Coral reef restoration is an increasingly important part of tropical marine conservation. Information about what motivates coral reef restoration as well as its success and cost is not well understood but is needed to inform restoration decisions. We systematically review and synthesize data from mostly scientific studies published in peer-reviewed and gray literature on the motivations for coral reef restoration, the variables measured, outcomes reported, the cost per hectare of the restoration project, the survival of restored corals, the duration of the project, and its overall spatial extent depending on the restoration technique employed. The main motivation to restore coral reefs for the projects assessed was to further our ecological knowledge and improve restoration techniques, with coral growth, productivity, and survival being the main variables measured. The median project cost was 400,000 US$/ha (2010 US$), ranging from 6,000 US$/ha for the nursery phase of coralgardening to 4,000,000 US$/ha for substrate addition to build an artificial reef. Restoration projects were mostly of short duration (1–2 years) and over small spatial extents (0.01 ha or 108 m²). Median reported survival of restored corals was 60.9%. Future research to survey practitioners who do not publish their discoveries would complement this work. Our findings and database provide critical data to inform future research in coral reef restoration.

Key words: coral reef restoration, costs, motivations, project duration, project spatial extent, survival of restored corals

Implications for Practice

- Most published coral reef restoration research is focused on improving the restoration approach and answering questions of ecological concern.
- Coral reef restoration is feasible but can be costly depending on the site selected and technique applied.
- A standardized reporting on cost would benefit development of new projects.
- Reporting on the social and economic benefits of coral reef restoration is needed.
- There is likely a substantial knowledge and communication gap between scientific researchers and practitioners which needs to be breached to move the field of coral reef restoration forward.
- We need to know the cost for employing a specific technique and its likelihood for success in order to invest our money strategically and maximize the outcome.

Introduction

The world’s coral reefs are under threat from stressors such as destructive fishing practices, overfishing, coastal development, and water pollution (Burke & Spalding 2011). These stressors are exacerbated by climate change (Hoegh-Guldberg et al. 2007; Hughes et al. 2017), which will increase the frequency of severe coral bleaching events and reduce the extent of healthy and mature reef assemblages globally in the future (Frieler et al. 2012). Active restoration (the process of actively assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed; SER 2004) may be necessary when natural ecosystem recovery is precluded (Perrow & Davy 2002). Coral reef restoration is often regarded as a small-scale emergency action to buy time (Shaver & Silliman 2017) while we tackle climate change and poor water quality at larger spatial scales (Hughes et al. 2017; IPCC 2018). However, repeated restoration might be necessary to promote recovery of reefs...
after successive bleaching events. Under these circumstances, reefs providing sources for new coral larvae would play an important role in accelerating the recovery of damaged systems (Hock et al. 2017). In order to conserve coral reefs and maintain ecosystem functions in the face of external threats, we may even need to consider new interventions such as engineered habitats or assisted evolution (Anthony et al. 2017).

When assessing the published scientific literature, the specific objectives of coral reef restoration projects are dominated by investigating the biological response of corals to transplantation (Hein et al. 2017), yet the underlying motivations are unknown (Bernhardt et al. 2007; Aradóttir et al. 2013). Motivations for restoration are defined as “answers to the question of why ecosystems should be restored” (Clewell & Aronson 2006). Similar to restoration of other marine coastal ecosystems (Bayraktarov et al. 2016), publicly available data on the cost and success of restoration techniques are sparse and inconsistently reported (Edwards & Gomez 2007; Iacona et al. 2018). Given the recent investments in coral reef restoration globally, knowing the cost of employing a specific technique and its likelihood of success are essential for planning for and developing of new restoration projects.

In this article, we review and analyze empirical results from mostly peer-reviewed published coral reef restoration projects (including some gray literature and personal communications) to explore the motivations for the projects using the framework developed by Clewell and Aronson (2006) (and used in evaluating terrestrial restoration by Hagger et al. 2017) and the ecological, economic, and social outcomes measured according to Wortley et al. (2013). We report on coral reef restoration success by synthesizing a database (available online doi:10.5061/dryad.sv798dm) containing information on cost, survival, project spatial extent, and duration for projects employing six common coral reef restoration techniques.

