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The cost and feasibility of marine coastal restoration

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Abstract. Land-use change in the coastal zone has led to worldwide degradation of marine coastal ecosystems and a loss of the goods and services they provide. Restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed and is critical for habitats where natural recovery is hindered. Uncertainties about restoration cost and feasibility can impede decisions on whether, what, how, where, and how much to restore. Here, we perform a synthesis of 235 studies with 954 observations from restoration or rehabilitation projects of coral reefs, seagrass, mangroves, saltmarshes, and oyster reefs worldwide, and evaluate cost, survival of restored organisms, project duration, area, and techniques applied. Findings showed that while the median and average reported costs for restoration of one hectare of marine coastal habitat were around US$80000 (2010) and US$1600000 (2010), respectively, the real total costs (median) are likely to be two to four times higher. Coral reefs and seagrass were among the most expensive ecosystems to restore. Mangrove restoration projects were typically the largest and the least expensive per hectare. Most marine coastal restoration projects were conducted in Australia, Europe, and USA, while total restoration costs were significantly (up to 30 times) cheaper in countries with developing economies. Community- or volunteer-based marine restoration projects usually have lower costs. Median survival of restored marine and coastal organisms, often assessed only within the first one to two years after restoration, was highest for saltmarshes (64.8%) and coral reefs (64.5%) and lowest for seagrass (38.0%). However, success rates reported in the scientific literature could be biased towards publishing successes rather than failures. The majority of restoration projects were short-lived and seldom reported monitoring costs. Restoration success depended primarily on the ecosystem, site selection, and techniques applied rather than on money spent. We need enhanced investment in both improving restoration practices and large-scale restoration.

Key words: *cost; feasibility; marine coastal ecosystems; rehabilitation; restoration; success and failure; synthesis.*

Introduction

Coral reefs, seagrass, mangroves, saltmarshes, and oyster reefs are highly productive and valuable marine coastal habitats (Kaly and Jones 1998, Grabowski and Peterson 2007, Barbier et al. 2011, Costanza et al. 2014). They provide food and biotic materials, coastal protection from storms and erosion, feeding and shelter from predation for commercial and non-commercial organisms, cultural services such as tourism or recreation (Liquete et al. 2013), and mitigation and adaptation to climate change (e.g., seagrass, saltmarshes, and mangroves; McLeod et al. 2011, Duarte et al. 2013). Many coastal communities, mostly in developing countries, depend on marine coastal ecosystems for food to stay alive (UNEP 2006).

The extent and condition of marine coastal ecosystems are threatened globally as a result of multiple and interacting processes (Halpern et al. 2008). These habitats have been degraded or transformed mainly through anthropogenic impacts such as land use change and habitat loss for associated species (UNEP 2006). Over the past few decades global coverage of mangroves and coral reefs has declined by more than 35% and 19%, respectively (Valiela et al. 2001, Wilkinson 2008), and loss continues with seagrass and mangroves declining at alarming rates of 7% per year (Orth et al. 2006, Waycott et al. 2009) and 1–2% per year (Valiela et al. 2001, Duke et al. 2007), respectively. More than 60% of the world's coral reefs are under immediate and direct threat from one or more local stressors, such as overfishing, destructive fishing practices, coastal development, and pollution (Burke and Spalding 2011) in addition to climate change (Hoegh-Guldberg

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et al. 2007). Stressors to seagrass include sediment and nutrient runoff, physical disturbance, invasive species, disease, commercial fishing practices, aquaculture, overgrazing, algal blooms, and global warming (Orth et al. 2006). Mangrove forests have been removed across the tropics for conversion to aquaculture ponds (Valiela et al. 2001, Alongi 2002, Giri et al. 2011), although clearing for forestry, agriculture and urban/industrial developments are important causes of loss in some locations. Saltmarshes have been highly modified by drainage for agriculture for centuries (Bromberg-Gedan et al. 2009), are severely affected by coastal eutrophication (Deegan et al. 2012), and are presently being replaced by mangroves due to climate change (Rogers et al. 2005, Saintilan et al. 2014). A recent investigation reported that more than 80% of native oyster stocks worldwide have been overharvested in the last century and most of the remaining stocks are close to functional extinction (Beck et al. 2011). While losses of marine habitats and ecosystem services can be counteracted by removing the threatening processes, restoration and rehabilitation are critical when natural ecosystem recovery is hindered by physical modifications of the coast, lack of recruitment, or where species dependent on the coastal habitats are facing local extinction due to habitat loss (Perrow and Davy 2002).

Ecosystem restoration is "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER 2004), while rehabilitation is the replacement of structural or functional characteristics of an ecosystem that have been diminished or lost (Field 1998). Active restoration is where management techniques such as transplanting, planting seeds and seedlings, or the construction of artificial habitats are implemented, while passive restoration is focused on removing the impact of environmental stressors such as pollution or poor water quality, which prevent natural recovery of the ecosystems occurring (Perrow and Davy 2002).

Rapidly increasing rates of ecosystem degradation, coastal development, environmental change, and low rates of natural recovery suggest that there is an urgent demand for restoration in marine coastal ecosystems. Ecosystem restoration is also crucial for emerging ecological offset policies, where impacts of development causing biodiversity and ecosystem services loss at one site are compensated for by conservation and restoration activities at another offset site (Madsen et al. 2010, Bull et al. 2013). Research on restoration has mainly focused on terrestrial, rather than on marine coastal ecosystems (Blignaut et al. 2013) and the monetary value of the ecosystem services (de Groot et al. 2012). However, decisions on whether to restore degraded marine coastal ecosystems can be impeded due to uncertainties around the costs and feasibility of restoration (Zimmer 2006, Zedler 2007, Suding 2011, Dahl and Stedman 2013, La Peyre et al. 2014). Further, the decision about whether we should restore or protect marine habitats hinges on the relative costs of the two options (Possingham et al. 2015).

We review and analyze results from restoration projects for coral reefs, seagrass, mangroves, saltmarshes, and oyster reefs. This information will support decision-makers, planners, and researchers in evaluating the cost and feasibility of marine coastal restoration. We have conducted a comprehensive assessment of peer-reviewed literature, accessible reports, and databases. Where data were not available, we have questioned practitioners about their experiences. We compare the costs and success rates of projects for each ecosystem with respect to the techniques that have been applied, assess differences in restoration between geographic locations, and evaluate project duration and areas covered. Through this review, we address two major questions: What are the biggest gaps in our knowledge of the costs and outcomes of restoration?, and How much do we need to know in order to guide conservation planning and policy in the era of restoration in ecology?

Approach

Systematic review

We reviewed primary literature, reports, and databases, and communicated with practitioners and researchers to build a comprehensive database of restoration projects of the last 40 years for five main marine coastal ecosystems: coral reefs, seagrass, mangroves, saltmarshes, and oyster reefs. We chose to report on these ecosystems due to their valuable goods and services and rapid rates of decline. Reporting on all five systems also allows for comparison of cost and feasibility across ecosystems. We undertook a systematic review using Web of Science (Core collection; Thomson Reuters, New York, New York, USA) and Scopus (Elsevier, Atlanta, Georgia, USA) databases. Databases were searched for peer-reviewed articles using the search terms "(ecosystemA* OR ecosystemB*) AND restor*", as well as "(ecosystemA* OR ecosystemB*) AND rehab*" to account for all literature on restoration and rehabilitation available by 21 November 2014. The terms ecosystemA and ecosystemB indicated two different names in use for the same ecosystem (e.g., coral and coral reef, mangrove and mangal, saltmarsh and salt marsh, shellfish and oyster). The search was confined by focusing on the key terms in the title and resulted in a total of 429 studies (89 studies for coral reefs, 54 for seagrass, 71 for mangroves, 134 for saltmarshes, and 81 for oyster reefs, respectively). In a second step, an EndNote (Version X7.0.2; Thomson Reuters, New York, New York, USA) search was performed within the full text (any field + PDF with notes) of the sources using the search terms (cost* OR feasib* OR surviv*) to only account for studies either indicating cost or feasibility/survival. In addition, relevant information was obtained by following on citations, personal communication with practitioners and researchers, and inspecting diverse restoration databases and webpages. The overall literature search and review resulted in the creation of one database containing data from five ecosystems with 71 studies for coral reefs (with 286 single observations), 52 (193) for seagrass, 54 (217) for mangroves, 34 (132) for saltmarshes, and 24 (126) for oyster reefs (Appendix S1: Table S1). An overview map of the worldwide locations of restoration projects is provided in Appendix S1 (Fig. S1). We refer to both active or passive restoration and rehabilitation as "restoration" to encompass all approaches used for comparison.

