



# Assessing the success of marine ecosystem restoration using meta-analysis

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R. Danovaro<sup>1,2</sup> , J. Aronson<sup>3,4</sup>, S. Bianchelli<sup>1,2</sup>, C. Boström<sup>5</sup>, W. Chen<sup>6</sup>, R. Cimino<sup>7</sup>, C. Corinaldesi<sup>8</sup>, J. Cortina-Segarra<sup>9,10</sup>, P. D'Ambrosio<sup>11</sup>, C. Gambi<sup>1</sup>, J. Garrabou<sup>12</sup>, A. Giorgetti<sup>1</sup>, A. Grehan<sup>13</sup>, A. Hannachi<sup>14</sup>, L. Mangialajo<sup>15</sup>, T. Morato<sup>16</sup>, S. Orfanidis<sup>17</sup>, N. Papadopoulou<sup>18</sup>, E. Ramirez-Llodra<sup>19</sup>, C. J. Smith<sup>18</sup>, P. Snelgrove<sup>20</sup>, J. van de Koppel<sup>21,22</sup>, J. van Tatenhove<sup>23</sup> & S. Fraschetti<sup>2,24</sup> 

Marine ecosystem restoration success stories are needed to incentivize society and private enterprises to build capacity and stimulate investments. Yet, we still must demonstrate that restoration efforts can effectively contribute to achieving the targets set by the UN Decade on Ecosystem Restoration. Here, we conduct a meta-analysis on 764 active restoration interventions across a wide range of marine habitats worldwide. We show that marine ecosystem restorations have an average success of ~64% and that they are: viable for a large variety of marine habitats, including deep-sea ecosystems; highly successful for saltmarshes, tropical coral reefs and habitat-forming species such as animal forests; successful at all spatial scales, so that restoration over large spatial scales can be done using multiple interventions at small-spatial scales that better represent the natural variability, and scalable through dedicated policies, regulations, and financing instruments. Restoration interventions were surprisingly effective even in areas where human impacts persisted, demonstrating that successful restorations can be initiated before all stressors have been removed. These results demonstrate the immediate feasibility of a global ‘blue restoration’ plan even for deep-sea ecosystems, enabled by increasing availability of new and cost-effective technologies.

Marine habitats face unprecedented threats, with no less than 66% of coastal areas already altered and degraded<sup>1</sup>. Bottom-contact fisheries that rely on indiscriminate trawling physically damage ca. 4.9 million km<sup>2</sup> (representing 1.3% of the global ocean) of the seafloor each year<sup>2,3</sup>. Other impacts such as litter and chemical pollution increasingly compromise key ecosystem processes and functions, at multiple scales, and threaten marine biodiversity<sup>4</sup>. In addition, whereas the physical impact of drilling for oil and gas extraction typically causes relatively localized ecosystem impacts<sup>5</sup>, underwater accidents such as the Deep-Water Horizon blowout in the Gulf of Mexico in 2010 demonstrate significant large-scale and long-term consequences for deep seafloor fauna<sup>6</sup>. In the next few years, anticipated exploitation through seabed mining will

expand over unprecedented spatial scales<sup>7</sup>, potentially impacting vast areas of the deep seafloor and its benthic ecosystems (e.g., deep-sea mining is targeting polymetallic-rich nodules on the Clarion-Clipperton Zone of the Pacific Ocean abyssal plains, an area extending over 4.5 M km<sup>2</sup> from Hawaii to Mexico)<sup>8,9</sup>. These examples illustrate just some of the direct impacts resulting from humanity's long exploitation of the global ocean, exacerbated by exponential increases in the extent, intensity, and diversity of human uses. This “blue acceleration” reflects a race among diverse and often competing interests for ocean food, material, and space<sup>10</sup>. In tandem, the global climate crisis adds synergistic and unpredictable degradation effects and drivers throughout the Earth-ocean system<sup>11–15</sup>.

A full list of affiliations appears at the end of the paper. ✉ e-mail: [r.danovaro@univpm.it](mailto:r.danovaro@univpm.it)

The UN Agenda 2030 has set a target of protecting 30% of the marine environment by 2030<sup>16</sup>. While crucially important for preserving pristine and highly biodiverse marine habitats, this ambitious target is probably insufficient, in itself, to reverse current declines in specific habitats and overall ecosystem functionality at seascape and bioregional scales. For this reason, the recovery of degraded marine ecosystems worldwide will require various kinds of ecological restoration interventions.

Ecosystem restoration refers to the process of halting and reversing degradation, resulting in improved ecosystem services and recovered biodiversity, refers to the process of assisting the recovery of degraded or destroyed ecosystems, helping regenerate and restoring their biodiversity and the ecosystem services they provide<sup>17</sup>.

The United Nations Decade on Ecosystem Restoration 2021–2030 calls for expanding and interconnecting active interventions and policies to promote and fund actions to aid and accelerate the recovery of impaired ecosystems of all types for the benefit of people and nature. This ambitious programme, led by the United Nations Environment Programme and the Food and Agriculture Organization of the United Nations (FAO), arose from growing awareness of the massive past and present degradation of most ecosystems on Earth, and the truly urgent need for society to reverse this spiral of degradation.

In many cases, as in terrestrial ecosystems, the reintroduction and expansion of ecosystem engineers and habitat-forming species (e.g., seagrass meadows, mangroves, kelp/macroalgal, tropical coral reefs, and temperate animal forests), forms the primary basis for marine ecological restoration; these taxa play a pivotal role in maintaining native biodiversity (offering, among other attributes, food and refugia

from predators) and sustaining ecosystem processes (increasing nutrient cycling, primary and secondary productivity).