**Methods**

**Data Collection**

We conducted a systematic literature search using Web of Science (Core collection; Thomson Reuters, New York, New York, U.S.A.) and Scopus (Elsevier, Atlanta, Georgia, U.S.A.) and the title search terms “(coral reef* OR coral*) AND restor*”, as well as “(coral reef* OR coral*) AND rehab*”. The search returned 141 studies spanning 27 years (1991–March 2018). An EndNote (Version X7.0.2; Thomson Reuters.) search was then performed within the full text using the search terms (cost* OR feasib* OR surviv*). Additional information was gathered by following on citations, personal communication with three practitioners, and inspecting diverse restoration databases and webpages. The systematic literature search returned 87 studies. Information on the restoration technique employed, cost per hectare of the restoration project, project spatial extent and duration, and survival of restored corals was extracted as “observations.” A data source may contain more than one observation, e.g. if a different coral species was examined or the restoration was carried out at multiple sites. Data from plots and figures were extracted graphically by using WebPlotDigitizer (https://automeris.io/WebPlotDigitizer/).

Data for costs and survival were calculated for the database as follows. Where only cost per coral colony was provided, calculations for the restoration cost per hectare were estimated by assuming a transplanting schedule with four coral colonies outplanted per m², or 40,000 coral transplants per hectare (Edwards & Gomez 2007) to convert cost per colony into cost per unit area. Based on a survival rate of restored organisms of 60.9%, 65,681 coral transplants would be required to populate 1 ha and yield 40,000 live corals. This median survival of restored corals was calculated from all observations reporting on survivorship in the database. Each survival value was averaged over the reported pre-transplant, transplant, and post-transplant survival per observation.

All reported costs were adjusted for inflation in each respective country based on consumer price index (CPI) to a base year of 2010 prices. Data required for economic conversion were downloaded from the World Bank Development Indicators (The World Bank 2019a, 2019b, 2019c). For a subset of countries, CPI data were unavailable, and these observations were excluded from further analyses, with the original data retained in the database for reference. If the CPI for a particular year was unavailable, CPI information for the next closest year to the year of data collection reported in the study was employed. If the study did not report the data collection year, the year preceding the publication date was used. For restoration costs incurred in 2018, the previous year CPI (2017) was used for conversion. For studies where local currencies were reported, 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 country’s inflation based on CPI to a base year of 2010 prices.

A second economic conversion was carried out to account for effects based on differences in the countries’ income. This conversion was based on the gross domestic product as a function of purchasing power parity (PPP). Therefore, we first converted U.S. dollar to the local value of one U.S. dollar in the developing country and then adjusted for inflation to obtain international dollar (Int$) at a base year of 2010 prices. The difference in cost from economic conversion based on CPI versus GDP (PPP) highlights the greater value (i.e. purchasing power) of one U.S. dollar relative to the official exchange rate of the foreign currency in countries with less developed economies.

**Motivations for Coral Reef Restoration**

For restoration motivations, variables measured, and reported outcomes, one set of response variables was extracted from primary studies (publications describing original research) where one study describes one restoration project. An exception was the study by Edwards and Gomez (2007), which contained information on five restoration projects. We searched within the abstract and the introduction of each study for the primary, secondary, and tertiary reasons for the restoration project using categories adopted from Clewell and Aronson (2006) and Hagger et al. (2017). Motivations for each coral reef restoration...
project were classified as idealistic (social, political, or cultural reasons seeking atonement for environmental degradation or reconnection with nature), experimental (seeking experimental data to answer ecological research questions or improve restoration approach), pragmatic (focusing on the ecosystem services that can be derived from a restored coral reef into the future), legislative (related to legal and policy requirements of governments and other large institutions to recover ecosystems which have suffered environmental impacts, e.g. habitat loss from development, mining, or ship grounding), and/or biotic (motivations aligned with the desire to enhance biodiversity). The categories idealistic, experimental, pragmatic, legislative, and biotic are not necessarily mutually exclusive but comprise a typology that facilitates their systematic description (Clewell & Aronson 2006).

Variables Measured

Variables measured were grouped into “attribute categories” and “sub-attribute categories” (Table S1, Supporting Information) modified from the International Standards for Ecological Restoration by the Society of Ecological Restoration (McDonald et al. 2016). Variables measured during monitoring of the restoration site were categorized as related to ecosystem function and processes (e.g. survival, growth, and productivity) but also the physical environment of the restoration site (temperature, water currents, turbidity, and pH) and the level of threats (invasive species, predators, and physical damage). Note that the International Standards classify variables such as survival, growth, and productivity under the attribute “ecosystem function” while these would be categorized as variables measuring the biological response of the ecosystem to the restoration intervention in other studies (e.g. Hein et al. 2017).