A database containing information on five ecosystems was created using data from the literature review (Reference to Ecological Archives and Dryad Digital Repository). Each ecosystem-specific database section contains the full reference, general information about the publication and project, the restoration action undertaken, species involved, location, a description on the type of cost reported, information on funding sources, project duration (in years), the area restored in hectare (ha), the converted restoration cost in US$2010/ha, feasibility information (including reasons for success or failure), and restoration success in terms of percentage of survival of restored organisms. For coral reefs, we also accounted for pre-transplant (i.e., survival of coral spat/larvae in culture before rearing them in nursery or out-planting), transplant (i.e., survival of coral fragments during nursery period), and post-transplant (i.e., survival of coral fragments after out-planting to the reef) survival, as well as for the overall survival averaged over the former three categories.

Data from plots and figures were extracted graphically by using WebPlotDigitizer (*available online*).[6] Not all information required for the database was directly available in every report, therefore, additional information was derived where possible. For oyster reefs, if survival of restored organisms was not reported, it was estimated based on percent cover of oysters on the reef (Konisky et al. 2013) or the percentage of successful reefs out of the number of total reefs restored (Powers et al. 2009). For the coral reefs records, where only cost per coral colony was provided (Shafir et al. 2006, Garrison and Ward 2008, Shaish et al. 2008, Ferse 2010, Levy et al. 2010, Nakamura et al. 2011, Guest et al. 2014), calculations for the restoration cost per area were based on a transplanting schedule with four coral colonies out-planted per m^2 or 40000 coral transplants/ha (Edwards and Gomez 2007). Accounting for a median survival of 64.5% (averaged over the reported pre-transplant, transplant, and post-transplant survival in the coral reef restoration database section), a total of 54200 coral transplants would be required to populate one hectare. The latter value was used for converting cost per colony to cost per unit area.

Restoration costs

All reported restoration costs were adjusted for inflation in each respective country based on consumer price index (CPI) to a base year of 2010 prices (Table 1; Appendix S1: Tables S2, S3). Data required for economic conversion were downloaded from World Bank Development Indicators (The World Bank 2014). For some countries and/or years, CPI data were unavailable (e.g., Taiwan, Maldives, Mayotte, Réunion, Virgin Islands [UK], French Polynesia, Micronesia, and New Caledonia); such observations were excluded from further analyses, but original data are available in the database (Reference to Ecological Archives and Dryad Digital Repository). If the CPI for a particular year was unavailable, the next closest year selected was data collection year. Otherwise, if data collection year was unavailable, the publication year minus one year was used. For restoration costs incurred in 2014, the previous year CPI (2013) was used for conversion. For studies where local currencies were reported (e.g., Australia, Indonesia, Vietnam, Europe), data were first converted to U.S. dollars using the foreign exchange rates from the Penn World Tables (Heston et al. 2012) and later adjusted to the respective countries' inflation based on CPI to a base year of 2010 prices. To account for effects based on differences in local economy (developed or developing), we performed a second economic conversion based on the gross domestic product as a function of purchasing power parity GDP (PPP). Here, we converted U.S. dollar to the local value of one U.S. dollar in developing countries and then adjusted for inflation to obtain international dollar (Int$) at a base year of 2010 prices (Table 1; Appendix S1: Tables S4, S5). The difference in cost between CPI and GDP (PPP)-converted costs highlights that the U.S. dollar has a greater value (i.e., purchasing power) relative to the official exchange rate of the foreign currency in countries with developing economies.

The cost description reported in the restoration database was used to group data into total project costs (including capital and operating cost), capital costs (cost for planning, purchasing, land acquisition, construction, and financing), operating costs (cost for maintenance, monitoring, and equipment repair and replacement), and in-kind cost (donations or volunteer labour) according to (Environmental Protection Agency 2012; Table 1). Although we attempted to include monetary restoration cost, other costs including opportunity cost, contingency cost, transaction cost, and time lag (Cairns 1994, Gutrich and Hitzhusen 2004, Levrel et al. 2012, Quétier et al. 2014) of the projects were rarely mentioned in the studies. Therefore, if all types of project costs were accounted for in all studies, the costs we report here would be greater. A detailed overview of cost and survival of restored organisms grouped by restoration technique applied for all investigated ecosystems can be found in Appendix S1: Table S7.

Feasibility

Ideally, the success of ecological restoration should be measured as how much of the previous ecosystem function and its resilience against stresses and environmental changes could be achieved after restoration efforts (Kaly and Jones 1998, Ruiz-Jaen and Aide 2005).

[6] http://arohatgi.info/WebPlotDigitizer/

Table 1. Median (and average in brackets) values of overall restoration cost per unit area and total restoration cost for coral reefs, seagrass, mangroves, saltmarshes, and oyster reefs.

		Restoration cost		Total restoration cost		PPP-adjusted restoration cost		PPP-adjusted total restoration cost	
Ecosystem	Economy	N	(2010 US$ per ha)	N	(2010 US$ per ha)	N	(2010 Int$ per ha)	N	(2010 Int$ per ha)
Coral reefs	Overall	42	165,607 (5,411,993)	16	162,455 (2,915,087)				
	Developed	18	1,826,651 (12,125,179)	8	282,719 (5,501,636)	19	1,489,964 (11,499,412)	8	207,247 (5,479,769)
	Developing	24	89,269 (377,104)	8	162,455 (328,537)	28	9,216 (60,726)	8	19,510 (48,309)
Seagrass	Overall	64	106,782 (399,532)	22	383,672 (699,525)				
	Developed	64	106,782 (399,532)	22	383,672 (699,525)	48	144,981 (444,604)	22	419,646 (725,326)
	Developing	…	…	…	…	…	…	…	
Mangroves	Overall	109	8,961 (62,689)	29	2,508 (15,017)				
	Developed	59	38,982 (108,828)	5	52,006 (45,311)	46	37,568 (93,281)	5	52,006 (42,801)
	Developing	50	1,191 (8,245)	24	1,771 (8,706)	44	172 (2,163)	25	230 (1,413)
Saltmarshes	Overall	73	67,128 (1,804,779)	40	151,129 (1,042,116)				
	Developed	73	67,128 (1,804,779)	40	151,129 (1,042,116)	67	75,362 (1,567,614)	35	213,690 (1,182,457)
	Developing	…	…	…	…	…	…	…	…
Oyster reefs	Overall	23	66,821 (386,783)	5	189,665 (859,080)				
	Developed	23	66,821 (386,783)	5	189,665 (859,080)	23	66,821 (386,783)	5	189,665 (859,080)
	Developing	…	…	…	…	…	…	…	…

Notes: Cost data are represented in 2010 U.S. dollars per ha accounting for inflation [consumer price index (CPI)] and in 2010 Int$ per ha taking into account the gross domestic product as estimated by the purchasing power parity (GDP; PPP). Total restoration cost includes only observations in which both capital and operating cost were reported. Data are represented as overall observations as well as projects in countries with developed and developing economies. The number of observations is indicated by N, while ellipses imply that no observations were available.

However, restoration success is typically reported in terms of item-based success, e.g., survival of planted transplants, seedlings, recruits, propagules, or spat. Item-based success is not adequate to represent the overall project feasibility where success criteria are linked to the recovery of ecosystem function and services (Ruiz-Jaen and Aide 2005). Many projects assessed in the present study did not aim at ecological restoration as defined by the Society for Ecological Restoration (SER 2004), but rather had other objectives. For example, some projects focused on the utilization of project funding for the establishment of the largest number of jobs (Stokes et al. 2012), community engagement (Brown et al. 2014), or political gain (Mann and Powell 2007). Due to the fact that restoration goals differed between restoration projects or were not clearly defined, we used item-based success such as survival of restored organisms as a closest estimate to overall restoration feasibility, although we acknowledge that this is not equivalent to success of ecological restoration where feasibility is based on an evaluation of ecosystem service recovery.

We define a highly successful ecological restoration project as one where the restoration goals required at least a 5-yr (monitoring) period and achieved ≥85% survival of restored organisms for the entire mitigation area (e.g., Roebig et al. 2012). We define restoration failure as projects with an outcome of ≤10% survival of restored organisms.