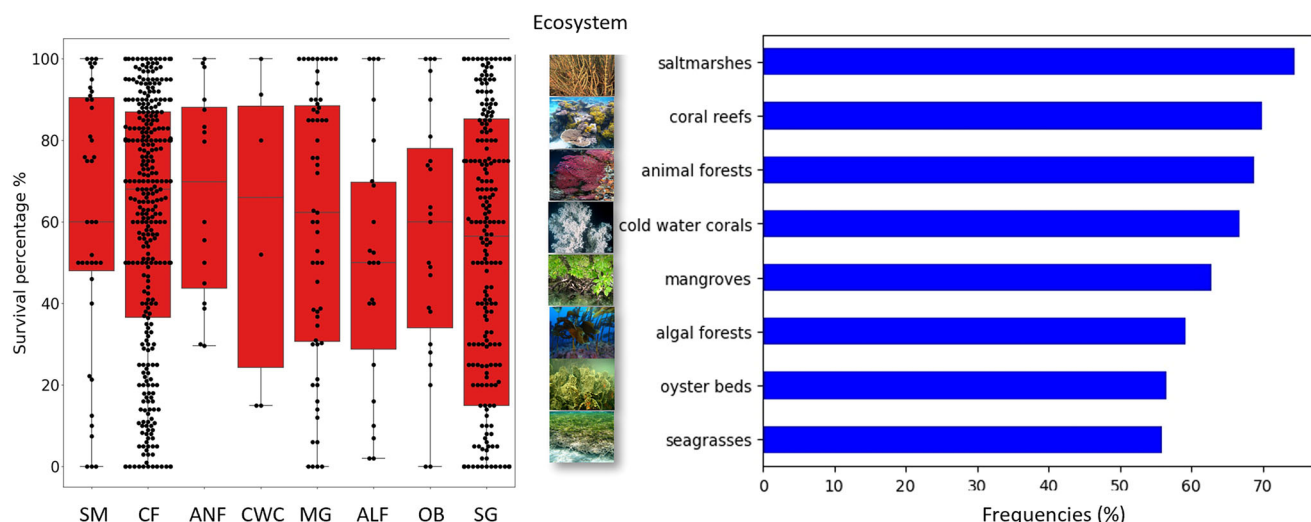
Many advocates of ecosystem restoration have documented that setting aside marine areas through management interventions can support “passive restoration”, i.e., spontaneous recovery promoted by the removal of disturbances, without the need for direct interventions<sup>18</sup>. Here, following the practice of many restoration scientists, we describe “passive restoration” in inverted commas because the term technically represents an oxymoron<sup>19</sup>. For example, fishery closure/restricted areas that strictly regulate access, accompanied by the removal of the main stressors (including all extractive activities), can promote the spontaneous recovery of degraded marine habitats<sup>20</sup>. However, scientific evidence suggests that the full recovery of degraded habitats through “passive restoration” could require considerable time periods (up to 100–200 years<sup>21</sup>), and some ecosystems may have difficulty recovering once physically destroyed<sup>22,23</sup>. This concern applies particularly to marine ecosystems that harbour habitat-forming species requiring centuries to create habitats and that have experienced physical damage<sup>24</sup>. The practical experience accumulated so far for damaged marine ecosystems indicates that an initial kickstart can significantly accelerate their recovery, along with ongoing active restoration measures (meaning direct interventions such as actively stabilising the seafloor or active propagation and planting of living organisms)<sup>25</sup> (Fig. 1).

In comparison with practitioners of terrestrial ecosystem restoration, marine ecosystem restoration scientists and managers have a much shorter and less extensive track record<sup>26</sup> and corresponding lesser experience in rehabilitation and restoration science and practice<sup>27–32</sup>. The existing uncertainties concerning returns on



**Fig. 1 | Marine ecological restoration in some soft and hard-bottom shallow-water habitats can now draw from largely established and standardised protocols.** Upper panels: a nursery for brown macroalgae to aid in restoring hard bottoms at shallow depths (left panel) and the transplant of habitat-forming species (e.g., gorgonians) for hard-bottom restoration in the Western Mediterranean Sea

(right panel). Lower panels: transplant of the endemic Mediterranean seagrass (*Posidonia oceanica*) (left); cultivation of pillow corals (e.g., *Cladocora caespitosa*) on hard bottoms (central); rearing of deep-water corals for subsequent transplanting into a defaunated deep-sea habitats (right).



**Fig. 2 | Outcomes of statistical analyses of success in ecological restoration based on survival of the reintroduced species in different marine habitats.** Illustrated are: (left panel) the box plots of the distribution of percentage of survival for the different habitat types ( $n = 759$ , i.e., all studies except 5 that were without success percentage; dots are real data, vertical line delimits the range of values, the

red box includes the 2 and 3 quartile, and the horizontal line within the box is the median; SM saltmarshes, CF coral reefs, ANF animal forests, CWC cold water corals, MG mangroves, ALF algal forests, OB oyster beds, SG seagrasses); (right panel) the frequency (expressed as percentage) of interventions with  $\geq 50\%$  survival ( $n = 759$  case studies).

investment in marine ecosystem restoration require a robust analysis of successes vs failures across regions and ecosystem types. A “successful restoration” refers to an “intervention that enables recovery of the biodiversity and ecosystem functions/services of a degraded ecosystem to values not significantly different than those in appropriate reference sites with relative intact, pre-disturbance structure, biodiversity, and functioning”<sup>17</sup>.

We therefore compared active restoration interventions at different spatial scales and in different habitats, including those most vulnerable to human impacts: tropical coral reefs, seagrasses, mangroves, oyster beds, saltmarshes, animal forests inhabiting hard bottoms at temperate latitudes (e.g., coral and gorgonian forests, coralligenous systems), macroalgal forests (including kelp and other seaweed forests) and cold-water corals from deep-sea ecosystems.

In this work, we show that the development of new approaches to marine ecosystem restoration enables expansion of efforts over larger spatial scales and even within impacted areas, as demonstrated by an increasing number of success stories showing the effective recovery of diverse habitat types.

## Results and discussion

We based our analysis of the success (and failure) of restoration interventions considering all available data sources and providing a comprehensive global literature analysis. In total, we analysed 764 marine restoration interventions. We evaluated the success of ecological restoration through: (a) a descriptive statistical comparison; (b) a formal meta-analysis and (c) mixed models conducted across the whole spectrum of “survival” data reported in the reviewed literature. We investigated the drivers of success and failure in restoration interventions and super-imposed the spatial distribution of these experimental interventions on a global map of cumulative anthropogenic impacts to understand the operability of restoration interventions in different environmental conditions. Finally, we considered the scalability of marine ecosystem restoration with a view to expanding and enhancing restoration efforts over larger spatial scales.

### Assessing the success of marine ecosystem restoration

Our analyses identify “survival” of re-introduced native habitat-forming species as the most common indicator of restoration success (all the 764 restoration interventions examined; see SOM, Fig. S1,