Restoration Outcomes

We searched in the abstract, results, and discussion of each study to identify the type(s) of outcomes reported as results. These were categorized as ecological, economic, and/or social (sensu Wortley et al. 2013) to provide an understanding of the broader outcomes being addressed.

Coral Reef Restoration Techniques

Information on six major techniques for coral reef restoration was extracted from the studies reviewed:

(1) Direct transplantation: harvesting of coral colonies or fragments from a donor site and the transplantation of these to a restoration site without the intermediate step of growing coral fragments in a nursery (Edwards & Clark 1998).

(2) Larval enhancement: flow-through facilities are used to aid fertilization and competent coral larvae are then seeded to a reef restoration site. The reared coral larvae can be either free swimming or attached to substrate (Chamberland et al. 2017).

(3) Coral gardening: involves two phases (Rinkevich 1995, 2000, 2005, 2008, 2014, 2015a, 2015b): (1) the collection

of coral fragments from donor colonies and growing these in field-based (in situ) or land-based (ex situ) nurseries and (2) outplanting the nursery-grown corals to the degraded reef using materials such as epoxy, cement, or cable ties to attach the corals to the substratum (Montoya-Mayo et al. 2016). The analyses were carried out for “Coral gardening” indicating the whole process using this technique for restoration and for its components “Collection and nursery phase” and “Transplantation phase” since this is how data were reported by the studies. Note that the individual components of the coral gardening approach cannot be considered as standalone restoration approaches.

(4) Substrate addition (artificial reefs): utilizes structures deployed on the seabed to mimic characteristics of a natural reef and is often followed by active coral transplantation (Clark & Edwards 1994, 1995).

(5) Substrate stabilization: damaged substrate (e.g. after storms or ship groundings on reefs) is restored to facilitate natural coral settlement and reef recovery (Lindahl 2003).

(6) Substrate enhancement with electricity: mimics the chemical and physical properties of reef limestone deposition, by encouraging the precipitation of calcium and magnesium on artificial substrates using electrical currents (Goreau et al. 2003). The technique was originally developed by Wolf Hilbertz in the 1970s and has led to the commercial product Biorock.

Results

Of the 87 studies extracted, 71 were primary sources (publications describing original research) and 16 were secondary sources (studies referring to original research published elsewhere, e.g. reviews). The 71 primary sources reported on 75 separate restoration projects. A single study could contain more than one observation. A total of 335 observations were retrieved from all primary and secondary studies. The motivations and reported outcomes were recorded at the restoration project level taking into account primary sources only.

One-third of the studies (n = 25) were from less economically developed countries (low income and lower middle income), 13 were from countries with an upper middle income, and the remaining studies were from high-income countries (n = 45) (Fig. 1). Four studies contained no information on the country in which the restoration project was carried out.

Reasons for Coral Reef Restoration

The dominant primary motivations for the restoration of coral reefs in the restoration projects reviewed were experimental reasons, such as to improve the restoration approach and answer ecological research questions, accounting for 65.3% of the projects (Fig. 2). A total of 17.3% of the projects carried out coral reef restoration because of an environmental impact such as hurricanes, ship groundings, or heavy storms and were inspired by legislative reasons. Restoration for biodiversity enhancement (biotic reasons) was the motivation for 10.7% of the projects. Pragmatic reasons for enhancing ecosystem
services such as fisheries production motivated 4.0% of the projects. Social reasons (idealistic), e.g. restoration for education purposes or awareness of the general public and restoration for biodiversity offsetting (legislative), were negligible (<2.0% of the projects). The secondary and tertiary motivations, where reported, were dominated by experimental reasons to restore coral reefs (Fig. 2).

Variables Measured and Reported

The majority (70.7%) of projects measured variables relating to ecosystem function (Fig. 3), including survival of restored corals, growth, and productivity (Fig. 4). This was followed by species composition (25.3%) indicated by metrics such as species present, richness or distribution, and physical conditions (2.7%) e.g. water temperature, salinity, turbidity, and water currents. The number of projects reporting on social aspects of restoration, such as measuring environmental awareness or community engagement was negligible (1.3%).