Statistical analyses

Statistical differences between restoration cost provided for projects in countries with developed economies and developing countries were analyzed by a non-parametrical Kruskal–Wallis one way ANOVA since cost data failed the test of normality (Kruskal and Wallis 1952). Statistical tests were performed for the ecosystems coral reefs and mangroves for CPI- as well as GDP (PPP)-converted costs but analysis was not possible for seagrass, saltmarsh, or oyster reefs because there were insufficient data from developing countries. A linear regression analysis was performed to identify whether there was a relationship between restoration cost and survival, or between cost and unit area of restored habitat. The latter was conducted to identify whether there are economies of scale in coastal ecosystem restoration projects (i.e., a decrease in restoration costs per unit area with increasing project areas). To examine how well different restoration projects performed overall, we conducted a simplified cost-effectiveness analysis of restoration cost, project area, and survival of restored organisms for observations where all required data were available. Cost-effectiveness analysis measures a least-cost way in achieving an objective for our case restoration, where the restoration cost per unit area and respective survival rate of restored organisms, is compared to the relative costs and outcomes of two or more alternatives (see Appendix S1 for more details; Wilson et al. 2012).

Results

The cost of marine coastal restoration

Out of a total of 954 observations from restoration projects, 33% reported on cost and 28% described what these costs included. From all observations reporting on cost, only 30% contained components of both capital and operating costs. Monitoring costs were specifically indicated for only 18% of all cost observations, while 29% included construction cost (Appendix S1: Table S1).

Overall cost for restoration varied considerably within and between ecosystems (Table 1). The median and average of restoration cost for all ecosystems was around US$80000/ha and US$1600000/ha, respectively. Total project costs, calculated for projects that included both capital and operating costs, for restoring seagrass, saltmarshes, and oyster reefs were two to four times higher than the median (US$150000–400000/ha, 2010; Table 1). Median total restoration costs for coral reefs were close to the overall cost value (Table 1). For mangroves, total restoration costs were 3.6 times lower than the median of overall costs.

The range of restoration cost, project area, project duration, and survival of restored organisms is shown for all ecosystems in Fig. 1. Compared with other ecosystems, mangrove restoration was the least expensive and targeted the largest areas (Fig. 1A, B). For coral reefs, seagrass, saltmarshes, and oyster reefs, only small-scale restoration efforts of <1 ha have been documented (Fig. 1B). The median project duration of restoration efforts ranged from 1 yr for coral reefs, seagrass, and mangroves to 2 yr for saltmarshes and oyster reefs (Fig. 1C). Of all observations on survival, 47% of the projects were assessed for ≤1 yr, 21% for between 1 and 2 yr, and 21% for longer than 2 yr, while 11% provided no information on project duration (Appendix S1: Table S1). Among all marine coastal ecosystems, the lowest survival was reported for seagrass with a median survival of 38.0% (Fig. 1D).

Restoration projects were described from around the world in both developed and developing countries. Most projects occurred in Australia, Europe and USA (Appendix S1: Fig. S1). Only coral reefs and mangrove restoration projects were reported from both developed and developing countries. Studies on the restoration of seagrass, saltmarshes, and oyster reefs were only documented in developed countries. Reported restoration costs were significantly lower (Kruskal-Wallis ANOVA; $p < 0.01$) for projects in developing countries compared to developed countries (Fig. 2). Total restoration costs for projects in developing countries were almost half as expensive for coral reefs and 30 times less for mangroves compared to costs in developed countries when accounting for economic conversion based on the countries' inflation. When taking into account the local value of U.S. dollars in developing countries by adjusting to GDP

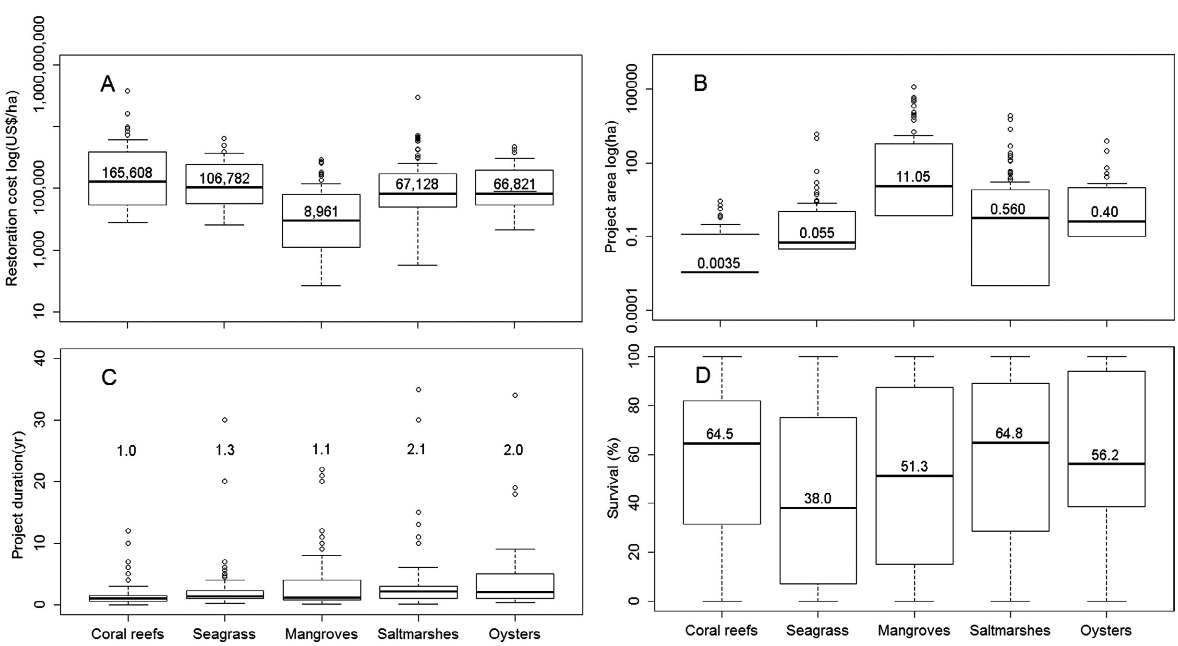

FIG. 1. Range of (A) cost, (B) project area, (C) project duration, and (D) survival for marine coastal restoration projects represented as box and whisker plots with minimum, quartiles, median, maximum, and outliers, for corals reefs, seagrass, mangroves, saltmarshes, and oyster reefs. Median values are indicated by numbers. Restoration cost (US$ 2010/ha) and project area (ha) are represented on a logarithmic scale.

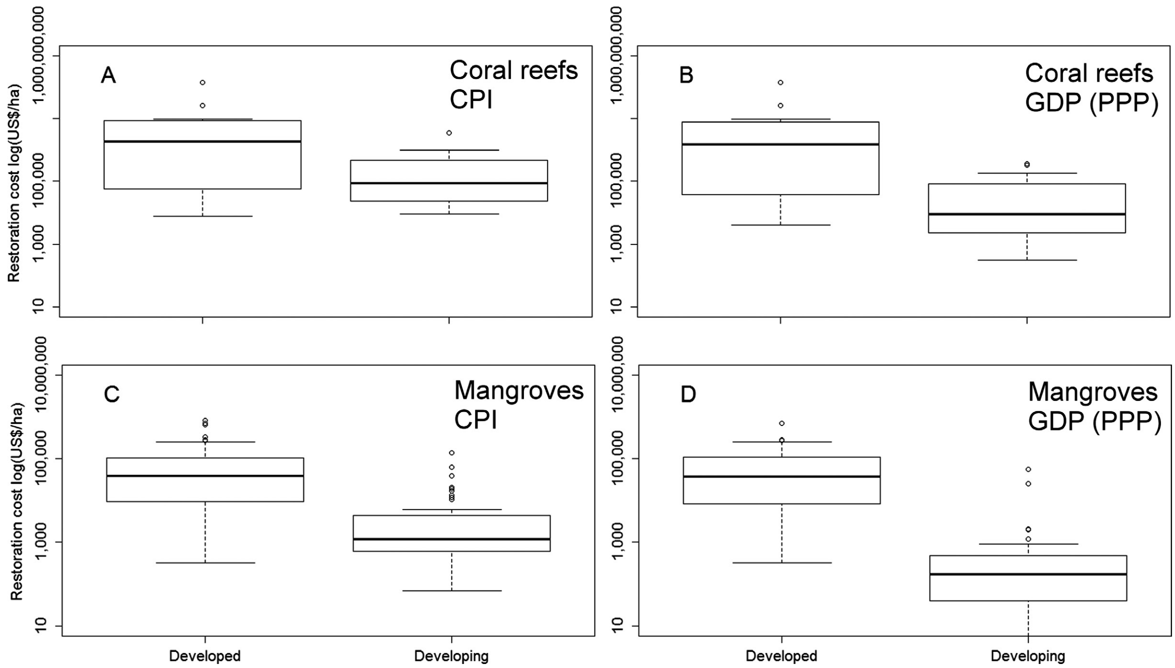

FIG. 2. Comparison between restoration of coral reefs and mangroves reported for countries with developed and developing economy. Costs for coral reefs restoration are shown as (A) CPI-converted and (B) GDP (PPP)-converted values; and for mangroves (C) and (D), respectively.