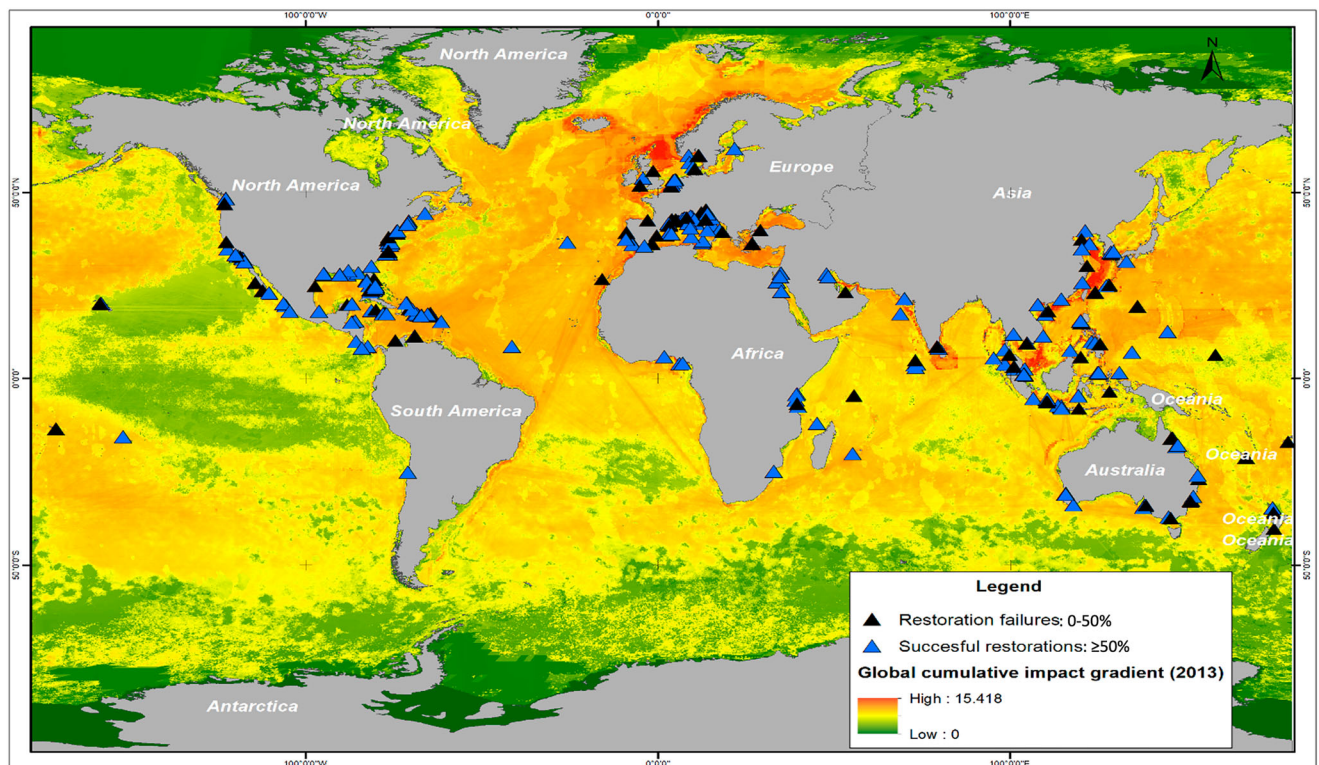
Tables S1 and S2 and Supplementary Data 1 for details on all data collected). Therefore, following on the consolidated literature<sup>33,34</sup>, we based our analysis of restoration success on assessment of survival of re-introduced habitat-forming species, which are essential for the recovery of biodiversity and ecosystem functions/services of degraded ecosystems<sup>13,15,28</sup>. The survival of the re-introduced species was unanimously indicated by all studies as the primary indicator of restoration success (100%; Fig. S1a). In addition, we censused other indicators of success reported in marine ecological restoration studies across different ecosystem types<sup>17,33</sup>, and identified the following additional major categories of indicators: (i) ecosystem functioning (biomass, production, growth; 11%), (ii) expansion (change in distribution of re-introduced habitat-forming species; 9.3%); (iii) biodiversity (2.4%), and (iv) environmental quality (0.3%; Fig. S1, SOM).

We then measured restoration success using three approaches: (1) using the full spectrum of results through descriptive statistics; (2) applying thresholds of survival for the re-introduced habitat-forming species with a descriptive statistic and (3) using a formal meta-analysis.

Using the first approach (i.e., without the use of thresholds), we calculated the median values (box plots in Fig. 2) that showed higher success for tropical coral reefs, habitat-forming species on hard bottoms (also defined here as “animal forests”) and cold-water corals of deep-sea ecosystems (range 66–70%), followed by saltmarshes, oyster beds, and mangroves (60–62%). The lowest median value was reported for algal forests and seagrasses (average survival 50–57%).

In the second approach, we used 50% as a threshold value for survival of the re-introduced habitat-forming species (a value widely accepted in the literature that enables comparison across studies<sup>34</sup>) to discriminate between successful (i.e., survival  $\geq 50\%$ ) and unsuccessful (i.e., survival  $< 50\%$ ) restoration efforts. Using this approach, we obtained an average success of ca. 64% for all restoration interventions (Fig. 2), with higher values for coral reefs, saltmarshes, cold-water corals of deep-sea ecosystems and animal forests (ranging from 67–74%), followed by oyster beds, macroalgal forest, and mangroves (57–63%). The lowest values were observed for seagrasses (average survival 56%). Assigning simple thresholds for measuring restoration success provides convenient and immediately comprehensible metrics that enable comparison with previous studies<sup>34</sup> but adds subjectivity given potential variability among different habitat-forming





**Fig. 3 | Global distribution of active marine habitat restoration sites and their overlap with cumulative impacts on marine habitats (Web Map from <https://hub.arcgis.com/datasets/esri:world-continents/explore> ArcGIS 3.2).** The Global Cumulative Impact Index calculations used available raw data<sup>2</sup> and produced scores from 0 to 15.4. The Global Cumulative Impact Index reports that

values >4.02 represent high impact, and values <2.739 represent low impact areas. Successful restoration indicates case studies with survival ≥50%. Restoration failures indicate cases with <50% survival and also include complete failures (0% survival).

species (for instance, oyster-bed restoration could be successful even with low survival percentages of seeded juveniles). Moreover, this approach may prove insufficient to assess accurately the success of restoration interventions.

For this reason, we integrated our assessment of restoration success with the third approach based on a formal meta-analysis conducted on the entire spectrum of data (i.e., without the use of an arbitrary cut-off; see Fig. S2 to visualize the output of the meta-analysis). The meta-analysis (based on Freeman-Tukey double arc-sine transformation to normalize and variance-stabilize the data; see SOM for details) enabled the definition of a ranking of habitats according to their restoration success, which reflects the results of the descriptive statistics and confirm the high potential for successful restoration interventions in all marine ecosystems investigated. In particular, the highest values were reported for saltmarshes and coral reefs, followed by animal forests and oyster beds, whilst lower values were observed for mangroves, algal forests and sea-grasses (Fig. S2; Egger's test = 0.90 indicating the lack of publication bias). The results of the multiple statistical analyses indicate the high probability of success of restoration interventions for all marine habitats investigated and suggest a clear potential for the development of marine ecological restoration<sup>35</sup>.

We also quantified the complete failures (i.e., survival = 0%) in habitat restoration by identifying case studies that showed no signs of recovery after the intervention and the loss of all the reintroduced habitat-forming species. We found that 69 out of 764 restoration interventions (on global average ca. 9%) showed complete failure (Fig. S3). Comparing different habitat types, the highest risk of failure was reported for seagrasses (17.6%), followed by saltmarshes and oyster beds (ranging from 7.7–8.7%), and by mangroves (ca. 6.8% respectively), whereas all other systems showed a very low number of

cases of complete failure (<5%) (Fig. S3; see Tables S1 and S2 and Supplementary Data 1 for the data set statistics, codebook, and details).