Coral Reef Restoration Outcomes Reported

The majority (76.0%) of coral reef restoration projects reported an ecological outcome only (Fig. 5). Some studies reported on social and ecological outcomes (13.3%), followed by ecological and economic outcomes (8.0%) while the least number of studies reported on all three outcome categories (2.7%). All projects reported at least an ecological outcome. Economic outcomes were not reported at all.

Project Cost, Spatial Extent, Duration, and Survival

The median reported cost from all observations \((n = 58)\) was \(404,147 \pm 18,927,043\) US$/ha (at base year 2010), while the project spatial extent \((n = 91)\) was \(0.01 \pm 0.454\) ha \((108 \pm 4,542\) m\(^2\)) with a survival \((n = 288)\) of \(60.9 \pm 32.2\%\), and a project duration \((n = 276)\) of \(1.0 \pm 1.7\) years (all median values ± standard deviation [SD]).

Out of a total of 335 observations, 17.3% (or 29.9% of 87 studies) reported on project cost and 14.3% (or 27.6% of the studies) described what restoration components these costs included. From all 58 observations (26 studies) reporting on cost, 37.9% of the observations (or 38.5% of the studies) reported on both capital (planning, purchasing, land acquisition, construction, financing) and operating (maintenance, monitoring, and equipment repair/replacement) costs highlighting that the cost values reported here are likely lower than the real total project cost.

Costs, survival rates, and project spatial extent varied substantially among the six restoration techniques (Table 1, Fig. 6). The median cost for substrate addition – artificial reef were highest with \(3,300,000 \pm 44,000,000\) US$/ha \((n = 10;\) median ± SD; Table 1). The cheapest restoration technique was the collection and nursery phase component of the coral gardening approach with median cost of \(28,000 \pm 20,000\) US$/ha \((n = 5;\) Table 1) and a survival of \(52.1 \pm 31.5\%\) \((n = 85;\) Fig. 6B). The variability in cost estimates was large and spanned five orders of magnitude (from 6,000 to 143,000,000 US$/ha) between the different restoration techniques (Table 1). The five case studies reporting on project duration of substrate...
Figure 2. Motivations reported for restoring corals reefs categorized as idealistic, experimental, legislative, pragmatic, and biotic \((n = 75)\).

Figure 3. Primary categories of variables measured within \(n = 75\) restoration projects.
stabilization projects lasted longest with 2.0 ± 3.6 years while studies employing artificial reef enhanced by electrical field were of shortest project duration with 0.3 ± 0.3 years (n = 10; Fig. 6C). The techniques of larval enhancement (n = 3) and substrate addition (n = 12) were deployed over the largest spatial extents with median values of 1,500 ± 849 m² and 2,342 ± 5,270 m², respectively (Fig. 6D). The 12 observations reporting on the coral gardening approach in its entirety and the six observations on building artificial reefs enhanced by electrical fields were reported for the smallest spatial scales and had median values of 12 ± 3,854 m² and 5 ± 0 m² of reef restored, respectively (Fig. 6D). Because the area of coral reef that is ultimately restored depends on the restoration schedule and is not directly related to the spatial area covered by a coral nursery, our reported observations on the collection and nursery phase of the coral gardening approach do not contain area estimates (Fig. 6D).

The median reported cost from all observations (n = 59) using the gross domestic product as a function of purchasing power parity GDP (PPP) was 72,861 ± 18,810,155 Int$/ha (at base year 2010). Cost in Int$/ha for the different coral reef restoration techniques are shown in Table 2.

Motivations for coral reef restoration differed between cost ranges. We separated the 27 observations from studies that reported both on motivations and cost into ranges of (1) <100,000 US$/ha, (2) between 100,000 and <1,000,000 US$/ha, and (3) >1,000,000 US$/ha. The primary motivation for (1) was to improve the restoration approach and answer ecological research questions (9 out of 12 observations). For (2) motivations covered biodiversity enhancement (n = 1), biodiversity offset (n = 1), improve restoration approach (n = 2), and restoration after environmental impact (n = 2). For (3) motivations were biodiversity enhancement (n = 1), improve restoration approach (n = 3), and restoration after environmental impact (n = 5).