(PPP), total restoration costs were 11 and 226 times lower in developing countries compared to developed countries for corals reefs and mangroves, respectively (Table 1).

An evaluation of the information provided in the Acknowledgements section of primary literature studies suggested that most funding for restoration was provided by government, mostly financing small-scale research projects. The next most abundant projects were financed partly by government and a non-governmental organization (NGO; Appendix S1: Table S6).

The feasibility of marine coastal restoration

Of all observations on marine coastal restoration, 61% provided information on survival of restored organisms as an item-based success indicator (Appendix S1: Table S1). Median survival was 64.5% for coral reefs, 38.0% for seagrass, 51.3% for mangroves, 64.8% for saltmarshes, and 56.2% for oyster reefs (Table 2). A frequency distribution of the number of observations and survival of restored organisms showed that while the number of studies reporting on successful coral reef restoration was high (tendency towards high survival > 70%), the observations of seagrass restoration had highest frequency at 0–5% survival (Fig. 3). For mangroves, saltmarsh, and oyster reefs the frequency distribution of survival rates had no clear peaks, with a range of survival rates observed (Fig. 3).

Cost-survival and effectiveness analyses

There was no significant relationship between percent organism survival and overall project cost per unit area for all ecosystems combined, or for coral reefs, seagrass, saltmarsh, or mangroves individually (Fig. 4). An analysis could not be performed for oyster reefs because only one single observation provided data on both cost and survival

TABLE 2. Success of restoration projects for coral reefs, seagrass, mangroves, saltmarshes, and oyster reefs.

Ecosystem	Economy	*N*	Success (% survival)
Coral reefs	Overall	293	64.5
	Developed	110	56.8
	Developing	112	68.3
Seagrass	Overall	141	38.0
	Developed	114	41.3
	Developing	27	11.0
Mangroves	Overall	106	51.3
	Developed	38	56.3
	Developing	68	44.7
Saltmarshes	Overall	28	64.8
	Developed	28	64.8
	Developing	…	…
Oyster reefs	Overall	64	56.2
	Developed	64	56.2
	Developing	…	…

Notes: Restoration success is represented by (%) survival of restored organisms. Data are shown as overall observations as well as projects in countries with developed and developing economies. The number of observations is indicated by *N*, while ellipses imply that no observations were available. For coral reefs, overall survival included 17 observations for which no project location or type of economy were indicated.

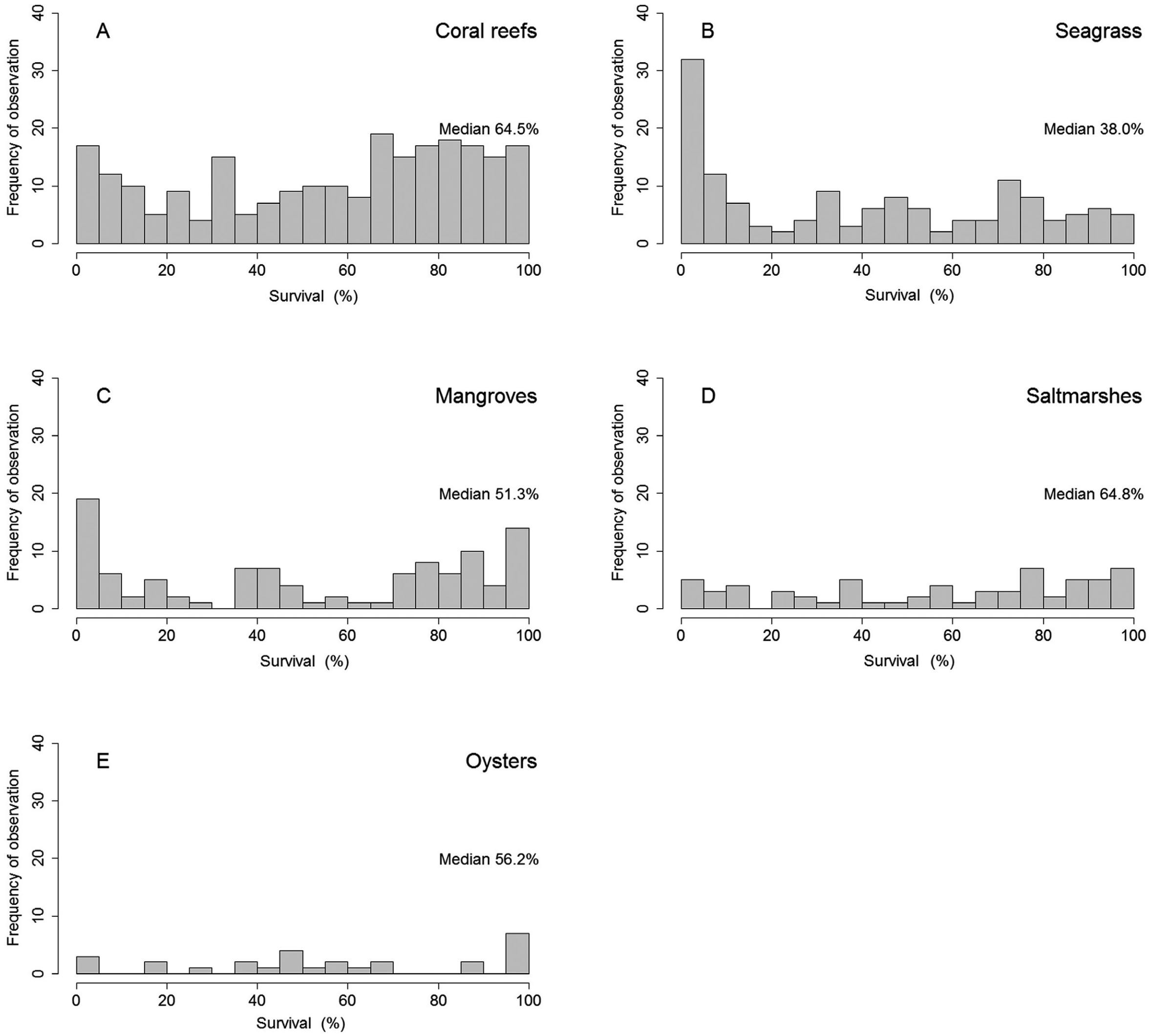

FIG. 3. Frequency distribution of restoration success (in % survival of restored organism) for (A) coral reefs, (B) seagrass, (C) mangroves, (D) saltmarshes, and (E) oyster reefs. Median values and observations are indicated by numbers.

(Fig. 4). Likewise, there was no relationship between percent survival and project duration (Appendix S1: Fig. S3).

Analysis on cost-effectiveness was only possible for 11% of all observations: those which provided information on cost, area, and survival, and these can be found in Appendix S1: Table S8. Analysis was not possible for oyster reefs because of insufficient data. The most cost-effective coral reef restoration projects were those where coral reef fragments were transplanted from donor colonies to a degraded reef, estimated at US$11717/ha in a developing country. In contrast, the least cost-effective approach for coral reef restoration used a combination of stabilizing substrate and transplantation of fragments (estimated at US$2879773/ha in a developing country). The most cost-effective seagrass restoration project was the transplantation of seagrass cores or plugs (US$29749/ha in a developed country), while the least cost-effective project used mechanical transplantation of seagrass (US$1196896/ha in a developed country). For mangroves, the most cost-effective project was planting of seeds, seedlings, or propagules (US$786/ha in a developing country), while the least cost-effective project used a combination of planting and construction (estimated at $US749215/ha in a developed country). Overall, restoration of saltmarshes was the least cost-effective among investigated ecosystems. The most cost-effective saltmarsh restoration project was estimated at US$1036956/ha for construction, clearing of exotic vegetation, and planting saltmarsh plants. The least cost-effective saltmarsh restoration project, estimated at US$112695652/ha, used hydrological restoration and planting of saltmarsh plants (Appendix S1: Table S8).

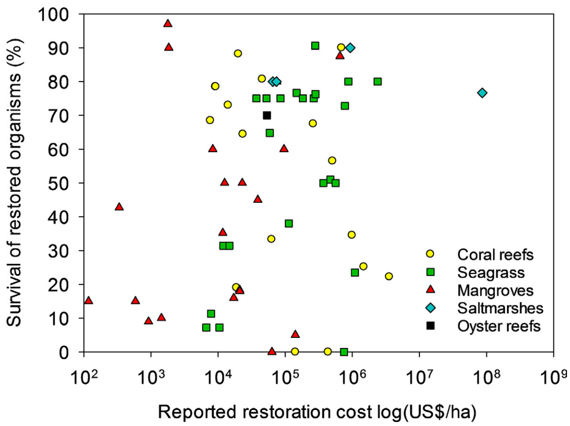

Fig. 4. Cost–survival relationship for the restoration of coral reefs, seagrass, mangroves, saltmarshes, and oyster reefs. Restoration costs (US$ 2010/ha) are displayed on a logarithmic scale.