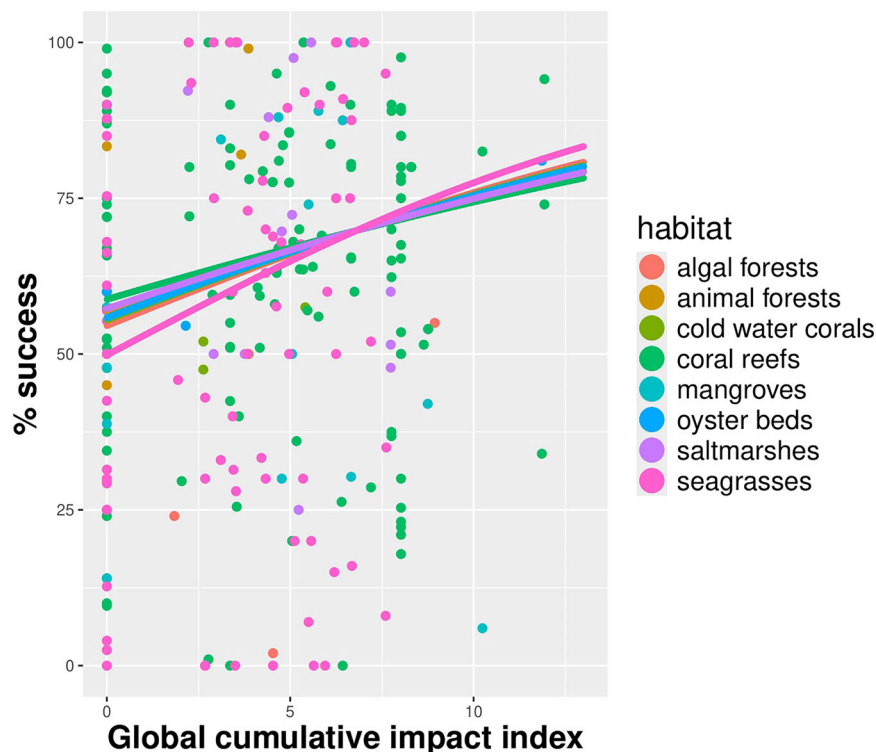
Despite the apparent tendency for restoration success to increase with the spatial scale of the intervention, our results indicate that success does not change significantly over different spatial scales, time, or across latitudes (Figs. S4 and S5A–C). This outcome suggests that in marine ecosystems, in contrast to reports for terrestrial ecosystems<sup>17</sup>, the spatial extent of restoration does not determine the success of the interventions. As a corollary of this conclusion, we can plan restoration interventions over large spatial scales<sup>26</sup> using multiple interventions at small spatial scales, that have an equally high expectancy of success and allow, at the same time, to better represent the natural variability and genetic diversity of native populations in different areas.

### Restoration success in impacted marine ecosystems

The analysis of restoration success in areas with cumulative impacts can provide useful insights to understand whether successful marine ecosystem restoration requires the selection of low-impact sites as a pre-requisite. Available data that overlap the Global Cumulative Impact Index<sup>1</sup> ( $n = 580$  out of 759 restoration interventions) indicate that ca. 32% of interventions were carried out in sites with low human impacts, in contrast to ca. 14 and 54% conducted in medium and highly impacted sites, respectively (Fig. S6).

Superimposing successful restoration interventions over the map of Global Cumulative Impacts (Fig. 3) suggests that the presence of putatively impacted areas does not preclude the success of intervention.

We also conducted a regression analysis between the global cumulative impact index and percentage of success using a mixed



**Fig. 4** | Regression analysis between the cumulative impact and the degree of success (expressed as percentage of survival of the species restored) based on a generalized linear mixed model (with aggregated data;  $n = 245$ ).

model, which showed a significant positive relationship for all marine habitats investigated (Fig. 4;  $p < 0.01$ ; excluding deep-sea habitats because of insufficient quantitative information). These results, based on different statistical approaches, suggest that restoration success can be higher in sites with medium or high levels of impact than in areas with low levels of cumulative impacts (Fig. S6).

Mapping the geographic distribution of restoration interventions for different ecosystem types (oyster beds, hard bottom habitat-forming species, macroalgal forests, cold-water corals, coral reefs, mangroves, salt marshes, and seagrasses) allowed us to gather similar results for all habitat types investigated (Fig. S7). These results expand current evidence that the proximity with pristine areas (such as marine protected areas) does not increase the success of habitat restoration<sup>29</sup>.

In terrestrial ecosystems, experts recommend focusing on low-impacted sites to increase success rate and improve cost-effectiveness of the intervention<sup>36,37</sup>. Inevitably, this strategy requires triage to identify the most suitable sites for investment in restoration, or the removal of existing stressors before starting the restoration interventions. For this reason, we investigated whether, before marine ecosystem restoration, the selected sites underwent interventions to remove or mitigate impacts, and we discovered that this occurred in less than 2% of restored sites. Therefore, only a very few interventions improved ecological conditions prior to restoration. Conversely to previous expectations, our results thus confirm that successful marine ecosystem restorations can be initiated before all stressors have been removed.

Our results also suggest that the major gains could be obtained by restoring heavily impacted areas, where not all stressors can be controlled, but restoration can still yield high success where it uses best evidence-based practice. This finding could lead to a shift in the current approach to marine ecological restoration, because it suggests that we can start with immediate restoration actions, without first waiting for the environmental amelioration (impacts removal,

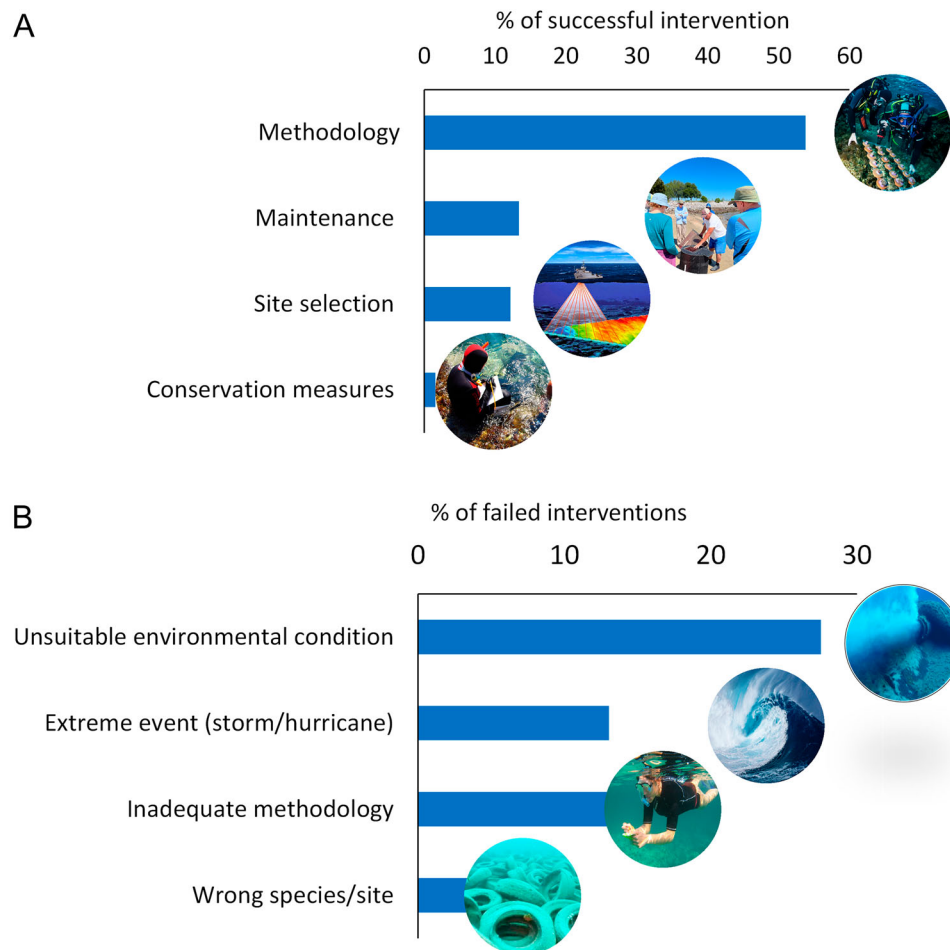
decontamination etc). In this sense we can anticipate benefits of investments in restoration of all degraded habitats.

