 being of the local and global citizens that benefit from their goods and services.

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294 295 296 *Competing interests*

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

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489 Table 1. Scale of loss of marine forests and scale of restoration success to date for select
490 countries and regions with available data. Restoring includes all active efforts to increase natural
491 seaweed habitats, including reducing stressors, transplants, or herbivore removals. Natural
492 recovery is not included (e.g., disease outbreaks of herbivores) nor is addition of artificial reefs
493 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. Thomsen 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 (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. 2020b)
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>	3400	excavation for coastal development	1800s	2.74	0.08	(Dahl and et al 2013). 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. 2020b)
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</i>	382,153 ^f	overgrazing, urbanization	unkno wn	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)

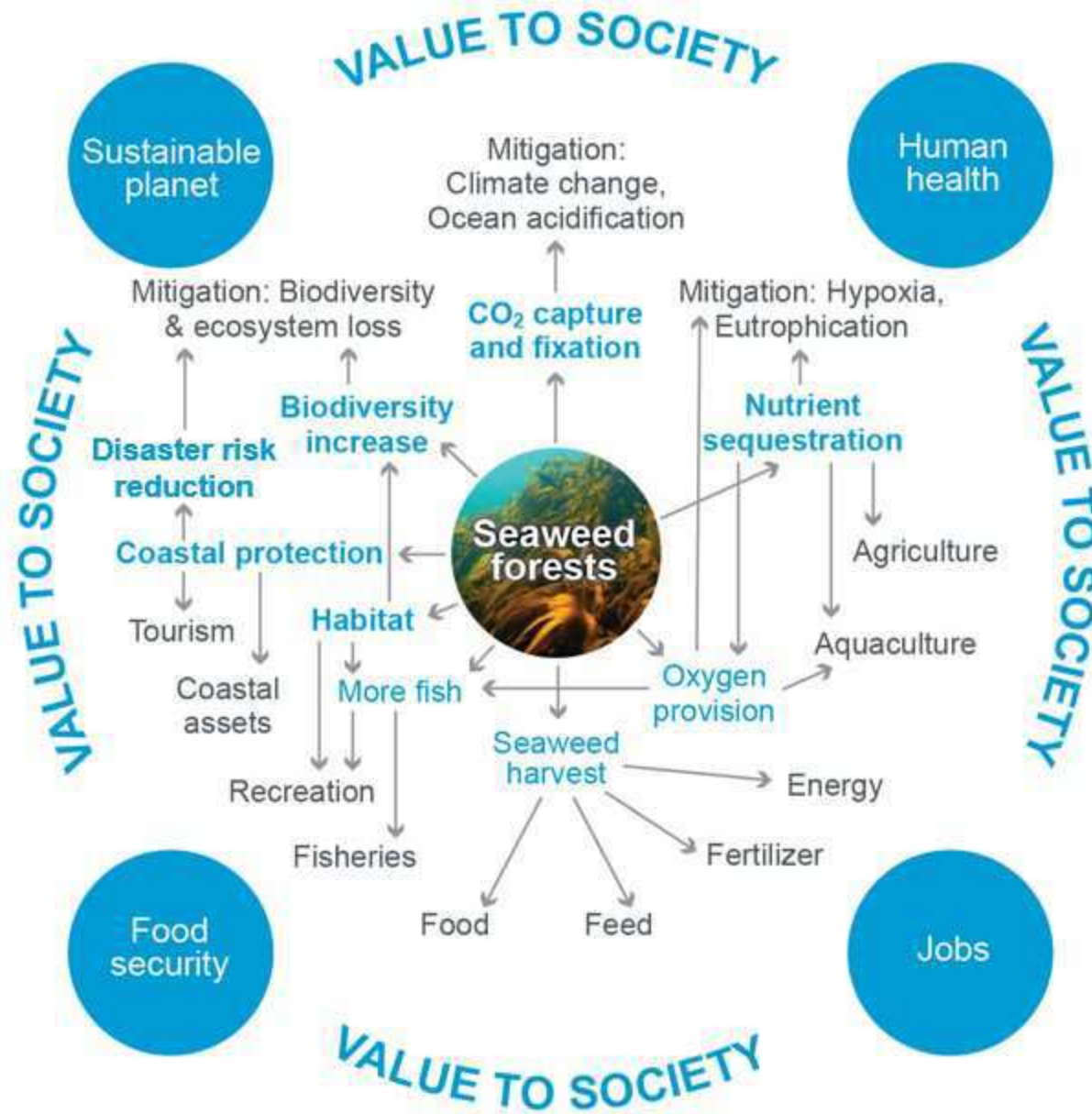
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495 ^aincludes both seaweed and seagrass forests. ^bValue corresponds to one of several rias in NW