**Discussion**

Here we present information on the most commonly applied coral reef procedures from published literature for which

---

**Table 1.** Range of cost (2010 US$/ha) for coral reef restoration observations with sample size (n), minimum, median, maximum, and standard deviation (SD). Cost converted based on consumer price index to a base year of 2010 prices.

| Restoration Technique | n   | Median (±SD)         | Minimum | Maximum         |
|-----------------------|-----|----------------------|---------|-----------------|
| 1. Direct transplantation | 20  | 218,305 (±2,339,609) | 9,198   | 8,382,653       |
| 2. Larval enhancement  | 6   | 523,162 (±1,878,894) | 6,262   | 4,333,826       |
| 3. Coral gardening (overall) | 3   | 351,661 (±136,601)  | 130,000 | 379,139         |
| a. Collection & nursery phase | 5   | 28,075 (±20,472)    | 9,262   | 56,150          |
| b. Transplantation phase | 2   | 761,864 (±1,033,831)| 30,835  | 1,492,893       |
| 4. Enhancing artificial substrates with an electrical field | 0   |                      |         |                 |
| 5. Substrate addition (artificial reef) | 10  | 3,341,754 (±44,100,144)| 14,076 | 142,667,803     |
| 6. Substrate stabilization | 8   | 370,986 (±9,040,923) | 91,044  | 26,100,000      |
Figure 6. Range of costs (A), survival of restored corals (B), project duration (C), and spatial extent of area restored (D) reported for coral reef restoration observations ($n = 335$) categorized by restoration methods and represented as box and whisker plots with sample size ($n$), minimum, quartiles, median, maximum, and outliers. Restoration cost (US$/ha at 2010) are displayed on a logarithmic scale.
motivations, variables measured, cost, success, project spatial extent, and duration have been reported. The techniques described here are not exhaustive (e.g., the method of micro-fragmentation [Forsman et al. 2015; Page et al. 2018] has not been considered), but are in broad agreement with those described by the coral reef restoration review by the Australian Reef Restoration and Adaptation Program (Boström-Einarsson et al. 2018). Coral gardening is among the most commonly used methods to restore coral reefs and consists of two subsequent phases (Rinkevich 1995, 2000, 2005, 2008, 2014). However, few studies report on the whole process from harvesting coral fragments from donor colonies, growing them in intermediate nurseries to outplanting corals to the degraded reef. Therefore, we report on the overall approach and on each phase individually.

The coral reef restoration projects assessed in this study are dominated by experimental motivations inspired by improving restoration approaches and answering questions of ecological concern. Our findings suggest that there is still ongoing development in the methods used to restore coral reefs. However, given that those charged with the task of carrying out large-scale coral reef restoration may rarely publish restoration results and most studies in the literature examined here were conducted by academics, we may be missing a substantial body of knowledge related to coral reef restoration. Bridging the divide between academic researchers and practitioners is a challenge in many conservation fields (Sunderland et al. 2009; Milner-Gulland et al. 2010); doing so will help advance the field of marine restoration ecology.

The majority (71%) of restoration projects in this review used measured variables which can partly inform on ecosystem function (Fig. 3) such as survival of restored corals, growth, and productivity. This concurs with Hein et al. (2017) who described that 88% of studies in the published literature measured survival and/or growth of restored corals as an indicator of coral reef restoration effectiveness. In comparison, a study on terrestrial restoration suggested that measurement of at least diversity, vegetation structure, and ecological processes would be necessary to assess the long-term persistence of an ecosystem (Ruiz-Jaen & Mitchell Aide 2005). It is questionable whether measuring site-based success indicators such as survival of restored organisms will be able to provide any information about the holistic ecological perspective of restoring ecosystem function and services.

Although many studies (Yap 2000; Van Diggelen et al. 2001; Epstein et al. 2003; Hernández-Delgado et al. 2014) recommend the assessment of social, economic, and cultural factors when assessing the effectiveness of coral reef restoration, this study confirms that the numbers of studies assessing social or economic factors have been negligible or are not existent. Reported coral reef restoration outcomes in this study were largely ecological (76%) and rarely focused on economic (e.g., job creation, obtaining higher fishing yields) or social aspects (community involvement, awareness, and environmental education) of the restoration project. This is in agreement with the study by Wortley et al. (2013) showing that over 90% of the ecological restoration projects spanning many terrestrial ecosystems and as reviewed from the scientific literature reported on ecological attributes while only 1% reported on social, economic, and ecological attributes altogether. This may reflect the relatively recent history of coral reef restoration and the small scale of the projects. There is a need to assess variables related to ecosystem services provided by the restoration of coral reefs which have positive economic impacts. Future restoration projects could make this a priority, particularly if social and economic outcomes (e.g., environmental education, changes in perception/belief due to awareness, community empowerment and stewardship, creation of jobs, capitalization of ecosystem services such as tourism, fisheries, coastal protection, etc.) are used as justification for these projects.