### Drivers of marine ecosystem restoration success

To identify the drivers of restoration success (i.e., factors determining or promoting the recovery of restored habitats), we re-examined in detail the entire data set (618 case studies examined) and identified the most relevant factors for restoration success (as reported by the authors in their publications). Our analysis of drivers has some limitations in that it depends on the experience of the practitioners and their ability to test correctly and/or identify the primary determinant of success in their restoration project. Thus, despite these results do not represent a quantitative analysis of the drivers of restoration success they offer useful clues for increasing the probability of success (or decreasing the probability of failure) in future restoration interventions.

Our analysis identified the restoration “methodologies” used as the main driver of success (ca. 54% of all successful restoration cases; Fig. 5). In this category, we included: (i) embracing new technologies for transplanted habitat-forming species, or using innovative mimicking solutions<sup>37–39</sup>, (ii) using refined protocols (e.g., new materials/design and/or targeting the biology of species in different regions), and (iii) combining species to enhance facilitative interactions. In the last decade, key advancements in protocols ranged from the simple in situ collection of organisms to their “cultivation” ex situ, under laboratory conditions for subsequent out-planting and reintroduction<sup>28</sup>. These new approaches also strive to minimize impacts on source habitats or to “reuse” organisms accidentally collected as bycatch by bottom trawling, especially in deep-sea ecosystems<sup>40</sup>.

Marine restoration has recently utilized the transplantation of entire portions of habitat which preserves important ecological interactions (including microbiomes)<sup>41</sup>. These methodological



**Fig. 5 | Main drivers of success and failure in marine ecological restoration.** Reported are: (A) data encompassing the entire set of positive outcomes of restoration interventions (i.e., excluding studies reporting complete failure and those reporting a survival rate <50%; data from Table S2, SOM); and (B) data

reporting the drivers of the complete failures ( $n = 69$  complete failures, 0% survival). “Maintenance” and “Site selection” circular photos credit: National Oceanic and Atmospheric Administration (NOAA); “Wrong species/site” circular photo taken from Navy Combat Camera Dive Ex-East (U.S. Navy via public domain).

advances have led to an increase in restoration success using the latest methodologies compared to pioneering approaches (Fig. S8).

Ongoing maintenance of restored habitats represents the second most-commonly mentioned driver of success in marine ecosystem restoration (ca. 13% success among all restoration cases), which emphasizes the importance of cooperating with local stakeholders (e.g., fishermen, diving centers). Recent development of new technologies (drones, satellites, microchips and nano-sensors)<sup>42</sup> further enhances the utility and importance of monitoring restoration interventions by increasing the frequency, accuracy, and efficacy of observations.

Site selection defines the third most-commonly mentioned driver of success (12% of all successful restoration attempts), particularly when: (a) high ecological connectivity is present; (b) selected sites offer potential refugia for those species sensitive to climate change (e.g., sites less exposed to thermal stress, etc.); and (c) selection emphasizes sheltered sites, which are less prone to certain types of physical disturbance (e.g., storms, wave action, erosion, sedimentation).

The fourth most frequently mentioned driver of success is the creation of buffer areas (i.e., marine protected areas, fishery restricted areas, or other effective area-based conservation measures), surrounding the restored site to remove/mitigate against pressures resulting from human activity. This strategy, adopted by only 2% of investigated cases, prevents or reduces the risk of unintended damage

to restored areas (e.g., by bottom contact fisheries or infrastructures). In future, this strategy could broaden the definition and scope of marine protected areas also include degraded sites with high conservation potential for recovering their original conditions.

Among the most-commonly mentioned drivers of complete failure of restoration interventions (i.e., survival = 0%) we report unsuitable environmental conditions (28% of all documented failures); occurrence of extreme events that caused massive mortalities (ca 13%); and the choice of inappropriate protocols or target species (together ca 17%).

### Costs and benefits of marine ecosystem restoration

The cost of a restoration project<sup>43</sup> may represent the single greatest challenge for marine ecosystem restoration, where the costs of restoration per hectare may be significantly higher (1–2 orders of magnitude) than in terrestrial habitats. Marine restoration costs might span from approximately 0.5–25 million USD per hectare for shallow-water habitats<sup>34</sup>, requiring justification for these active interventions that changes the narrative from upfront costs to return on investments<sup>44,45</sup>.

Ecosystem goods and services (EGS) (e.g., abundant and healthy food, disease prevention, oxygen production, contaminant abatement, nutrient cycling, coastal protection, carbon sequestration, and climate mitigation) are just some of the EGS yielding public benefits provided by marine ecosystems undergoing restoration<sup>43</sup>. These



benefits can be valued in various ways (e.g., through total economic value or using contingent valuation methods, including discrete choice experiments and the willingness to pay)<sup>43,44</sup>, and even monetized (e.g., market values for increased billfish catch or increased blue tourism)<sup>45</sup>.

Cost-benefit analyses increasingly provide evidence of the significant societal-benefit value related to the restoration of marine ecosystems<sup>46</sup>. For example, a global spatial cost-benefit analysis showed that the monetary value provided by ecosystem services exceeds the costs of restoration for coral reefs, mangroves, salt-marshes, and seagrasses<sup>47</sup>. Using non-market welfare measures to evaluate ecosystem service benefits, recent studies also reported a relatively high benefit-cost ratio for deep-sea ecosystem restoration<sup>44</sup>. Examples include the potential benefits of marine genetic resources (from yet undiscovered species, molecules, enzymes or materials from marine biodiversity), the support that these ecosystems offer in terms of protection from ongoing climate change impacts<sup>48</sup>, as well as cultural values related to all marine ecosystems. In particular, the cost-benefit analyses conducted on vulnerable marine ecosystems impacted by bottom-contact fisheries or infrastructures (such as pipelines and oil platforms) indicate that the socio-economic benefits of ecosystem restoration (in terms of welfare improvement, contribution to climate targets, blue growth, food security, and jobs) cover the high restoration costs<sup>44</sup>.

Existing economic assessments of coastal-ecosystem restoration report benefit-cost ratios typically between 0.05 and 1.7<sup>46</sup> (where 1 corresponds to 100% return on investment) reaching a value of 4 for coral reef restoration<sup>47</sup>. The restoration of Mekong Delta mangrove forest (1500 km<sup>2</sup>) and macroalgal forests (1 million ha in a single project by the Kelp Forest Alliance -<https://kelpforestalliance.com/Kelp-Forest-Challenge-Roadmap.pdf>), could provide economic benefits ranging from 59 to 194,000 USD/ha/yr<sup>49</sup>. These results demonstrate the potential to go far beyond demonstration studies in marine restoration.

The increasing number of large-scale interventions from coral reef and kelp forest restoration indicate that society is ready to promote large-scale investments that include private restoration projects<sup>50</sup>. At the same time, emerging industrial sectors and associated pressures increase the need for careful assessments of costs and benefits of their activities<sup>51</sup>. The emerging sector of deep-sea mining, for instance, offers a particular vexing concern for its potential impacts, in that no scientific evidence to date can guarantee restoration of the fragile abyssal ecosystems hosting polymetallic nodules<sup>52</sup>. Abyssal ecosystem restoration, by operating at great depths and in extreme conditions, requires support of large vessels and sophisticated technologies<sup>15</sup> that can cost 5–50 times more than in coastal ecosystems (up to 75 million USD per hectare<sup>15</sup>). Consequently, the costs of restoration of deep-sea habitats impacted by seabed mining may well prove to be significantly higher than the economic return, creating major issues to be addressed by policymakers and corporations obligated by law to undertake compensatory actions<sup>15</sup>.

