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Review

Bright Spots in Coastal Marine Ecosystem Restoration

Megan I. Saunders[1,2,3,*], Christopher Doropoulos[1], Elisa Bayraktarov[1,2,4], Russell C. Babcock[1], Daniel Gorman[5], Aaron M. Eger[6], Maria L. Vozzo[7,8], Chris L. Gillies[9,10], Mathew A. Vanderklift[5], Andy D.L. Steven[1], Rodrigo H. Bustamante[1], and Brian R. Silliman[11]
[1]CSIRO Oceans and Atmosphere, Queensland Biosciences Precinct, St Lucia, QLD, Australia
[2]Centre for Biodiversity and Conservation Science, School for Biological Sciences, The University of Queensland, St Lucia, QLD, Australia
[3]Centre for Marine Socioecology, Institute for Marine and Antarctic Studies, Hobart, TAS, Australia
[4]eResearch Services, Griffith University, Gold Coast, QLD, Australia
[5]CSIRO Oceans and Atmosphere, Indian Ocean Marine Research Centre, Crawley, WA, Australia
[6]Centre for Marine Science and Innovation, School of Biological, Earth, and Environmental Sciences, University of New South Wales, Kensington, NSW, Australia
[7]Sydney Institute of Marine Science, Mosman, NSW, Australia
[8]Department of Biological Sciences, Macquarie University, Macquarie Park, NSW, Australia
[9]The Nature Conservancy Australia, Carlton, VIC, Australia
[10]TropWATER, The Centre for Tropical Water and Aquatic Ecosystem Research, James Cook University, Townsville, QLD, Australia
[11]Nicholas School of the Environment, Duke University, 135 Duke Marine Lab Road, Beaufort, NC, USA
*Correspondence: megan.saunders@csiro.au
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SUMMARY

The United Nations General Assembly calls for ecosystem restoration to be a primary intervention strategy used to counter the continued loss of natural habitats worldwide, while supporting human health and wellbeing globally. Restoration of coastal marine ecosystems is perceived by many to be expensive and prone to failure, in part explaining its low rates of implementation compared with terrestrial ecosystems. Yet, marine ecosystem restoration is a relatively new field, and we argue that assessments of its potential to answer this call should not rely on typical outcomes, but also to learn from successful outliers. Here, we review successful restoration efforts across a suite of metrics in coastal marine systems to highlight 'bright spots'. We find that, similar to terrestrial systems, restoration interventions can be effective over large spatial expanses (1,000s–100,000s ha), persist for decades, rapidly expand in size, be cost-effective, and generate social and economic benefits. These bright spots clearly demonstrate restoration of coastal marine systems can be used as a nature-based solution to improve biodiversity and support human health and wellbeing. Examining coastal marine restoration through a historical lens shows that it has developed over a shorter period than restoration in terrestrial systems, partially explaining lower efficiencies. Given these bright spots and the relative immaturity of coastal marine ecosystem restoration, it is likely to advance rapidly over the coming decades and become a common intervention strategy that can reverse marine degradation, contribute to local economies, and improve human wellbeing at a scale relevant to addressing global threats.

Introduction

The global environmental crisis, including biodiversity loss, habitat degradation, and climate threats, harms human health and wellbeing [1–3]. In 2020, for the first time ever, the World Economic Forum ranked climate change and several related environmental issues as the top five risks to global economic stability in terms of likelihood [4]. Solutions are urgently needed and will require leadership, trans-disciplinary approaches, international frameworks and national roadmaps, political and financial commitments, and strong governance (e.g., [5]). At present, society is flooded with messages regarding the degradation of, and challenge of repairing, Earth's natural capital [6]. To balance this message, experts have recently called for 'Earth optimism' – an approach that gives evidence-based focus to and evaluation of successes in existing practices [7–10]. This focus on successful solutions, even if represented by outliers, can inspire creative and transformative ideas that advance existing interventions or identify novel ones [7,9,10].

Over recent decades to centuries, continued declines of coastal ecosystems have occurred globally such that the global coverage of saltmarshes, mangroves, seagrasses, oyster reefs, kelp beds and coral reefs has been reduced by 35–85% [11–17]. At least 775 million people globally have high dependence on coastal marine ecosystems [18]. These systems provide services such as sequestering carbon at twice the rate of terrestrial forests [19], supporting habitats for half of assessed commercial fish stocks [20], underpinning food supplies for 500 million people [18], reducing concentrations of human-derived pathogens [21], supporting eco-tourism that can fuel local economies and small countries [22], and reducing wave energy on shorelines by up to 95% [23]. As such, intact coastal ecosystems improve human health, physically as well as psychologically [1,24]. We urgently need evidence-based discourse that will inspire innovative conservation solutions (e.g., [25–27]) and ultimately reverse coastal ecological degradation. Re-establishing coastal marine ecosystems at large scales will play a key role in supporting human health and wellbeing [24,28], achieving the UN Sustainable Development Goals [29], and adapting to and mitigating global climate change [30].