Our review of published scientific literature, reports and other available sources shows a large variation in cost reported for the different techniques used in coral reef restoration. While the median reported cost over all observations is around 400,000 US$ to restore 1 ha of coral reef habitat, costs reported for the techniques most commonly applied ranged between 6,000 and 4,000,000 US$/ha. Because coral reef restoration studies rarely report on cost in a consistent manner, it is important to note that the values provided here are estimates only. Reporting on the total cost of coral reef restoration projects can be challenging. This is especially true because not all restoration projects are carried out for the same reasons or have the same specific
objectives. For costs that have been reported, there is a large variation within and between intervention type, location, and study species. Estimates of total restoration cost (including both capital and operation costs to account for the different components of a restoration project) require a standardized approach when reporting on cost. Similar issues with extracting restoration costs from the literature were also noted for other marine coastal ecosystems, e.g. seagrass, mangroves, saltmarsh, and shellfish (Bayraktarov et al. 2016). Coral reefs, as particularly charismatic ecosystems, attract volunteers willing to participate in the restoration work which adds to the difficulty to account for the real cost of labor. A productive approach for further work would be to design a survey to elicit information from coral reef restoration practitioners to collate total restoration costs in a standardized way. Ideally, guidelines for standardized reporting on costs for management interventions need to be followed (e.g. by Iacona et al. 2018) in order to compare restoration to other conservation interventions.

Survival of restored organisms is often reported as an item-based success indicator by studies on marine coastal restoration (Bayraktarov et al. 2016). Here, survival differed between the life stages of corals at which the restoration technique is targeted, with high survival rates (>50%) for coral gardening and low survival rates (<25%) where techniques are focused on coral larvae. Yet, survival has been assessed only in the short term (1–2 years after restoration) and the number of long-term studies such as Haisfield et al. (2010) and Garrison & Ward (2012) is small. Previous work has highlighted that survival of restored organisms is not a good indicator for the overall project success (Bayraktarov et al. 2016) because of the different life histories among species and lack of standardization between restoration projects. In addition, coral reef restoration literature is likely biased toward studies reporting on success (Bayraktarov et al. 2016), while only a few studies have described failures (e.g. Fox 2004; Fadli et al. 2012; Cooper et al. 2014).

Here we propose an avenue toward setting clear objectives and quantifying success in achieving those objectives. Ideally, overall restoration project success should be measured as progress toward the specific project objectives. These should be specific, measurable, achievable, realistic, and time-bound (SMART) (McDonald et al. 2016). At least one of the objectives should aim at returning the ecosystem function and resilience of an ecosystem through restoration (Ruiz-Jaen & Mitchell Aide 2005). The project would also need to account for the effect of environmental stochasticity (extreme events such as floods, heat waves, hurricanes), which is why the selection of the site for restoration is critical. Of equal importance are social factors related to whether local communities will adopt and maintain the restored ecosystem—thus an early involvement of local stakeholders is crucial for overall restoration success into the future (McDonald et al. 2016). The fact that biological responses to the restoration intervention such as survival together with growth and productivity continue to be the dominant variables measured, as we report in this review, may indicate that coral reef restoration is still at an early phase (Hein et al. 2017).

With a median restored area of 0.01 ha (108 m²) coral reef restoration reviewed here has been mainly practiced on small, experimental scales. However, restoring corals at larger scales is possible (e.g. 0.52 ha and 0.15 ha; Montoya-May et al. 2016; Chamberland et al. 2017). Because studies in this article are mainly research-based, they have inherent limitations such as the period of funding. This may be one of the reasons why the projects reported here tend to be relatively short and over small experimental scales. For instance, a review that evaluated non-peer-reviewed sources and surveyed practitioners reported a median restored area of 300 m² (Boström-Einarsson et al. 2018) in comparison to the 108 m² reported here. This gap may be closed by gathering data from those charged with the task of carrying out large-scale coral reef restoration by either a survey or other means.