Cost-area analyses, economies of scale

Total restoration cost (including capital and operating cost) per unit area remained constant for coral reefs and seagrass as the size of the project increased, indicating that economies of scale did not occur (Fig 5). However, project size tended to be small (<1 ha for coral reefs and <10 ha for seagrass; Fig 3), and it is possible that this relationship would change if larger project areas were examined. For mangroves, saltmarshes, and oyster reefs, restoration cost per unit area had a non-significant linear regression with increasing project area (Fig. 5). There were fewer studies for oyster reefs than for mangroves and saltmarshes (Fig. 5). Large-scale restoration efforts of more than 10 ha were documented for mangroves with areas of up to 120000 ha (e.g., Erftemeijer and Lewis 1999). For saltmarshes, most restoration projects had a target area between one and 10000 ha.

The most successful ecological restoration projects

There were only 13 restoration projects (2% of all observations reporting on survival) with a duration of ≥5 yr and ≥85% survival of restored organisms that were classified as highly successful (sensu Roebig et al. 2012). The 27 most successful restoration projects achieving ≥85% irrespective of project duration are summarized in Table 3.

For coral reefs, restoration projects achieving survival of ≥85% irrespective of project duration were those that used coral gardening or coral farming techniques (43% of all observations reporting on survival), transplantation of coral colonies or fragments from donor colonies (53% of all observations reporting on survival), and those that cultured corals or used coral "seeding", i.e., out-planting of juvenile corals to the reefs (4%). Only one coral restoration project could be considered as highly successful (Table 3). This project was conducted in the Philippines and used coral gardening (Table 3).

For seagrass, the restoration projects reporting highest survival used a range of techniques, including transplantation of seagrass seedlings, sprigs, shoots, or rhizomes (57% of all observations on survival), transplantation of aquacultured seagrass (11% of all observations on survival), deployment of Hessian bags (11% of all observations on survival), and transplanting seagrass cores or plugs (10% of all observations on survival). Only two highly successful studies were reported, and these used manual transplantation of *Posidonia australis* shoots in a sheltered bay in southern Western Australia (Table 3).

Techniques in mangrove restoration that achieved survival rates of more than 85% were those where the facilitation of natural mangrove recovery was achieved through planting of seeds, seedlings, or propagules (72% of observation on survival), planting of saplings or small trees (11% of observation on survival), reconversion of aquaculture ponds to mangrove habitat (9% of observation on survival), and hydrological restoration (5% of observation on survival). Only two studies were highly successful (Table 3). One of the studies monitored mangroves planted after hydrological restoration, whereas the other facilitated natural recovery of mangroves by clearing invasive plants, removing dredged material, recontouring the site to intertidal elevations favourable for mangroves, excavating tidal creek systems to enhance flushing, and planting of smooth cord grass to trap mangrove seeds at high tide from adjacent forests in Florida (Table 3).

The most successful saltmarsh restoration projects used construction and planting of saltmarsh plants (39% of observations on survival), as well as planting saltmarsh seeds, seedlings, or sods (56% of observations on survival). Three studies reported highly successful saltmarsh restoration (Table 3). Two of these projects involved construction, excavation of the restoration site, and subsequent backfilling with clean soil, as well as planting of saltmarsh plugs, and the other project monitored differences between restored and reference sites (Table 3).

For oyster reefs the establishment of no-harvest sanctuaries for oysters created by natural or artificial substrate (30% of all observations reported on survival) and transplanting juvenile oysters obtained from hatchery to the reefs (18% of all observations reported on survival) achieved ≥85% survival of restored oysters (Table 3). The only highly successful oyster reef study described the establishment of several oyster reef sites in no-harvest sanctuaries in North Carolina (Table 3).

Challenges and failures of marine coastal restoration

Restoration project failure (≤10% survival of restored organisms) occurred for a number of reasons which varied among the different ecosystems (Table 4).

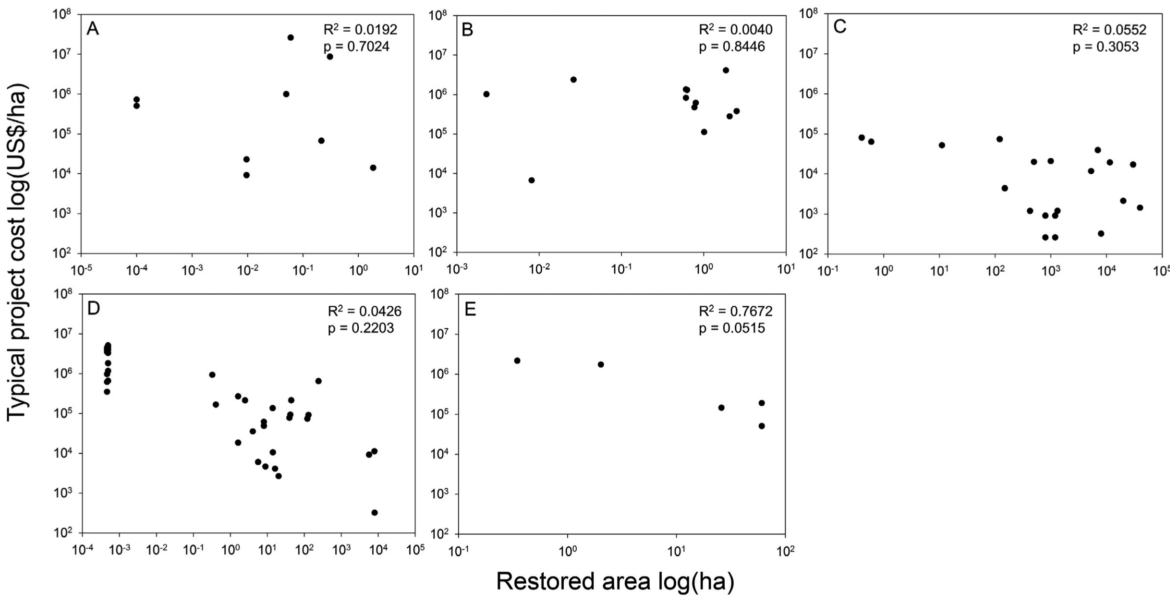

FIG. 5. Relationship between total cost per unit area and area restored for the restoration of (A) coral reefs, (B) seagrass, (C) mangroves, (D) saltmarshes, and (E) oyster reefs. Cost data, classified as total restoration cost per unit area in log (US$ 2010/ha), are displayed as function of area restored in log (ha). Results of linear regression analysis are displayed in the upper right corner of each diagram.

For coral reefs, low survivorship was related mainly to inadequate site selection (e.g., sites with high sedimentation rates or strong currents), unsuitable substrate for transplantation (e.g., sand or bamboo), or stochastic events (e.g., warm- or cold-water anomalies; Table 4). High mortality was reported for approaches that used culturing and seeding of coral spat or transplanting juvenile corals to degraded reefs. Project duration also influenced project failure, with a few studies reporting low transplant survival after 10 years (Table 4).

For seagrass, poor site selection was a very important factor influencing restoration failure. Restoration efforts often failed due to planting of seagrass shoots at high wave energy locations without anchoring, inappropriate anchoring, or planting at sites with high levels of sediment movement and erosion (Table 4). The type of transplant also influenced failure rates, with transplantation of seeds often leading to incomplete germination. In some cases, failure was caused by stochastic events (e.g., flood damage or severe storms). Further reasons for failure were illegal trawling activities, marine contamination, and poor water quality. Inadequate seed storage procedures were identified as detrimental in one study. Areas impacted by several anthropogenic factors, such as thermal stress due to a power plant, cement tailings, oil contamination, discharge from saline ponds, or impacts associated with close proximity to a river mouth, were described as unsuitable for seagrass restoration (Table 4).

Mangrove restoration often failed when planting of collected seeds, seedlings, propagules, or saplings occurred within habitats which would not support their natural recruitment (e.g., mudflats or abandoned shrimp ponds where the tidal regime is unsuitable). Additionally, planted mangroves were typically damaged by barnacles, filamentous algae, and sedimentation. A lack of community involvement also led to failure of mangrove restoration efforts as people damaged restoration sites (e.g., trampling by local fishermen; Table 4).

In saltmarshes, rates of survivorship were strongly dependent on the species used and whether locally collected native or imported saltmarsh plants were planted. Locally collected species typically had higher transplant survival. Planted saltmarsh seedlings were particularly sensitive to multiple stressors including high salinity, sediment deposition, algal smothering, and animal activity (e.g., grazing; Table 4).