'Nature-based solutions' are the sustainable management and use of nature for tackling societal challenges [31]. They are being given serious consideration at high levels, as evidenced by recent discussions at the Conference of the Parties (COP) in Madrid, Spain in December 2019. One of the key approaches to nature-based solutions is ecological restoration, defined as "the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed" [32]. The United Nations declared that 2021–2030 will be the 'UN Decade on Ecosystem Restoration'. In this Review, we focus on active ecological restoration, which involves restoration of hydrological or substrate conditions and/or reintroduction of desirable biota [33]. In marine environments, despite relatively low implementation to date, ecological restoration is proposed as a key strategy to rebuild the oceans [34]. However, substantial challenges remain to bridge the gap between goals, such as restoration of at least 15 percent of degraded ecosystems by 2020 (Convention on Biological Diversity Aichi Target 15, under revision for 2030) and current levels of implementation.

Relatively low implementation of restoration in marine compared with terrestrial or freshwater environments [35] is likely related to the greater challenge of working in the marine environment, but is also likely influenced by low confidence in outcomes [36]. Examination of median values reported primarily in peer-reviewed literature suggest that marine coastal restoration projects are typically small scale (<1 ha), short duration (1–2 years), expensive (>US $100,000s ha^{-1}), and have low item-based survival [37–39]. These summary statistics may highlight an important reason why investment in restoring marine systems has trailed behind similar efforts in other systems [35] — why invest in something that is likely to fail, or may have more uncertain outcomes compared with more established management approaches? Despite these limitations, new approaches are needed to rebuild the oceans, and a narrative that focuses on optimistic elements of practice can contribute towards these new approaches being realised [34]. Across a range of systems, identifying social-ecological 'bright spots' can help define values, features, and processes which have and thus will likely again underpin positive change [9,40,41].

Here, we first review the relative histories of restoration in six coastal marine ecosystems in comparison to terrestrial forests, which is the most developed field of restoration. A historical lens allows us to gain perspective on relative progression of research and practice. Identifying and learning from successful innovation is essential for accelerating adoption of methods and can often generate further advances.

Next, we identify 'bright spots' of active restoration efforts in six coastal marine ecosystems (Figure 1) as assessed across a suite of metrics. We base this analysis on publicly available sources, including peer-reviewed papers, grey literature, and in some instances guided by a published database of restoration cost and feasibility (see Supplemental Methods). These sources represent a fraction of restoration projects and are biased towards projects communicated by the scientific community [42]; however, a comprehensive global database of coastal marine restoration projects is not currently available [34]. For each ecosystem, we highlight a restoration project that: firstly, was conducted over a large spatial extent relative to other projects for that ecosystem; secondly, demonstrated ecological persistence as assessed using long-term monitoring, retrospective analysis, or remote sensing data; thirdly, expanded rapidly in space based on empirical data or remote sensing imagery; fourthly, was achieved for relatively low cost compared with other projects for that ecosystem; or finally, generated social and/or economic benefits. Based on 5 metrics for 6 ecosystems, this search yielded 30 bright spots — a few exemplary studies are highlighted in more than one bright spot.

While empirical assessment of project 'success' against stated objectives was outside of the scope of this study, all studies indicated evidence of partial or complete ecological recovery or generation of socio-economic benefits in the reported monitoring timeframe. Inconsistencies in how projects are designed, monitored and reported preclude a fully factorial assessment of each parameter for each project; however, we extracted the data for each metric from each project where available (Table S1). To identify the causes of project success, we extracted this information as reported (Table S1), and then provide a synthesis of this information. Lastly, we evaluated whether these bright spots can act as predictive windows into the potential for coastal marine restoration as a nature-based solution to reverse biodiversity loss and improve human wellbeing at a scale that can help reverse ecosystem degradation.

Interpreting Marine Restoration Success through a Historical Lens

When assessing success of a field it is important to understand its history [43]. If we are early in the development of a particular field, we know that advances are still likely to be made as they have for other fields with longer histories. Here, we use a systematic literature search (Supplemental Methods, Table S4) and provide additional context to parameterise: the relative histories of restoration in marine ecosystems compared with forests; and the rate of increase in scientific research on restoration for each marine system.

Interest in the Relatively Young Field of Marine Restoration Is Increasing Rapidly

For terrestrial forests compared with marine ecosystems, there were earlier first and 100th publications in the systematic literature review (Figure 2A). For forests, there was also earlier evidence of restoration for 'modern ecological' purposes, which is loosely defined as the recovery of an ecosystem for ecological rather than for resource provision purposes (e.g., [32,44]) (Figure 2A). However, the earliest citations in the earliest 20 records in the systematic literature search tell a slightly different story (Figure 2A), with earlier records related to oyster restoration (1881) for oyster fisheries recovery, than for terrestrial forests for timber provision (1902). This discrepancy may be due to limitations of the literature search, or perhaps because reforestation was very well established and therefore scarcely reported in early scientific literature. For instance, afforestation is evident from ancient Egypt and Greece [45,46]. Interestingly, people have undertaken restoration-like actions in marine systems for