### Investing in marine ecosystem restoration

Boosting marine ecosystem restoration will require three main types of enablers: (1) policy/regulatory enablers to create the conditions and, eventually, obligations to restore damaged marine habitats; (2) economic enablers (including valuation of social-economic and cultural benefits to justify investments); (3) technological enablers (i.e., operating in all marine habitats and at large spatial scales). The first enabler encompasses three policy/regulation dimensions: (a) at an international level, the UN is promoting “ecosystem restoration” as a global priority for the decade 2021–2030, requiring appropriate investments<sup>53</sup>; (b) at a national (or federal) level, development of new policies including those inspired by the “Nature Restoration Law”, which will push EU member states to restore degraded marine

ecosystems, with targets of restoring 20% of degraded habitats by 2030, 60% by 2040 and 100% by 2050<sup>54,55</sup>. Concurrently, the RESTORE Act in the USA, established by the Gulf Coast Restoration Trust Fund in the U.S. Treasury Department after the Deepwater Horizon oil rig drilling in the Gulf of Mexico Horizon<sup>56</sup>. Additionally, at a local level, in most countries, the Polluter Pays Principle obliges private industry(s) causing environmental damage to cover restoration costs.

Regarding the economic enablers (b) referred to above, we note that despite high social acceptance for marine ecological restoration<sup>57</sup> and private sector recognition of the social and environmental benefits of restoration activities<sup>58</sup>, public funding remains, so far, the primary funding source for most restoration projects given the difficulty of private business cashing in on projected benefits. However, the importance given by the United Nations to ecosystem restoration has significantly boosted interest from private companies, some of which have redirected or reshaped their priorities to embrace ecosystem restoration as a “good investment”. Investing in a “nature-positive economy” also has implications for new job opportunities, novel eco-sustainable seafood, materials, and infrastructure<sup>58,59</sup>, but society must plan creative financing mechanisms to provide more economic incentives to private business and entrepreneurship in marine ecosystem restoration. New economic and policy-driven measures (including Environmental Impact Assessment procedures) are promoting private investments in three main sectors: (a) compensation interventions (i.e., ecological restoration) of marine habitats impacted by maritime infrastructure (including sealines, renewable energy production—offshore windfarms and floating solar platforms, during their installation, operation, or decommissioning); (b) blue bonds, which represent today what green bonds meant 10 years ago, oriented to restoration interventions; and (c) fundraising for blue restoration initiatives (e.g., charities collecting funding for restoring tropical marine ecosystems impacted by ghost nets and plastic<sup>60</sup>).

The third set, technological enablers, emphasizes the need for ongoing improvement and development of new and emerging technologies for marine ecosystem restoration. Despite the high current costs of technologies enabling shallow-water ecosystem restoration over large spatial scales or in deep-sea ecosystems<sup>15,61</sup>, researchers are experimenting with restoration protocols that will soon reach a readiness level (TRL >8) enabling extensive use<sup>62</sup>. The widespread application and upscaling of restoration actions for cold-water corals and other habitat-forming species at depths below conventional or technical scuba diving limits will depend on future availability of accessible, cost-effective underwater technology. This technology includes low-cost AUVs, crawlers, and the so-called Badminton approach<sup>40</sup> (attaching bycatch animal colonies to cobble supports and returning them to the restoration site directly from a boat) billed as a large-scale and cost-effective restoration method for cold-water coral gardens. Consequently, we predict that technological developments for marine ecosystem restoration will offer important business and innovation opportunities in the near future and this possibility certainly provides cause for optimism.

### Management strategies supporting marine ecosystem restoration

Clearly, governments and institutions responsible for defending public interest must maximize the effectiveness of all active restoration actions in marine ecosystems, cost-effectiveness regarding their ability to assist the recovery of associated biodiversity and ecosystem functions, and the resulting benefits that restored ecosystems provide to humans through enhanced quality and quantity of ecosystem services. In other words, we must establish active restoration as one of the recognised priority strategies and solutions for reversing past and ongoing marine habitat degradation, mitigating the losses incurred by future extraction and construction actions that may be authorized, penalizing wilful corporate disrespect of regulations and, taken

collectively, maintaining and recovering healthy and biodiverse marine ecosystems and seascapes.

Appropriate management strategies can certainly enhance and increase the return on investment for restoration interventions. For instance, coupling “passive” and active restoration interventions could expand the areal extent of positive effects of active restoration, while providing an instrument to safeguard costly restoration interventions. Implementation of “passive restoration” such as creating buffer areas surrounding the active restoration intervention site, within the larger framework of maritime spatial planning and sustainable management schemes, could substantially increase ecological and societal benefits, reduce unit costs of interventions, and yield higher return on all investments in ecosystem restoration. However, few initiatives embrace such a strategy today and best practices to maximize contributions of buffer areas to achieve these hoped-for multiple benefits will require specific assessments for different habitat types.

### Future perspectives

Our study provides robust evidence for successful or highly successful marine ecosystem restoration for all marine habitat types undergoing restoration so far, and efforts can now expand to the deep sea. Parallel evidence of a low risk of complete failure for most marine habitat types corroborates this encouraging result. Secondly, restoration can be scalable upward at all latitudes tested so far (from 0 to 60°) through existing regulations and financing instruments. Third, marine ecosystems do not require large-scale interventions as a pre-requisite for success. Fourth, we demonstrated high restoration success even in impacted marine areas, which support the possibility of immediate actions to restore marine all degraded habitats, accelerating the socio-economic benefits deriving from investments in restoration. This finding, together with positive results of benefit-cost analyses that includes non-market welfare measures<sup>63,64</sup> supports current international agreements to curb biodiversity loss (including the Kunming-Montreal Global Biodiversity Framework of the UN Conference of the Parties to the Convention on Biological Diversity) and can contribute to change the narrative from concerns about the significant costs to the potential benefits realized through investments in restoration. Despite the huge potential for marine ecosystem restoration, considerable work remains in two main directions: (1) improved protocols for increasing success of restoration interventions on all degraded habitats including those for which we have limited or no experience yet (e.g., polymetallic nodules, hydrothermal vents, and cold-seeps); (2) lowering costs of marine ecosystem restoration to extend spatial scales of intervention while simultaneously engaging the private sector.

### Methods

Our literature survey aimed to collect available information on active restoration interventions across marine habitats at a global spatial (i.e., worldwide) and over a broad temporal scale (year 1950 onward). We considered the available scientific literature (i.e., papers in international journals, contributions to scientific congresses) of restoration interventions carried out at the international, national, or regional level by scientific communities or public administrations for territory management purposes. The search encompassed only marine habitats (spanning shallow intertidal to deep-sea habitats) and included land-sea interface habitats, such as mangroves and saltmarshes, which we considered fully part of marine seascapes. Overall, we identified 8 main habitat types of interest: coral reefs, seagrasses, saltmarshes, mangroves, macroalgal forests, cold-water corals, animal forests, and oyster beds. The specific aim was to assess the success or failure of restoration interventions on marine habitats, also including their relationship to habitat typology, intervention sites, spatial extent and duration of intervention, and level of anthropogenic impact. The selection therefore was carried out using the search for “restoration”,

intended as “assisted regeneration or reconstruction” of damaged marine habitats<sup>17</sup>. We intentionally excluded restoration approaches focusing only on genetic data, metabolism, physiology or taxonomy. We specifically focused our attention on the success/failure of restoration interventions and the relative drivers.