There were only few studies explicitly reporting on the failures or lessons learned from oyster reef restoration. Failure was documented where sites were unsuitable such as sites with sandy-bottoms which resulted in burial of oyster shells, or sites with high-energy flow regimes. Often, buried oysters were reported as overgrown by tunicates, bryozoans, barnacles, and small mussels (Table 4).

DISCUSSION

Restoration of marine coastal ecosystems is required for social, economic, and ecological purposes. This study provides the first comprehensive review of cost and feasibility of marine coastal restoration projects for five important ecosystem: coral reefs, seagrass, mangroves, saltmarsh, and oyster reefs. We identified a wide range

Table 3. Restoration projects achieving ≥85% survival.

Ecosystem	Restoration action	Cost (US$ per ha)	Duration (yr)	Literature
Coral reefs	Coral fragments grown in a bottom nursery; monitoring and maintenance protocol performed monthly; out-planting of corals to the reef not taken into account	3,993	5	Shaish et al. (2008)
	Deployment of artificial reef structures; transplanting fragments from donor colonies	…	≤1	Villanueva et al. (2010), Tortolero-Langarica et al. (2014)
	Deployment of artificial reef structures; transplanting of whole colonies	…	4	Edwards and Gomez (2007)
	Ex situ coral cultivation (sexual propagation) and out-planting of juvenile corals	…	≤3	Rinkevich (2005), Omori et al. (2007)
	Coral farming facilitated by electrical field	…	0.3	(Borell et al. 2009)
	Crowing corals in in situ nurseries	…	≤3	Epstein et al. (2001), Putchim et al. (2008), Ferse and Kunzmann (2009), Levy et al. (2010), Johnson et al. (2011), Griffin et al. (2012), Pizarro et al. (2012), Schopmeyer et al. (2012), Calderon et al. (2015), Ng and Chou (2014)
	Growing corals in in situ nurseries and out-planting	…	1	Bowden-Kerby and Carne (2012)
	Transplantation of nursery grown corals	…	≤0.5	Edwards and Gomez (2007), Lirman et al. (2010)
	Transplanting fragments from donor colonies	…	≤1.5	Bowden-Kerby (2001), Gleason et al. (2001), Yeemin et al. (2006), Omori (2010), Gomez et al. (2014), Oyamada et al. (2014)
	Transplanting of whole coral colonies	6,91,224*	≤2.3	Edwards and Clark (1999), Gleason et al. (2001), Rinkevich (2005), Yeemin et al. (2006), Edwards (2010), Ngai et al. (2013)
Seagrass	Transplanting seagrass (seedlings, sprigs, shoots, or rhizomes)	…	≥5	Bastyan and Cambridge (2008), Ganassin and Gibbs (2008)
	Aquaculture and transplanting (seagrass seeds, seedlings, or rhizomes)	…	≤1.5	Balestri and Lardicci (2012, 2014)
	Deployment of hessian bags	…	1.1	Collings (2008)
	Transplanting seagrass (cores or plugs)	32,348*	≤1.3	Thorhaug (2001), Ganassin and Gibbs (2008)
	Transplanting seagrass (seedlings, sprigs, shoots, or rhizomes)	…	≤1	Ganassin and Gibbs (2008), Tanner et al. (2014)
Mangroves	Hydrological restoration: facilitation of a natural recovery	…	5	Lewis (2005)
	Planting mangroves (seeds, seedlings, or propagules)	…	11	Proffitt and Devlin (2005)
	Habitat conversion, planting	…	≤0.5	Toledo et al. (2001)
	Planting mangroves (saplings or small trees)	…	<2	Teas (1977), Goforth and Thomas (1979), Ainodion et al. (2002)
	Planting mangroves (seeds, seedlings, or propagules)	1,821	≤3	Teas (1977), Teas et al. (1989), Ainodion et al. (2002), SER (2007*a*), Primavera and Esteban (2008)
	Planting mangroves (seeds, seedlings, or propagules), construction	6,55,563	0.5	Sosnow (1986)
Saltmarshes	Construction, excavation and backfilling with clean soil, as well as planting of saltmarsh-plants containing plugs	9,33,260*	≤13	Dawe et al. (2000), SER (2012)
	Comparison of restored with reference saltmarsh	…	15	Staszak and Armitage (2013)
	Construction, planting saltmarsh	…	≤3.5	Lindig-Cisneros and Zedler (2002), Zedler et al. (2003)
	Planting saltmarsh (seeds, seedlings, or sods)	…	≤1	Anastasiou and Brooks (2003), Konisky and Burdick (2004), Armitage et al. (2006), Castillo and Figueroa (2009)
Oyster reefs	Creating a no-harvest sanctuary with natural or artificial substrate	…	>5	Powers et al. (2009)
	Hatchery rearing of native oysters (and seeding)	…	<0.5	Zarnoch and Schreibman (2012)

Notes: Restoration costs are given in (2010 US$ per ha) and project duration is provided in years (yr). Cases represented by only one observation providing information on cost are indicated by asterisks. Ellipses denote data were not available.

TABLE 4. Summary of failures (≤10% survival of restored organisms) in marine coastal restoration..

Ecosystem	Restoration Action	Duration (yr)	Area (ha)	Reasons for failure	Literature
Coral reefs	Deployment of artificial reef structures; transplanting fragments from donor colonies	…	0.025	Rapid rise in seawater temperature	Fadli et al. (2012)
	Ex situ coral cultivation (sexual propagation) and out-planting of juvenile corals	<1	0.003	Lack of knowledge on the factors that influence early post-settlement mortality of juvenile corals	Cooper et al. (2014)
	Growing corals in ex situ nurseries	<1	…	Low survivorship of juvenile corals in the reef	Edwards and Gomez (2007)
	Growing corals in nurseries	≤2	<1	Low survivorship of juvenile corals; damage on donor colonies by pruning; cold-water anomaly	Epstein et al. (2001), Ferse and Kunzmann (2009), Bongiorni et al. (2011), Johnson et al. (2011), Schopmeyer et al. (2012)
	Stabilizing of substrate	3	0.0001	Small-scale treatments broke apart or were scattered by strong water currents or buried by rubble after 2.5 Yr	Fox et al. (2005)
	Transplanting fragments from donor colonies	<2	…	Size-dependent survivorship of fragments; inadequate substrate (bamboo); coral bleaching; algal growth; physical loss of fragments	Edwards and Clark (1999), Bowden-Kerby (2001), Quinn et al. (2005), Ferse (2010), Williams and Miller (2010)
	Transplanting fragments from donor colonies	10–12	<3	Only a small number of transplanted colonies were alive after 10–12 yr	Edwards (2010), Garrison and Ward (2012)
	Transplanting of whole coral colonies	1	…	Inadequate site selection: high-sedimentation at restoration site	Ammar et al. (2000)
Seagrass	Aquaculture and seeds germination	…	…	No survival of plants from germinated seeds at ambient laboratory temperature	Christensen et al. (2004)
	Aquaculture and transplanting (seagrass seeds, seedlings or rhizomes)	<1	…	Seedlings attached to nylon nets or hessian bags had low survival	Irving et al. (2010), Zarranz et al. (2010)
	Aquaculture and transplanting (seagrass seeds, seedlings or rhizomes)	3	15.4	Poor water quality and ineffective seed storage	SER (2007*b*)
	Aquaculture and transplanting (seagrass seeds, seedlings or rhizomes); anchoring	<1	0.002	Physical loss of transplants	Bird et al. (1994)
	Hessian bags	≤3	…	Mortality due to breakdown of hessian bags and wave-exposure	Collings et al. (2007), Wear et al. (2010)
	Transplanting seagrass (cores or plugs)	≤3	<1	Inadequate site selection: sediment movement; project abandoned due to flood damage	Ganassin and Gibbs (2008)
	Transplanting seagrass (seedlings, sprigs, shoots, or rhizomes)	<3	<1	Not anchored plants were lost in the first winter after planting; inadequate site selection with sand as substrate and high wave energy; severe storms destroyed the transplants; transplantation efforts destroyed by illegal trawling activities and marine contamination; multiple stressors: thermal stress due to a power plant, cement tailings, oil contamination, discharge from saline ponds, close proximity to a river mouth	Thorhaug (1985), Meehan and West (2002), McNeese et al. (2006), Bastyan and Cambridge (2008), Ganassin and Gibbs (2008), Oceana (2010)

(Continued)