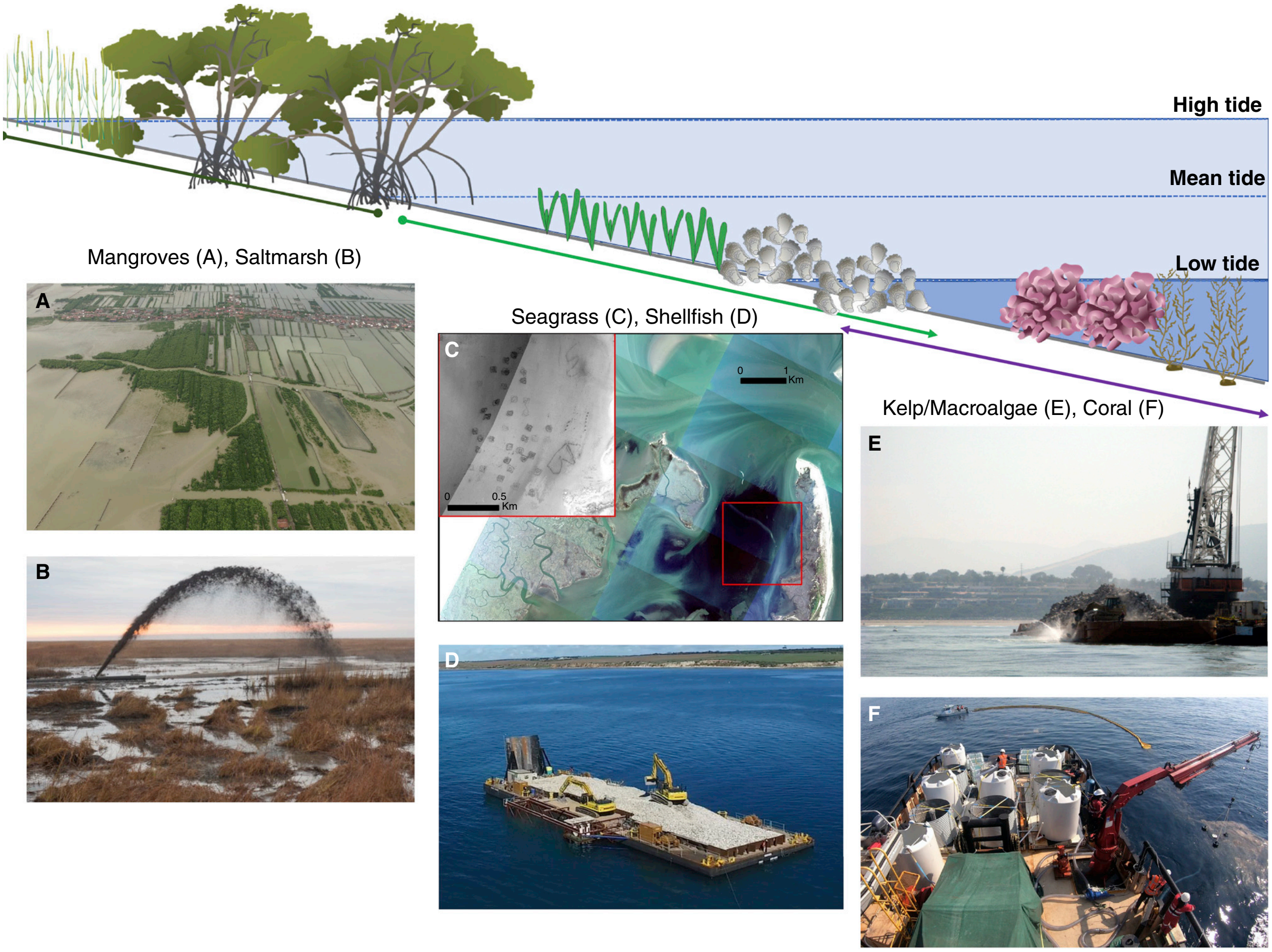

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Figure 1. Large scale marine restoration projects in the coastal seascape.

(A) Mangroves in Java, Indonesia (image courtesy of Wetlands International and the Building with Nature Indonesia project www.indonesia.buildingwithnature.nl). (B) Saltmarsh in NW USA (image courtesy of David Harp). (C) Aerial photos of seagrass (dark patches) in 2004 (inset) and 2018 in Virginia, USA (image courtesy of Robert J. Orth, VIMS SAV Monitoring Program). (D) Oyster reef construction in Gulf St Vincent, Australia (image courtesy of The Nature Conservancy). (E) Kelp restoration in California (image courtesy of UCSB SONGS Mitigation Monitoring Program). (F) Coral larvae restoration trials on the Great Barrier Reef (image courtesy of Remment ter Hofstede). Cartoon images from Ian Image Gallery made by Tracey Saxby, Diana Klein, Jane Thomas and Joanna Woerner.

millennia, including hydrological modification, transplanting, and weeding. For instance, cultivation of marine gardens by coastal First Nations in British Columbia, Canada at least 3000 years ago [47,48], and installation of saltmarshes in the Netherlands for coastal reclamation as early as the 13th century [49]. Interest in coastal marine restoration is increasing through time as assessed by the proportional number of scientific papers published each year relative to the field of conservation (Figure 2B; Table S3). In sum, there is a clear trend of increasing interest in marine restation, and on average that interest came after elevated interested in terrestrial systems.