### Search methodology

To allow the highest transparency and replicability of the data mining, we used Scopus, and ISI Web of Knowledge, which represent the most reliable data bases, and then we compared the results from these two data bases. The data search was carried out in July 2024, using the highest international standards as follows: first, we defined a preliminary benchmarking strategy, using the first attempts based on previous studies<sup>29</sup>; then compared different searches obtained from Scopus and ISI Web of Knowledge, using entire and the truncated words as reported in the following strings:

ISI WEB: (TI=((seagrass\* OR saltmarsh\* OR oyster OR mangrov\* OR macroalg\* OR kelp OR coral\* OR coralligen\* OR (cold AND water AND coral\*) OR (animal AND forest\*)) AND (restor\* OR transplant\* OR outplant\* OR trasloc\* OR reloc\*) AND (success\* OR surviv\* OR fail\*))) OR (AB=((seagrass\* OR saltmarsh\* OR oyster OR mangrov\* OR macroalg\* OR kelp OR coral\* OR coralligen\* OR (cold AND water AND coral\*) OR (animal AND forest\*)) AND (restor\* OR transplant\* OR outplant\* OR trasloc\* OR reloc\*) AND (success\* OR surviv\* OR fail\*))) OR (AK=((seagrass\* OR saltmarsh\* OR oyster OR mangrov\* OR macroalg\* OR kelp OR coral\* OR coralligen\* OR (cold AND water AND coral\*) OR (animal AND forest\*)) AND (restor\* OR transplant\* OR outplant\* OR trasloc\* OR reloc\*) AND (success\* OR surviv\* OR fail\*))).

SCOPUS: (TITLE-ABS-KEY (seagrass\* OR saltmarsh\* OR oyster OR mangrov\* OR macroalg\* OR kelp OR coral\* OR coralligen\* OR (cold AND water AND coral\*) OR (animal AND forest\*)) AND TITLE-ABS-KEY (restor\* OR transplant\* OR outplant\* OR trasloc\* OR reloc\*) AND TITLE-ABS-KEY (success\* OR surviv\* OR fail\*))).

The results of the procedure are illustrated in Fig. S9 and reported in Table S1 (SOM). Searches were undertaken within “Article titles”, “Abstracts”, and “Keywords”. We considered all scientific literature (i.e., papers in international journals, contributions to scientific congresses) on marine restoration interventions carried out at the international, national, or regional level by scientific communities or public administrations for management purposes. When we found a “review paper” we also considered the references reported therein to check for potential additional information sources.

### Eligibility criteria

We included all documents identified by the search engines using the strings reported above, to be exhaustive of all the literature produced, and at the same time, focused on the specific research topic. Papers were included when dealing with: (a) restoration interventions carried out in marine ecosystems; (b) different typologies of marine habitats, (c) identifiable location (latitude and longitude), (d) identifiable year/date of intervention etc.

We defined the eligibility of the published studies including the following criteria: (a) documents reporting the results of restoration interventions; (b) documents reporting the methodology used for the intervention; (c) documents reporting the marine habitat typology, country, site, latitude and longitude; (d) documents reporting indicator/s of success, and the typology of indicator and its measure. Conversely, we considered ineligible documents based on complementary studies (e.g., those focusing only on natural resilience, theoretical studies, studies based only on stakeholder engagement or focused only on socio-economic aspects of restoration).

### Exclusion criteria and data extraction

We considered further only those documents fulfilling the eligibility criteria. We used the following criteria for exclusion of documents as



ineligible: (a) duplicated (reported in more than one data base) or repeated entries (duplicates from the same data base); (b) not available or wrong citations; (c) not pertinent entries (dealing with terrestrial or freshwater ecosystems, seabirds, etc.); (d) entries not reporting data on ecological restoration interventions as focused on other aspects of restoration (e.g., genetic, physiology, taxonomy, policy, etc.). After this screening, two reviewers extracted and crosschecked the data independently. Each reviewer built an Excel table reporting all the data extracted. This Table included (reported in SOM as Table S2) included: (i) methodological approach and protocols; (ii) biogeographic region, country, and site, (iii) latitude and longitude, (iv) habitat type, (v) year of the intervention and relative duration, (vi) spatial extent of the intervention, (vii) success/failure as declared by Authors, (viii) variable indicator of success; and ix) drivers of success.

For documents reporting more than one intervention, data were crosschecked with all the interventions already documented to avoid duplications. A quality check ensured that none of the documents referred to the same restoration intervention. All duplicates were removed from the data set.

Through this process we started from 6403 documents (from Scopus and WoS combined; Table S1) and, after eligibility selection, and application of criteria for exclusion we obtained 339 documents. Several documents included results of more than one intervention and from different marine habitats or regions; for this reason, we censused a total of 764 active restoration interventions, of which 759 reported a complete set of data including the percentage of survival, which we report in the list of References in Supplementary Data 1.

### Analysis of restoration success

We define success of a restoration as interventions where re-introduced habitat-forming species showed evidence of “survival” (i.e., indication of eventual self-sustaining or expansion of the restored taxa<sup>17</sup>) over time for the transplanted species. In the analyses, we considered survival (expressed as %), from 0 to 100%. We used the collected data either to provide a descriptive statistic using the entire data set or applying a cut-off of 50% survival of re-introduced organisms to discriminate between successful ( $\geq 50\%$  survival) and unsuccessful ( $< 50\%$  survival) interventions and for the meta-analysis (full spectrum of data without cut offs). At the same time, acknowledging that a given restoration process might take years, we considered “time” as a factor in analyzing restoration interventions, in terms of number of years from the intervention to the end of the reported monitoring (i.e., data collection on survivorship). Given that the relevant literature varied in terminology, we grouped indicators of success reported in the publications into 5 categories: (1) survival of transplanted species, (2) spatial expansion of restored species, (3) positive effects on ecosystem functioning (e.g., enhancement of metabolism biomass, reproduction), (4) effects on environmental quality (e.g., habitat provisioning, reduced sedimentation), and (5) effects on local biodiversity (e.g., number of species, excluding non-indigenous species, NIS; see SOM for details).

### Meta-analysis

To analyse variability in restoration success among different habitat types, we used the Meta-Analysis technique<sup>65</sup>. The meta-analysis used the proportion of the success rate (after Freeman-Tukey Double arcsine transformation) as the effect size<sup>66,67</sup>, and multilevel mixed-effects models. We used spatial extent as sample size, and the product of spatial extent and success rate as the estimated event count for each habitat type (the analysis was developed using R packages meta and metafor, version R 4.3.1<sup>68,69</sup>). We summarized the process of data collection and selection for the meta-analysis in a PRISMA flow chart<sup>70</sup> illustrated in Fig. S9; Annex 1 provides the complete checklist. We considered the 759 of the 764 restoration interventions as 5 studies did not provide data on survival percentage and used a single

proportion design within-study because of the absence of controls. To solve the potential “with-study dependency” we used multilevel mixed-effects models, in which multiple data points were nested under the same reference. Since the data showed high variability among interventions, we could not assume these interventions came from a homogeneous population (i.e., explained only by a fixed effect plus a sampling error). To account for between-study variability and solve the potential ‘within-study dependency’, we used multilevel mixed-effects models, in which multiple data points were nested under the same reference. Moreover, a Freeman-Tukey Double arcsine transformation was applied to the proportions to normalize their distribution and stabilize their variance.