Table 4. Continued

Ecosystem	Restoration Action	Duration (yr)	Area (ha)	Reasons for failure	Literature
	Transplanting seagrass (shoots or sprigs); anchoring	<0.5	…	Mortality due to covering with sand; use of inadequate anchoring system; heavy swell conditions and commercial hauling across the transplant site	Thorhaug (1983), Meehan and West (2002), Ganassin and Gibbs (2008)
	Transplanting seagrass by peat pot method	1	0.157	Not specified	Bologna and Sinnema (2012)
	Transplanting seagrass seeds	<1.5	<1	Inadequate site selection: heavily disturbed site; low seeds survival	Thorhaug (1985), Christensen et al. (2004)
	Transplanting seagrass sprigs and hessian bags	0.7	…	No survival of springs due to hessian bag matting	Irving et al. (2010)
Mangroves	Hydrological restoration: facilitation of a natural recovery, planting	4.0	0.2	Inadequate site selection: planted seedlings were damaged by high tides and waves	Motamedi et al. (2014)
	Planting mangroves (saplings or small trees)	≤3	…	Planting site was destroyed; mangrove trees were planted too deeply into the water of the soft dredge-spoil which submerged the trees;	Teas (1977), Ainodion et al. (2002)
	Planting mangroves (seeds, seedlings, or propagules)	≤1.5	<54	Planting site was destroyed; inadequate elevation of planted mangroves; tidal inundation; seedlings washed away by strong flood waters from a creek; tidal flooding; anthropogenic factors such as garbage, digging up of substrate and trampling by fishers; barnacles, filamentous algae and sediments damage following inundation; inadequate site selection: planting of mangroves at oiled sites	Teas (1977), Teas et al. (1989), Day et al. (1999), Lewis (2001), Ainodion et al. (2002), Primavera and Esteban (2008)
	Planting mangroves (seeds, seedlings, or propagules)	21	256	Failure due to low temperature in winter	Chen et al. (2009)
	Planting mangroves (seeds, seedlings, or propagules) on mudflats	0.8–5	≤40000	Failure due to uprooting by strong waves, sun scorching, barnacle infestation, inability to produce new roots; infestation with barnacles; mudflats were classified as unsuitable for mangroves planting	Erftemeijer and Lewis (1999)
	Planting mangroves (seeds, seedlings, or propagules), construction	1.0	0.6	Infestation with barnacles, active sedimentation, and fishermen disturbance on site	Hashim et al. (2010)
Saltmarshes	Construction, planting saltmarsh	2.0	8	Multiple stresses caused plant mortality: high salinity, sediment deposition, algal smothering and animal activity	Zedler et al. (2003)
	Growth measurements at oil spill impacted site	3.0	0.260	Saltmarsh plants were severely impacted by oil spill	Bergen et al. (2000)
	Planting saltmarsh (seeds, seedlings, or sods)	<2.5	<1	Locally collected saltmarshes had a higher survival than imported plants; intolerance of saltmarsh plants to saline flooding	Burchett et al. (1998), Konisky and Burdick (2004), O'Brien and Zedler (2006), Beck and Gustafson (2012)
Oyster reefs	Establishing a no-harvest sanctuary at reefs created by natural or artificial reef substrate	<9	…	Inadequate site selection due to sandy-bottom and burial of oysters, energetic flow regime, overgrowth by tunicates, bryozoans, barnacles, and small mussels	Powers et al. (2009)

Notes: Project duration is provided in years (yr) and restored area is given in hectare (ha). Ellipses denote data were not available.

of costs and success rates for marine coastal restoration projects, which depended on the ecosystem type, geographic location, and approach used.

Cost of restoration

Our review shows that the cost for marine coastal restoration projects depends on the ecosystem restored, the economy of country where the restoration projects were carried out, and on the restoration technique applied. While the overall reported median and average costs for restoration of one hectare marine coastal habitat were around US$80000 (2010) and US$1600000 (2010) respectively, the real total costs are likely to be two to four times higher if both capital and operating costs are included, increasing costs (median) to US$150000–400000/ha (2010).

Unfortunately, not all studies provided cost data in a comprehensive manner. It was often not possible to split the available cost information into capital and operating costs, or to account for the different components of restoration (planning, purchasing, land acquisition, construction, financing, maintenance, monitoring, and equipment repair/replacement). Despite the incomplete nature of cost data, our values are similar to the cost reported by 13 studies on restoration of coastal ecosystems with a range of US$250000–500000/ha (in 2007), which were compiled by a recent review examining the benefits of restoration (De Groot et al. 2013). However, where their study examines data for several systems combined, the present study distinguishes between the different types of marine coastal ecosystems, providing a more comprehensive synthesis based on a higher number of restoration studies.

The restoration of mangroves was a special case for which the least amount of funding was spent. Our median total restoration costs for mangroves of US$3000/ha (2010) are below the range estimated for the restoration of coastal wetlands of US$11000–530000/ha (2007) based on seven studies (De Groot et al. 2013). The relatively low cost of mangrove restoration is likely to be related to the high number of community- and volunteer-based projects, the high availability of mangrove seeds, seedlings, and propagules, and also possibly due to the relative accessibility of mangrove restoration sites (Adame et al. 2015).

Restoration of marine coastal ecosystems is more expensive than for other ecosystems. The total (median) cost estimates for marine coastal restoration presented here are 10–400 times higher than the maximum cost reported for the restoration of inland wetlands (US$40000/ha, 2007), freshwater systems (US$16000/ha, 2007), tropical (US$7000/ha, 2007) and temperate forest (US$3000/ha, 2007), woodlands (US$1000/ha, 2007), and grasslands (US$1500/ha, 2007; De Groot et al. 2013). The upper range of total cost reported for marine coastal restoration in the present study are up to eight times higher than the maximum costs estimated by conservation organizations for acquisition and management of terrestrial protected areas of US$10000–50000/ha (2012; Armsworth 2014). Thus, compared to terrestrial ecosystems marine coastal ecosystems, particularly coral reefs, seagrass, and oyster reefs, are more expensive to restore.

The feasibility of marine coastal restoration

Surprisingly, survival of restored organisms was not related to cost. Rather, restoration success (defined as survival) varied for the different ecosystems (e.g., restoration success of seagrass was low, while for coral reefs and saltmarshes it was higher) and restoration techniques (e.g., transplanting of adult colonies was more successful than out-planting of coral larvae or juveniles). Causes of restoration failure, which was likely underreported (Hobbs 2009, Knight 2009, Suding 2011), were mainly linked to inadequate site selection, stochastic events, or human disturbance. In general, unsuitable sites were characterized by altered hydrological conditions, high wave and flow energy, and inadequate substrate. Historical reports on the presence of ecosystem may provide guidance on whether the site is suitable for restoration (Precht and Robbart 2006, van Katwijk et al. 2009). Before starting any restoration action, the abiotic conditions, and whether these could support the marine coastal ecosystem must be known and well understood (Laegdsgaard 2006, Precht and Robbart 2006). In contrast to marine coastal ecosystems, restoration success in the terrestrial environment was positively correlated with investment (Ruiz-Jaen and Aide 2005). In terrestrial ecosystems, restoration techniques are sufficiently advanced such that high levels of investment are rewarded (Ruiz-Jaen and Aide 2005). Currently this appears not to be the case in marine coastal ecosystems, although as restoration science in marine systems matures larger investments may achieve relatively larger gains. Both the dynamic nature of marine coastal ecosystems, which are inundated by seawater and often experience large fluctuation in wave energy and other environmental conditions, and the nature of the organisms (e.g., corals are invertebrates with limited environmental tolerances) contribute to the challenges of restoration in marine coastal habitats.

Success in restoration of marine coastal ecosystems was assessed as short-term survival rates, while success in terrestrial ecosystems was mainly assessed by measurement of the diversity, vegetation structure, or ecological processes (Ruiz-Jaen and Aide 2005). The focus on survival indicates that restoration science in marine coastal ecosystems is still in an early phase. Clearly, restoration of marine coastal ecosystems is feasible, although expensive, with room for improvement in restoration techniques and in the monitoring of the effectiveness/success of projects. We observed a large range in survival rates indicative for success which mainly differed based on ecosystem with higher success rates for coral reefs and saltmarshes, and lowest for seagrass. This is in agreement with previous studies reporting on the challenges related to seagrass restoration (Fonseca 2006, 2011, Ganassin and Gibbs 2008, van Katwijk et al. 2009, Cunha et al. 2012).