Bright Spots in Marine Coastal Restoration

Large-Scale Habitat Restoration Has Occurred for Most Coastal Marine Habitats

The spatial extent of exceptionally large-scale restoration projects for the six ecosystems based on publicly available sources varied from 2 ha for coral reefs [50] to 195,000 ha for mangroves (Table 1A) [51,52]. Projects >1000 ha have been achieved for mangroves, saltmarshes and seagrasses. Of the ecosystems assessed, kelp and coral reefs have been restored over the smallest spatial extents (71 and 2 ha, respectively [50,53]). The largest restoration and afforestation projects have occurred in mangroves. For instance, extensive planting in locations where mangroves existed previously (‘restoration’) as well as newly accreted mudflats (‘afforestation’) was achieved in the Bangladesh Sundarbans through coordinated efforts in 1966–1990 [52], and ongoing to present day [51] led by the Ministry of Environment and Forests with international investment and community support [52].

Restored Coastal Marine Ecosystems Can Persist for Decades and Expand Ten-fold in Size

There is empirical evidence of ecological persistence over decades for all six coastal marine ecosystems following restoration

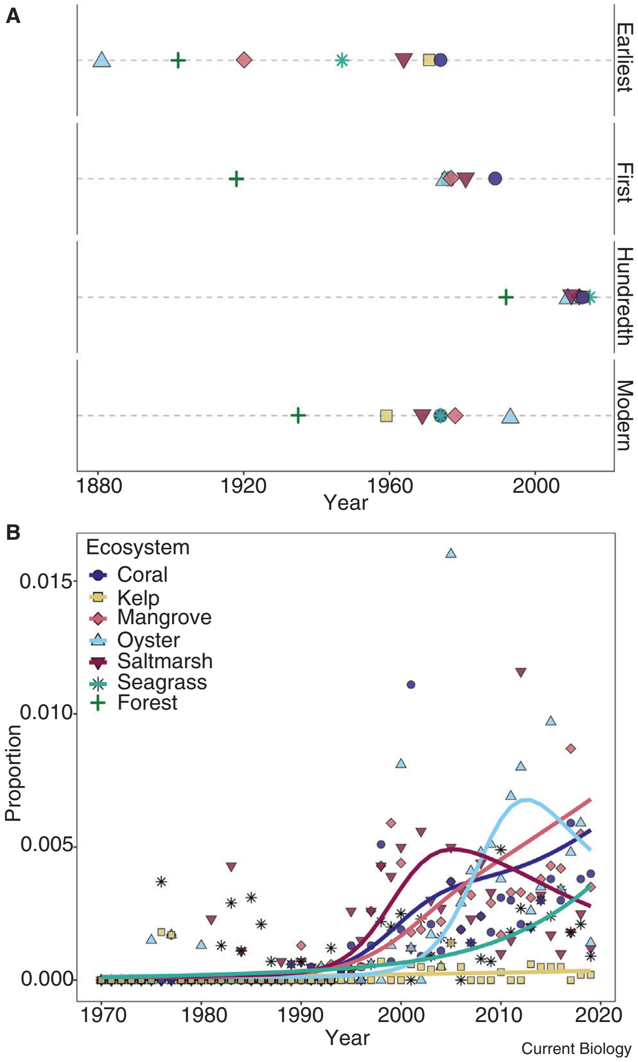

Figure 2. Timeline of restoration in six marine ecosystems based on a systematic literature search.

(A) Relative history for each marine ecosystem in comparison to terrestrial forests as assessed by four metrics. 'Earliest' = Year of earliest reference cited in earliest 20 papers of a systematic literature search; 'First' = Year of earliest publication in systematic literature search; 'Hundredth' = Year of 100th publication in systematic literature search. 'Modern' = Year that restoration for the purpose of modern ecological restoration was initiated (e.g., to restore an ecosystem, rather than just to restore provision of a particular ecosystem service). (B) The number of publications in each year for each coastal marine ecosystem is standardised to the number of publications in the field of marine conservation in that year, with lines indicating Generalised Additive Model fits (Table S3; Forests not included in panel B).

(Table 1B). On an Indonesian coral reef, colonisation and persistent growth of corals was reported for at least 14 years after restoration, which consisted of adding stable substrata to reefs impacted by blast-fishing [54]. Site examinations of seagrass meadows in Florida, USA, which were restored up to 32 years previously, demonstrated that most restored meadows still persisted and many had similar coverage and species composition compared with reference meadows [55]. In addition to long-term ecological persistence, there can be long-term social and economic benefits from restoration programs. For instance, one of the world's longest running mangrove restoration and afforestation programs, in Bangladesh, generated an estimated 5 x 10^6 days of employment for local villagers over a 25-year period [52].

Looking forward, continued persistence of restored marine habitats subject to climate change is a pressing issue that will require careful consideration, planning and innovation [27]. Now, and even more so in the future, setting achievable targets for marine recovery will require explicit consideration of ecological change over time, variability in space, and differences in perceptions regarding degraded vs intact habitats [56].