Implications for Practice

Coral reef restoration has been practiced at small experimental scales while a transition to large, whole reef system scales is poised to occur. Innovation enabling coral reef restoration at an industrial scale is already happening by harvesting wild coral spawn slicks (Doropoulos et al. 2019) and employing assisted evolution to make restored corals resilient to climate change (van Oppen et al. 2017). A fast advancement of coral reef restoration is driven by international agreements toward restoration such as the Aichi Biodiversity Target 15 and Sustainable Development Goals by the Convention on Biological Diversity, The Bonn Challenge, or the recently announced United Nations 2021–2030 Decade on Ecosystem Restoration. These agreements stimulate increased funding for restoration. In Australia for example, funding of AUD100 million has been recently allocated toward the research and development phase of the Reef Restoration and Adaptation Plan, which aims to develop, trial, and deploy coral reef restoration interventions for the Great Barrier Reef (GBR) (https://www.gbrrestoration.org/the-program). While being a substantial investment, this amount of funding may appear rather small when taking into account the size of the GBR (35 million hectares) and the median cost of 400,000 US$ to restore 1 ha of coral reef as we found from the published literature. Although this figure may discourage in a first instance, the range of costs observed in this study differs by orders of magnitude for different restoration techniques, which represents an important source of information for the coral restoration community and could be used to target future provision of limited funds. Further research and development in the coral restoration space should focus on interventions that are both inexpensive and successful. A wide range of costs within intervention categories offers hope for future minimizing of costs to a level where restoration projects can become achievable at scale.

This review reveals that there is a large variability in the cost reported for different coral reef restoration techniques from the primary literature, reports, and published data repositories. These cost ranged from a median value of 28,000 US$/ha for the collection and nursery phase of the coral gardening approach to 4,000,000 US$/ha for substrate addition to build an...
artificial reef. Cost values were relative estimates only and did not always report on the total project cost. Survival of restored corals, often reported as the major variable monitored, ranged between 17.3% and 77.5%, depended on the life history that the technique targeted, and was largely documented for short time frames only (1–2 years after restoration). Most published projects were motivated by the desire to elicit experimental data for the purpose of increasing our knowledge or improving the methodological approach and reported an ecological outcome while social and economic aspects of the restoration were rarely assessed. Published literature may be biased toward experimental small-scale restoration projects carried out by academics while large-scale projects by restoration practitioners may not be captured—this remains to be assessed and is an important area of future research. A comparison of costs and success between the interventions used in coral reef restoration could be enabled by reaching out to those charged with the implementation of coral reef restoration projects and eliciting their knowledge through a survey on cost and success.

Acknowledgments

We acknowledge Audrey Van Herwaarden for economic conversions of cost data in the database and Dr Sabah Abdullah for revision and comments on an early draft of this manuscript. This research was funded by the Australian Research Council (ARC) Centre of Excellence for Environmental Decisions, a Future Fellowship awarded to K.A.W, and was also supported by the Australian National Environmental Science Program’s Tropical Water Quality Hub (L.B.-E.). All authors declare that there is no existing conflict of interest. We acknowledge the positive input from two anonymous reviewers that helped to improve this article significantly.

LITERATURE CITED

Anthony K, Bay LK, Costanza R, Firn J, Gunn J, Harrison P, et al. (2017) New interventions are needed to save coral reefs. Nature Ecology and Evolution 1:1420–1422

Aradottir ÁL., Petursdottir T, Halldorsson G, Svavarssdottir K, Arnalds O (2013) Drivers of ecological restoration: lessons from a century of restoration in Iceland. Ecology and Society 18:33

Bayraktarov E, Saunders MI, Abdullah S, Mills M, Beher J, Possingham HP, Mumbay PJ, Lovelock CE (2016) The cost and feasibility of marine coastal restoration. Ecological Applications 26:1055–1074

Bernhardt ES, Sudworth EB, Palmer MA, Allan JD, Meyer JL, Alexander G, et al. (2007) Restoring rivers one reach at a time: results from a survey of U.S. river restoration practitioners. Restoration Ecology 15:482–493

Boström-Einarsson L, Cecarelli D, Babcock RC, Bayraktarov E, Cook N, Harrison P, et al. (2018) Coral restoration in a changing world—a global synthesis of methods and techniques. Report to the National Environmental Science Program. Reef and Rainforest Research Centre Ltd, Cairns, Australia.

Burke L, Spalding M (2011) Reefs at risk. World Resources Institute, Washington D.C.