Data collected from the publications and used for the meta-analysis produced the funnel plot<sup>71,72</sup> reported in Fig. S10, which indicated the absence of publication bias in accordance with the Egger’s regression test<sup>73</sup> ( $p$ -value = 0.90).

### Relationships in space, time, and geographical setting using mixed-effects models

We used mixed-effects models to investigate patterns between survival percentage and the other quantitative covariates (spatial extent of the intervention, years from the intervention, and latitudinal gradient), utilizing the *lme4* package, after data aggregation to avoid giving more weight to studies with more samples ( $n = 245$ ).

### Analysis of restoration success in relation to the levels of impact

We mapped the distribution of the Global Cumulative Impact Index using ArcGIS 10.1, superimposing georeferenced restoration interventions to showcase their global distribution for different habitat types (i.e., oyster beds, coralligenous habitat, macroalgal forests, cold-water corals, coral reefs, mangroves, salt marshes, and seagrasses) ArcGIS 10.1 (Fig. S7). Each intervention was super-imposed on the Global Cumulative Impact Index (based on the dataset available at <https://kn.b.ecoinformatics.org/view/doi:10.5063/F19Z92TW>)<sup>1</sup>. The dataset comprised impacts of: artisanal fishing, demersal destructive fishing, demersal non-destructive high bycatch fishing, demersal non-destructive low bycatch fishing, direct human impact, inorganic pollution, invasive species, light pollution, nutrient pollution, oil rigs, ocean acidification, ocean-based pollution, organic pollution, pelagic high bycatch fishing, pelagic low bycatch fishing, sea level rise, sea surface temperature, shipping, and UV<sup>2</sup>. The Global Cumulative Impact Index ranged from 0 to 15.4, with values  $> 4.02$  representing sites of high impact, and values  $< 2.74$  representing low impact sites<sup>2</sup>. Where a given study site had no score, reflecting source raster (coverage) of the data sources, we calculated the value for the point from adjacent cells with valid values using bilinear interpolation (Fig. 3 main text and Fig. S7 for each habitat type).

### Analysis of the drivers of restoration success and failure

From the data collected on success and failure we carried out an additional in-depth analysis on each publication where the authors identified the driver(s) of the outcomes of the restoration intervention. We grouped the drivers of success reported by the authors (only for the sites with documented restoration success, for a total of 233 interventions), into 4 categories: (1) appropriateness of the restoration methodology used (reported here as “methodology”, and including protocol, methodology, technology, strategy regarding organism density, facilitation, or restoration of reproduction), (2) monitoring and maintenance of the restoration intervention over time (reported here as “maintenance”, and including amelioration/requalification, predation management/ exclusion, reduced human impact, and stakeholder collaboration to avoid further impacts); (3) suitability of the site selected for restoration (reported here as “site selection”); and (4) enforcement of the restoration intervention with conservation measures (reported here as “conservation measures”).

We also identified the drivers of complete failure (survival = 0%) categorized as: (1) “unsuitable environmental conditions”, (2) “inappropriate site selection”, (3) “extreme events” and (4) “inadequate methodology”.

### Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

### Data availability

Additional statistics, meta-analysis, and a PRISMA checklist can be found in the Supplementary Information file. All data used in this study can be found in Supplementary Data 1 and have been deposited in Figshare here: <https://doi.org/10.6084/m9.figshare.23635449>.

### Code availability

The code and scripts used for the analyses along with a README file can be found here: <https://doi.org/10.24433/CO.6643300.v1>.

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## Author contributions

R.D., S.F., and S.B. designed the study. R.D., S.F., and S.B. wrote the first draft. P.D. produced the ArcGIS images and related analyses. A.Gi. carried out the meta-analysis and related figures and interpretation. J.A., C.B., J. C.-S, C.C., C.G., J.G., A.Gr., A.H., L.M., T.M., S.O., E.R.-L., C.J.S., and P.S. contributed to the interpretation of the results and to the draft revision. R.C., W.C., N.P., J.V.K., and J.V.T. contributed to the economic and management analysis. All co-Authors contributed to the Discussion and the revision the final version of the ms.

## Competing interests

The authors declare no competing financial and non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Additional information

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**Correspondence** and requests for materials should be addressed to R. Danovaro.

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<sup>1</sup>Dept. of Life and Environmental Sciences, Polytechnic University of Marche, Ancona, Italy. <sup>2</sup>National Biodiversity Future Centre, Palermo, Italy. <sup>3</sup>Center for Conservation and Sustainable Development, Missouri Botanical Garden, St. Louis, MO., USA. <sup>4</sup>Ecological Health Network, Cambridge, MA, USA. <sup>5</sup>Environmental and Marine Biology, Åbo Akademi University, Åbo Turku, Finland. <sup>6</sup>Norwegian Institute for Water Research (NIVA), Oslo, Norway. <sup>7</sup>National Cluster Blue Italian Growth, Naples, Italy. <sup>8</sup>Department of Science and Engineering of Matter, Environment and Urban Planning (SIMAU), Polytechnic University of Marche, Ancona, Italy. <sup>9</sup>Department of Ecology - IMEM, University of Alicante, Alicante, Spain. <sup>10</sup>Society for Ecological Restoration, European Chapter, Bruxelles, Belgium. <sup>11</sup>Stazione Zoologica "Anton Dohrn", National Institute of Marine Biology Ecology and Biotechnology, Naples, Italy. <sup>12</sup>Institut de Ciències del Mar (ICM-CSIC), Barcelona, Spain. <sup>13</sup>Earth and Ocean Sciences, University of Galway, Galway, Ireland. <sup>14</sup>Laboratory of Environment Biomonitoring, Coastal Ecology and Ecotoxicology Unit, University of Carthage, Zarzouna, Tunisia. <sup>15</sup>Université Côte d'Azur, CNRS, UMR 7035 ECOSEAS, Nice, France. <sup>16</sup>Institute of Marine Sciences - OKEANOS, University of the Azores, Ponta Delgada, Portugal. <sup>17</sup>Fisheries Research Institute (ELGO DIMITRA), Kavala, Greece. <sup>18</sup>Institute of Marine Biological Resources and Inland Waters, Hellenic Centre for Marine Research, Heraklion, Crete, Greece. <sup>19</sup>REV Ocean, Lysaker, Norway. <sup>20</sup>Departments of Ocean Sciences and Biology, Memorial University of Newfoundland, St. John's, Canada. <sup>21</sup>Department of Estuarine and Delta Systems, Royal Netherlands Institute for Sea Research (NIOZ), Texel, The Netherlands. <sup>22</sup>Groningen Institute for Evolutionary Life Sciences, University of Groningen, Groningen, The Netherlands. <sup>23</sup>Environmental Policy Group, Delta Climate Center, Wageningen Economic Research, Wageningen University, Wageningen, The Netherlands. <sup>24</sup>Department of Biology, University of Naples Federico II, Naples, Italy. ✉ e-mail: [r.danovaro@univpm.it](mailto:r.danovaro@univpm.it)