For all six ecosystems, once patches have been restored, they can expand laterally (Table 1C; Table S2). For instance, in Virginia, USA, propagation and dispersal of seagrass seeds over 125 ha facilitated patch expansion to 1700 ha [57]. This resulted in measurable co-benefits, removing an estimated 170 tons of nitrogen and sequestering 630 tons of carbon per year [58]. Oyster reefs can expand laterally and vertically after initial deployment of reef substrates and oysters [59]. For many systems, success of plantings increases with the number of planting units [60] or size of patches [61]. However, patch expansion rates (% yr^{-1}) typically decline with patch size (for seagrass, see Figure S1). Therefore, planting design schemes should explicitly assess the trade-offs in these factors. For saltmarsh, small modifications to planting design (clumped vs. dispersed plantings) can double survivorship and biomass [62]. For oysters, the vertical relief of patches is a critical factor influencing restoration success, with patches >30 cm in height supporting greater oyster density, survival and complexity than those <30 cm [63]. In sum, careful attention to the number, size, and spacing of planting units [60,62,64] can maximize the regenerative capacity of ecosystems.

Costs of Coastal Marine Restoration Vary Widely, Are Rarely Assessed, but Can Represent the Best-Value Choice

Synthesis of primarily peer-reviewed data suggests that median costs for coastal marine restoration projects are in the hundreds of thousands of dollars per ha [37]. However, examination of outliers indicates that there are examples of projects <\$70,000 ha^{-1} (in 2010 US dollars) for all ecosystems [39,65]. These values ranged from ∼\$300 ha^{-1} (saltmarsh, mangroves), ∼\$10,000 ha^{-1} for seagrass and kelp, to ∼\$60,000 ha^{-1} for oysters and coral reefs (Table 1D). For most of the ecosystems, these estimates are for projects that were demonstrated to be ecologically successful (e.g. for corals [66], cited in [54]); for kelp, the costs are published estimates based on aquaculture, although the process is similar. The low-cost examples are particularly inexpensive for intertidal ecosystems (mangroves and saltmarsh). However, low-cost mangrove restoration is frequently criticised for high failure rates [67]. For a little more (∼\$1,200 ha^{-1}), a community-based mangrove ecological rehabilitation project in Indonesia included community participation, education and training, and reported substantially increased plant density within three years of restoration [67].

The costs of coastal marine restoration are challenging to parameterize [37,38,68], in part due to the disparate techniques used, a wide range of socio-economic and environmental contexts under which restoration occurs, and inconsistencies in reporting [68]. Further, operational coastal marine restoration is often conducted by organisations that are not strongly

Table 1. Restoration projects for six coastal ecosystems.

Metric of success		Ecosystem					
		Saltmarsh	Mangroves	Seagrass	Oyster reefs	Coral reefs	Kelp
(A) Large scale	**Value (ha)**	4550	195,000	125, expanded to 1,700	140	2	71
	Location	Delaware, USA	Sundarbans, Bangladesh	Virginia, USA	Maryland, USA	Sulawesi, Indonesia	California, USA
	Reference	[115,116]	[51,52]	[57]	[95,96]	[50]	[53]
(B) Long duration	**Value (yrs)**	13	20	32	12	14	19
	Location	British Colombia, Canada	Sri Lanka	Florida, USA	North Carolina, USA	Komodo, Indonesia	California, USA
	Reference	[87]	[102]	[55]	[90]	[54]	[53]
(C) Patch expansion	**Value (% yr^{-1})**	60	19	115	120	48	902
	Location	Baarland, The Netherlands & Florida, USA	Shenzhen, China	Virginia, USA	North Carolina, USA	Sulawesi, Indonesia	California, USA
	Reference	[62]	[117]	[57]	[59]	[50]	[89]
(D) Low cost	**US$/ha @2010**	332	365	6,653	50,584	66,665	13,442
	Location	Florida, USA	Philippines	South Australia, Australia	New Jersey and Delaware, USA	Komodo, Indonesia	Washington, USA
	Reference	[65] based on [91]	[65] based on [118]	[65] based on [88]	[65] based on [100]	[66] cited in [54]	Supplementary, based on [119]

(A) Large scale, (B) persistent in time ('Long duration'), (C) patches expanding in time, or (D) low cost compared with other projects. When multiple references are given in a cell, they refer to the same project. For seagrass and coral, (A) and (C) are obtained from the same study; for kelp (A) and (B) are from the same study. Patch expansion rates should not be compared across ecosystems, as they are influenced by patch size. Cost data are converted from reported values to USD base year 2010 ha^{-1}.

incentivised to publish in peer-reviewed literature, such as consultancies, NGOs or governmental organisations, due to time constraints or commercial in confidence issues, and data are therefore often not publicly available. Future research to parameterise costs of restoration and the factors influencing those costs is warranted.

While it is generally preferable to protect intact habitats rather than to restore degraded habitats [32], there are clear instances where, to meet set objectives, restoration is the most appropriate and cost-effective action. Cost-effectiveness is distinct from low-cost in that it factors in the costs, as well as the outcomes of a set of actions, assessed against a particular objective, with a fixed timeline and budget [69]. As such, conservation actions with a relatively high cost per unit area, such as active marine restoration, can be more cost-effective than other lower cost interventions [70,71]. Economic analysis of the costs and benefits of oyster restoration in North Carolina, USA, produced expected benefits ranging from $2 to $12 for every dollar invested in terms of enhanced recreational fishing, improved water quality, and commercial fishing [72].