496 Spain. ^cRestored area is mainly addition of artificial reefs and does not directly correspond to the
497 area of natural reef lost. ^dCoarse estimate of km of coastline loss based on seaweed forest margin
498 of 0.1 – 0.2 km from shore multiplied by the km of degraded rocky coastline (~ 100 - 150 km).
499 ^eCoarse estimate of area based on the average kelp forest margin of 0.23 km from shore (Filbee-
500 Dexter and Scheibling 2017) multiplied by the km of coastline loss. ^fEstimated from portion of
501 transects in barrens state along 600 km of coast between 5 and 15 m depth.
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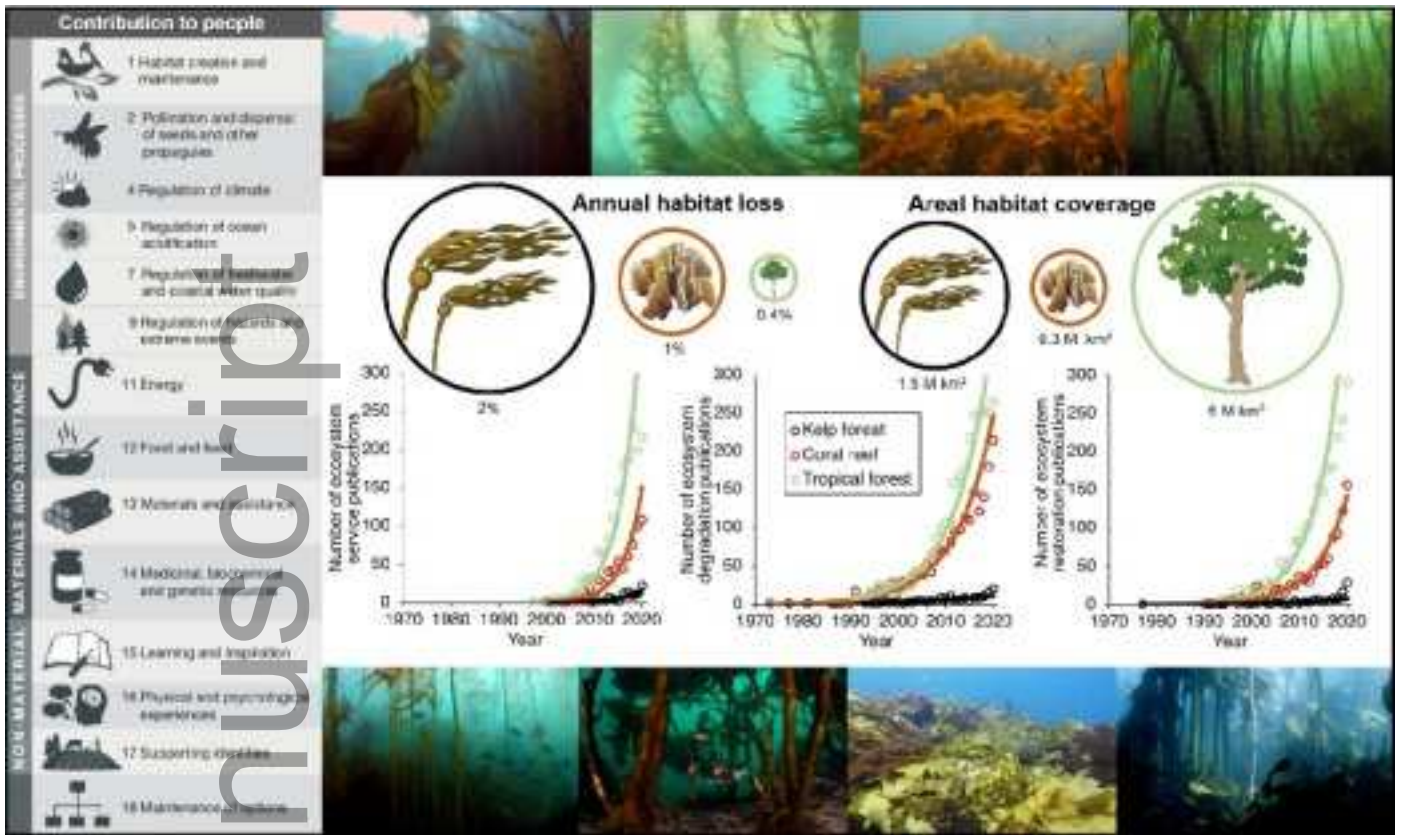
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Figure 1. Value proposition for marine forest restoration. Including some of the key direct ecosystem services and function provided by marine forests.

Figure 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 have 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 Díaz et al. (2019).

Figure 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.





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Restoration practitioners

Commercial seaweed industry

Local stakeholders

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