How much and where to restore

One of the primary aims of marine coastal restoration efforts is the delivery of ecological goods and services (SER 2004, Grabowski and Peterson 2007, Rey Benayas et al. 2009, Barbier et al. 2011, De Groot et al. 2013). To achieve this goal consistently, the costs and feasibility of restoration projects over relevant spatial scales must be reliably estimated. For most marine coastal ecosystems, only small-scale restoration projects have been reported of a few hectares or less while the scales of anthropogenic degradation are in the order of 10–1000000 ha (Edwards and Gomez 2007). In 2006, a study reported that restoration research on coral reefs had been focused on the development of techniques (Zimmer 2006) rather than on assessing the application of established methodologies in large-scale restoration projects. Our review indicates that little has changed since 2006 and many studies are still small scale and experimental. However, to achieve no net loss of coastal habitats (e.g., biodiversity offset policies (Maron et al. 2012, Bull et al. 2013, Bell et al. 2014, and Bell et al. 2014) the scale of restoration of coastal marine ecosystems should at least match the scale of degradation. To date, only restoration of mangroves in marine coastal systems has been reported for larger areas of up to 120000 ha. But these projects are not always successful. Efforts over 20 years at a cost of over US$17.6 million in the Philippines were used to restore 44000 ha of mangrove forest, which largely failed with only 10% gain in mangrove habitat (Samson and Rollon 2008, Lewis 2009). No doubt large scale restoration projects are urgently needed to achieve socioeconomic benefits of ecosystem services delivery (De Groot et al. 2013).

Restoration of coral reefs and mangroves was significantly less expensive (up to 30 times) in countries with developing compared to developed economies. However, we assume that we could not account for all restoration projects in developed countries due to a lower incentive to publish and report eventually leading to a reporting bias with a strong impact on restoration costs. Sharma et al. (2010) presented a correlation between the level of development and the level of disclosure and reporting of restoration projects. When accounting for the local values of U.S. dollar in developing countries, the costs for restoration would be up to 200 times less than in developed countries. If projects involve a consensus and integration of local communities and stakeholders, (e.g., Brown et al. 2014), marine coastal restoration can be most cost-effective in countries with developing economies. Many developing countries have some of the largest extents of the marine coastal habitats assessed in this study, high levels of diversity and endemism (e.g., Indonesia), and large populations reliant on delivery of goods and services from marine systems. Thus investment in restoration in developing countries is likely to be beneficial for both the environment and society. However, despite potentially low cost-effectiveness of restoration in developing countries, corruption and fraud often afflicts restoration projects in those countries, and there is an urgent need to reform financial governance to foster investor's confidence in conservation efforts and help alleviate poverty among local communities (Barr and Sayer 2012).

Project duration

Most restoration projects in our database had a duration of no more than one to two years corresponding to the lifetime of development projects, research grants, or academic theses. The short project duration of marine coastal restoration projects have been criticized as being unsuitable to assess recovery of ecosystem function (Kaly and Jones 1998) and that the outcome of restoration (success or failure) is directly related to the period of observation (e.g., for seagrass restoration; Bell et al. 2014). Depending on the degree of disturbance and nature of the ecosystem, full recovery may take decades to centuries (Clewell and Aronson 2007). For example, mangroves require at least 20–25 years to reach maturity (Lugo and Snedaker 1974, Odum 1975) with natural succession occurring over periods of 15–30 years if hydrology has not been disrupted and supply of natural propagules is provided (Field 1998, Lewis 2005). Research and monitoring of restored sites over longer time periods is necessary to assess the long-term success of restoration projects and should be embraced by investors in marine coastal restoration.

Conclusions and Lessons Learned

The present literature synthesis showed that there are four main criteria for marine ecosystem restoration projects to achieve success: (1) understanding of ecosystem function (e.g., physical and biological conditions required for the ecosystem to thrive), (2) removal of the anthropogenic stressors that impede natural regeneration (e.g., pollution, eutrophication, altered hydrology, physical damage), (3) clearly defined criteria for the measurement of restoration success, and (4) long term monitoring of 15–20 years rather than <5 years. Further, highly effective marine coastal restoration projects typically involved the community in the restoration actions, transferred knowledge among scientists, practitioners, community members, and administrative organisations (including lessons learnt from failures), and included a broad range of stakeholders in the decision-making process (Bernhardt et al. 2007, Suding 2011, Brown et al. 2014).

The following points summarize what we have learned from data synthesis of available literature and suggest the direction for future research in marine coastal restoration.

(1) Most marine and coastal restoration projects have focused on developed countries and in particular Australia, Europe, and USA. Data from developing countries are urgently needed, in particular for seagrass, saltmarsh, and oyster reefs, given that large numbers of people rely directly on the goods and services provided by these systems.
(2) Investment in restoration projects in developing countries can achieve up to 30 times more unit area of habitat in developing countries compared to developed countries. When accounting for the local value of the U.S. dollar in developing nations cost incurred for restoration is lower by up to 200 times. Given a fixed cost of investment, projects in developing countries will result in the greatest area of habitat.
(3) Mangroves were the least expensive ecosystem to restore, whereas corals were the most expensive. Reasons for the low-cost nature of restoration of mangroves are likely related to the high numbers of community- or volunteer-based projects, the availability of wild mangrove seeds, seedlings, or propagules, and relatively easier access to restoration sites. Given a fixed cost of investment, mangrove restoration will yield the largest area of restored habitat among the five ecosystems assessed.
(4) The majority of funding for published marine coastal restoration projects has been financed by governmental or non-governmental organisations (NGO). This was reflected by typically small-scale experimental research projects rather than large-scale restoration projects. Partnerships among government and other private, community, or NGO entities and development of markets for ecosystem services may provide opportunities for enhanced investment (Murtough et al. 2002).
(5) The majority of studies reported item-based success in terms of survival and lacked clearly defined and measurable success. Where criteria for success were stated explicitly, they typically aimed for simple metrics, such as a particular level of biomass or coverage, and rarely focused on the recovery of ecosystem function or services. Granted, the latter is a much more challenging task, but where possible should be the ultimate aim of ecological restoration.
(6) Restoration projects in saltmarshes and coral reefs reported the highest survival rates of around 65%, while seagrass restoration projects had lowest survival rate of 38%. Survival rates of restored organisms varied considerably within and among all ecosystems and projects, and complete failures were common. Often inadequate site selection caused project failure despite the restoration technique being effective elsewhere. We cannot rule out the possibility that most published literature is likely to be biased towards successes rather than failures and many of the lessons learned have been undocumented. Therefore, we suggest that all projects report on cost, success, and habitat area, including those projects that fail completely. The database of this manuscript can serve as a specific template on how to report cost and feasibility of marine coastal restoration projects.
(7) Project duration was generally limited to only one to two years, which is not sufficient to allow for evaluation of full recovery. Projects should be longer (15–20 years) and specifically measure parameters that describe ecological recovery of the ecosystem (including vegetation structure and diversity) as well as the associated functions (including ecological processes) and services (see point 5).
(8) The largest restoration project areas were observed for mangroves, while coral reef and seagrass restoration projects were focused only on small-scale, experimental restoration research. For restoration in marine systems to be used as a tool for conservation, restoration projects will need to be conducted and to succeed over larger spatial scales to match the scale of anthropogenic degradation of ecosystems (10–1000000 ha).
(9) There was no clear relationship between the costs spent and success of marine coastal restoration projects. We suggest this reflects a necessity of maturation in the science of restoration in marine coastal ecosystems compared to terrestrial ecosystems, likely influenced by the relatively high logistical challenges involved in working in marine environments. At present, the data suggest that increasing the amount of investment in a project will not necessarily improve its likelihood of success. Instead, careful consideration of site selection and restoration technique are likely to be the most important factors determining success.
(10) There was no evidence for economies of scale in studies reporting on total restoration costs. This suggests that restoration techniques are not yet sufficiently robust to such that larger investments lower cost per unit effort. Further studies will be required to achieve a transition from small-scale to large-scale restoration of marine coastal ecosystems.

This study synthesizes knowledge to data on the cost and feasibility of ecological restoration in marine coastal ecosystems and identifies a number of gaps in current knowledge. Critically, best practice protocols should be developed that include criteria for reporting on monitoring activities to identify the most cost-efficient restoration techniques and avoid project failure. As restoration is increasingly used to offset the impacts of development and industrial activity, it is important to close knowledge gaps of restoration cost and success, and to improve the reporting on current projects. Optimal conservation outcomes in the future will require both protection and restoration (Possingham et al. 2015), depending on their relative costs, the rate at which habitat is being lost, and the time required between restoring a habitat and recovery of its ecosystem services. The societal benefits achieved by restoring habitat can be high. Given that extinction and biodiversity loss rates are increasing (Worm et al. 2006) and that natural ecological recovery is often limited to non-existent, restoration may be a critical tool used to secure a sustainable future in coastal marine ecosystems.

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Supporting Information

Additional supporting information may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/eap.1294/suppinf

Data Availabilty

Data associated with this paper have been deposited in Dryad: http://dx.doi.org/10.5061/dryad.rc0jn