Social and Economic Benefits of Coastal Marine Restoration Are Likely Common, but Rarely Measured

The UN Decade of Ecosystem Restoration describes restoration as a major nature-based solution that meets a wide range of national priorities and global development goals [73]. This holds true in marine environments, where restoration can provide wider social and economic benefits to society, although these benefits are not as widely reported as the ecological outcomes of restoration [38,74,75]. If we are mostly measuring outcomes related to nature, but not benefits to people, we cannot assess full progress of restoration against broader socio-ecological objectives. Success of conservation projects more broadly is commonly linked to strong community support and engagement (e.g., [41]). Therefore, setting social and economic objectives, and reporting outcomes of those objectives, are essential to increase the success of coastal marine restoration [76]. Here, we evaluate whether there are examples of social and economic benefits provided by each of the ecosystems (Table 2).

There is strong evidence of socio-economic benefits provided by restoration for saltmarsh [77], mangroves [78], coral reefs [79], and oysters [80]; indications of benefits provided by restoration of kelp [81]; and early suggestions of benefits provided by restoration of seagrass (Table 2) [82,83]. Through our examination of the literature, it is apparent that in many cases, the benefits of restoration appear to be inferred rather than explicit. For example, intact coastal ecosystems are known to provide valuable ecosystem services; therefore, it is inferred that restoration will bring back those services. More explicit support for the benefits of restoration is provided when a study quantifies the benefits that are accrued following restoration (e.g., [80]).

Economic benefits of restoration are evident from our examples for oysters, coral and kelp. Installation of a 22 ha oyster reef in Texas created employment for a dozen people and contributed US $691,000 yr^{-1} to GDP through enhanced habitat for recreational fishing, and US $1.273 million in related economic activity such as revenue from accommodation, fuel and boat maintenance (Table 2) [80]. This project was a component of the American Recovery and Reinvestment Act (ARRA) of

Table 2. Examples of social and/or economic outcomes of restoration in six coastal marine ecosystems.

		Ecosystem					
Metric of success		Saltmarsh	Mangroves	Seagrass	Oyster reefs	Coral reefs	Kelp
Social and economic outcomes	**Type of benefit**	Environmental education and awareness; gains in science education	Quality of life, local economy, and fisheries enhancement	Environmental awareness and engagement	Job creation, recreational fisheries enhancement	Employment, training, environmental education and awareness	Fisheries enhancement and increased livelihoods
	Details	Surveys and test scores for fourth grade students who participated in From Seeds to Shoreline®, a place-based education program centred around saltmarsh gardening, indicated an increase in assessments of student attitude and engagement in learning science, and an increase in test scores after the implementation of the From Seeds to Shoreline® program.	Mikoko Pamoja Project; the sale of carbon credits accrued through mangrove restoration and the voluntary carbon market funded hospital equipment, school books and infrastructure to provide clean water. Fisheries were enhanced from the improvement in fish habitat resulting from restoration.	Research on socio-economic benefits of seagrass restoration is nascent. However, here the authors report that engagement of community members in restoration and monitoring raised environmental awareness and created a sense of ownership over project success.	Half Moon Reef; surveys of recreational fishers and guides after restoration indicate increases in recreational fishing contributing US $691,000 yr^{-1} to GDP, and US $1.273 million in related economic activity. Reef creation generated 12 jobs.	In a survey of practitioners 6 out of 12 projects reported socio-economic benefits. These include: training and certifying local fisherman, divers, and volunteers; engaging with local hotels and tourist providers; guided tours to nurseries; education outreach; and direct employment.	The Korean Fish Stock Enhancement Program, which included kelp restoration, increased fishermen's annual income by 95% and contributed to securing livelihoods by consistently increasing income.
	Location	South Carolina, USA	Kwale County, Kenya	South Australia, Australia	Texas, USA	8 countries in Latin America	Korea
	Reference	[77]	[78,99]	[82] cited in [83]	[80]	[79]	[81]

2009, which the United States National Oceanic and Atmospheric Administration (NOAA) administered for coastal habitat restoration projects nationally. An estimated 1409 jobs were created from 50 ARRA projects administered by NOAA in the first year and half [84]. Importantly, economic benefits of restoration are evident even for projects with limited ecological success. For instance, a coral restoration project in Aceh, Indonesia, reported an increase in tourism, at least IDR 80 million (~US $5,400 in 2006) injected into the local economy, and creation of 3 jobs [85]. Despite the corals bleaching a year later, the authors explicitly reported on the pronounced economic benefits provided by the project.

There can be pronounced social benefits from restoration [75], including increased community engagement and education. Surveys of fourth grade students who participated in saltmarsh gardening as part of a place-based education project indicated that participation increased their environmental awareness and engagement [77]. For coral reefs, a survey of restoration projects in Spanish-speaking Latin America found that 6 out of 12 projects explicitly reported on socio-economic benefits, some of which included engaging with local hotels and tourist providers; providing guided tours to nurseries; education outreach to students, fisherman, locals, and tourists; and direct employment for administration and maintenance of activities [79]. Communities can also benefit from restoration through payments for ecosystem services (PES) schemes, such as carbon projects [86]. For mangroves, income resulting from PES in The Mikoko Pamoja Project in Kenya was invested into local communities to improve access to clean drinking water, healthcare and education [78]. Future research on social benefits from restoration could be assessed using metrics of social conditions such as access, beneficiaries, and quality of benefit [75], and to track how much local communities and stakeholders were involved in the project design from the outset.

Learning from the Bright Spots

Here, we outline a synthesis of biophysical, technological, and socio-economic factors contributing to restoration project success (Table S1).

Biophysical

Context-specific requirements in relation to specific environment and ecology. Successful projects consider the specific environmental and ecological context of the restoration site. For instance, long-term success of low-tech coral rehabilitation was predicated in addressing the specific conditions that caused reef degradation — rectifying absence of stable substrate — while other conditions were amenable to recovery [54].

Restoring habitats with sufficient connectivity to source populations. The large-scale examples for saltmarsh, kelp, and coral, and the low-cost example for seagrass all cited proximity and/or sufficient hydrological connectivity to intact habitats as a factor contributing to success [53,54,87,88].

Mitigating multiple stressors using layered interventions. Many of the successful projects incorporated a layered strategy to the intervention plan. For instance, for coral and kelp restoration, culling algal-farming damselfish and kelp-grazing urchins was essential [50,89]. For oyster restoration sites in North Carolina, restoration included placing the sites within marine protected areas to minimize harvesting and direct damage [90].

Adaptive management to provide additional, rapid responses when required. Being positioned to respond quickly to unforeseen events that may prevent the achievement of restoration goals was cited as a key factor in several of the large-scale and long-duration examples [50,52,53,87]. For instance, long-term monitoring of saltmarsh restoration in British Columbia, Canada, identified that quick actions to rectify ponding were required to resume the recovery trajectory [87].

Optimising regenerative capacity of systems though low-cost modifications in planting design. Relatively small adjustments to planting design that minimize negative interactions and maximize positive interactions among planting units can yield large increases in planting success for little to no extra cost [52,62].

Technological

Use of low-cost technology that is cheap and scalable. For the saltmarsh low-cost example, it was relatively inexpensive to rectify biophysical conditions in an impounded area without the need for transplanting [91]. For coral reefs, low-tech and locally appropriate solutions to providing stable substate were used, such as ‘spiders’ [50], or quarried local rock [54].

Use of propagules. The key innovation to the large-scale seagrass project was the use of seeds [57]. The use of propagules such as seeds or larvae has long been employed for restoration of some systems, such as mangroves and oysters [92]. For others, including seagrass, coral, and kelp, such technology is not yet widely used. However, there is evidence that it can be [57], and research is underway to advance these approaches (e.g., [93]). For corals in remote locations, preliminary modelling suggests that harvesting, culturing and releasing embryos from wild spawn slicks could reduce the costs per ha of restoration by orders of magnitude compared with transplanting approaches (Supplemental Methods, Table S5, Figures S2, S3, S4).

Socio-economic

Partnerships. Restoration projects are implemented by people and organisations with diverse backgrounds and agendas [5,94], including scientists, government agencies, NGOs, the private sector, and community groups. Interdisciplinary and interorganisational collaboration was a key feature in the large-scale examples for coral [50], seagrass [57], mangroves [52], and oysters [95,96], and the socio-economic bright spots for all ecosystems.

Strong local involvement and support from local community. Community support and involvement is known to be a key factor contributing to marine conservation success [36,97,98]. In the present study, 5 out of 6 socio-economic bright spots reported on community or stakeholder engagement and included relevant socio-economic aims or objectives. For instance, one of the keys to the success of the Mikoko Pamoja mangrove restoration project in Gazi Bay Kenya was the high level of participation, ownership and support from residents [99].

Legal or policy mandates. Policy and legal drivers, such as offsetting impacts of development, are behind the examples for low-cost oyster, large-scale saltmarsh and kelp, and long-duration seagrass projects [53,55,87,100]. For example, legally mandated restoration can be credited for the consistent upkeep, monitoring, and evaluation of restoration sites such as the Wheeler North Reef in California [53].

Sufficient financial investment and commitment to long-term monitoring and maintenance. Commitment of funding and time contributes to long-term monitoring and management, with substantial levels of government funding in particular associated with marine restoration success [98,101]. For the large-scale oyster example, USA congressional appropriation for funding was reported as key to project implementation [100]. When projects are low cost for a given area, but there is a lot of funding, then restoration can be scaled up over large extents (e.g., [95,96,102]).

Looking to the Past and across Systems Can Help to Guide the Future of Marine Coastal Restoration

Moving towards large-scale restoration in coastal marine ecosystems is required to achieve socially and ecologically meaningful outcomes, but there are concerns that efforts to scale-up may compromise on the ecological integrity of projects [76]. Lessons from past experience should be incorporated. For instance, in mangroves, large-scale efforts have often relied on planting early successional species which may not survive well in the long-term [103]. While we focus on active restoration, mitigating stressors (passive restoration, such as removal of key grazers or predators, or mitigating water quality issues [104]) is often required first or in addition to active restoration to yield faster or more complete ecosystem recovery. Challenges remain for restoration in all ecosystems. Ecological considerations include the ability to restore sites to comparable conditions as reference sites, or to fully recover ecosystem functions [105]. Socio-economic hurdles include complex governance structures, lack of restoration-focussed policies, and land tenure issues [36]. Recognition of these challenges is underpinning a new narrative, where restoration aims to deliver partial ecological recovery for particular ecosystem services [106], or even the development of novel ecosystems [107], rather than trying to return to historical baseline conditions (e.g., [108]).

One way of interpreting these findings is that, with a relatively recent scientific history of restoration in marine environments, in combination with the challenges inherent in working in the marine realm, it is not surprising that the relative rate of failures are still common (e.g., [37]), technological challenges remain, and, with the exception of mangroves, very large scales of restoration have not routinely been achieved or even attempted.

Looking forward, it appears that the impact of coastal marine restoration is set to increase dramatically. Private sector investors and multilateral financing institutions are scoping out investable large-scale marine restoration projects and, in particular, those focused at nature-based solutions — the birth of ‘blue infrastructure finance’ [109]. While the impact on conservation funding of a COVID-19-induced financial crisis remains to be seen, funding towards ecological restoration was a major component of the United States post Global Financial Crisis economic stimulus plan [84], suggesting that investing in nature-based solutions may be an important component of future national rebuilding plans after such crises. An engaged finance community and the commitments from the UN Ocean Summit with a focus on nature-based solutions, in combination with The UN Decade on Ecosystem Restoration, is an immediate opportunity to advance the scale of marine restoration. These efforts would be aided by further developing the economic and social arguments for restoration, such as through means typical of any normal infrastructure project or development [e.g., business cases, benefit-cost analyses, and (environmental) economic accounting].

Conclusions

> *"The next century will, I believe, be the era of restoration in ecology."*
>
> –*E.O. Wilson (1992)* [110].

We are in early stages of modern marine restoration knowledge in comparison with terrestrial reforestation and other cultivation sciences. In terrestrial ecosystems, ecological restoration is widely accepted and implemented as a necessary tool, with early efforts aimed at the provision of resources such as timber [45], and more recent efforts for ecosystem services such as management of erosion, biodiversity recovery and CO_2 sequestration [111,112]. In terrestrial settings, it is conventional wisdom that we replant after destruction to increase recovery rates. Despite evidence of a long history of modification of marine ecosystems [47,48], this is not yet the *status quo* in the marine realm.

Despite the short history of coastal marine restoration, there are bright spots to inspire future efforts. Projects covering 100s–1000s ha have occurred in over half of the marine systems we assessed, and scaling-up restoration may in fact reduce failure rates [60]. Once restored, patches of restored habitat can expand and coalesce. Even though median costs can be hundreds of thousands of dollars per ha, there are many examples for all ecosystems costing much less, and the long-term financial benefits derived from gained ecosystem services can repay the cost within a decade, demonstrating that restoration can be cost-effective [72]. Investment into restoration clearly provides social and economic benefits to communities, creating jobs for many people, and contributing to economic recovery from economic downturns. Technological advancements are occurring (e.g., [93,113]) that will help to achieve greater efficiencies and to restore larger areas, as has occurred in agricultural and silviculture systems. Coordinated efforts involving multiple stakeholders, long-term commitments to restoration, financial commitments, and/or legislative requirements are all contributing to restoration achievements.

Analysis of bright spots generated general trends in actions that helped contribute to success at large scales. Future research and approaches should focus on: firstly, how these actions vary in importance across different habitats and contexts (e.g., in and out of Marine Protected Areas); secondly, how generation of ecosystem services varies with size and age of restored habitats; thirdly, implementation of restoration projects in conjunction with mitigation of stressors such as land-based contaminants; fourthly, actively working with social scientists to integrate human motivations and behaviours into project planning and implementation; fifthly, being more inclusive in terms of technology, other fields, and diversity of stakeholders; and finally, working with stakeholders and economists to develop the business case for restoration, and to incorporate new project measures that can support future sustainable finance initiatives (e.g., payment for ecosystem services, offsets, environmental economic accounting).

This Review provides a basis to inspire constructive and successful actions for positive feedbacks in our social-ecological systems. Bold attempts at terrestrial restoration on massive scales are being attempted such as the 'Green Great Wall' [114], the Bonn Challenge to restore 150 million hectares of the world's degraded and deforested lands by 2020, and the New York Declaration on Forests to restore 350 million hectares of degraded and deforested lands by 2030. In marine environments, similar global targets exist only for mangroves (Global Mangrove Alliance target to increase the global area of mangroves by 20% by 2030) [5]. With broader uptake and implementation, it should be possible for coastal marine restoration actions to accelerate the recovery, integrity and resilience of degraded ecosystems, which will support biodiversity and improve human health and wellbeing. With continued advances, marine ecosystem restoration can be elevated to a key, rather than minor, management intervention in the marine conservation tool chest.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.cub.2020.10.056.

DECLARATION OF INTERESTS

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