Chamberland VF, Petersen D, Guest JR, Petersen U, Brittman M, Vermeij MJA (2017) New seedling approach reduces costs and time to outplant sexually propagated corals for reef restoration. Scientific Reports 7:12

Clark S, Edwards AJ (1994) Use of artificial reef structures to rehabilitate reef flats degraded by coral mining in the Maldives. Bulletin of Marine Science 55:724–744

Clark S, Edwards AJ (1995) Coral transplantation as an aid to reef rehabilitation: evaluation of a case study in the Maldives Islands. Coral Reefs 14:201–213

Clewell AF, Aronson J (2006) Motivations for the restoration of ecosystems. Conservation Biology 20:420–428

Cooper WT, Lirman D, Vangroningen MP, Parkinson JE, Herlan J, Mcmanus JW (2014) Assessing techniques to enhance early post-settlement survival of corals in situ for reef restoration. Bulletin of Marine Science 90:651–664

Doropoulos C, Elzinga J, ter Hofstede R, van Koningsveld M, Babcock RC (2019) Optimizing industrial-scale coral reef restoration: comparing harvesting wild coral spawn slicks and transplanting gravid adult colonies. Restoration Ecology. https://doi.org/10.1111/rec.12918

Edwards AJ, Clark S (1998) Coral transplantation: a useful management tool or misguided meddling? Marine Pollution Bulletin 37:474–487

Edwards A, Gomez ED (2007) Reef restoration concepts and guidelines: making sensible management choices in the face of uncertainty. Coral Reef Targeted Research & Capacity Building for Management Programme, St Lucia, Australia

Epstein N, Bak RPM, Rinkevich B (2003) Applying forest restoration principles to coral reef rehabilitation. Aquatic Conservation: Marine and Freshwater Ecosystems 13:387–395

Fadli N, Campbell SJ, Ferguson K, Keyse J, Rudi E, Riedel A, Baird AH (2012) The role of habitat creation in coral reef conservation: a case study from Aceh, Indonesia. Oryx 46:501–507

Forsman ZH, Page CA, Toonen RJ, Vaughan D (2015) Growing coral larger and faster: micro-colony-fusion as a strategy for accelerating coral cover. PeerJ 3:e16

Fox HE (2004) Coral recruitment in blasted and unblasted sites in Indonesia: assessing rehabilitation potential. Marine Ecology Progress Series 269:131–139

Frieler K, Meinshausen M, Golya A, Mengel M, Lebek K, Donner SD, Hoegh-Guldberg O (2012) Limiting global warming to 2°C is unlikely to save most coral reefs. Nature Climate Change 3:165

Garrison VH, Ward G (2012) Transplantation of storm-generated coral fragments to enhance Caribbean coral reefs: a successful method but not a solution. Revista de Biologia Tropical 60:59–70

Goreau TJ, Hilbertz W, Azeex A, Hakeem A, Dodge R, Despainge G, Shwaiko C (2003) Restoring coral reefs, oyster banks, and fisheries by seawater electrolysis: coastal zone management and tourism applications. In: Oceans 2003. Celebrating the past … teaming toward the future. Vol 2. IEEE, San Diego, California. doi: 10.1109/OCEANS.2003.178407.

Haggar V, Dwyer J, Wilson K (2017) What motivates ecological restoration? Restoration Ecology 25:832–843

Haisfield KM, Fox HE, Yen S, Mangubhai S, Mous PJ (2010) An ounce of prevention: cost-effectiveness of coral reef rehabilitation relative to enforcement. Conservation Letters 3:243–250

Hein MY, Willis BL, Beeden R, Birtles A (2017) The need for broader ecological and socioeconomic tools to evaluate the effectiveness of coral reef restoration programs. Restoration Ecology 25:873–883

Hernández-Delgado E, Mercado-Molina A, Alejandro-Camis P, Candelas-Sánchez F, Fonseca-Miranda J, González-Ramos C, et al. (2014) Community-based coral reef rehabilitation in a changing climate: lessons learned from hurricanes, extreme rainfall, and changing land use impacts. Open Journal of Ecology 4:918–944

Heston A, Summers R, Aten B (2012) Penn World Table version 7.1. Centre for International Comparisons of Production, Income and Prices at the University of Pennsylvania, Philadelphia

Hock K, Wolff NH, Ortiz JC, Condle SA, Anthony KRN, Blackwell PG, Mummy PJ (2017) Connectivity and systemic resilience of the Great Barrier Reef. PLoS Biology 15:e2003355

Hoegh-Guldberg O, Mummy PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, et al. (2007) Coral reefs under rapid climate change and ocean acidification. Science 318:1737–1742

990
Hughes TP, Kerry JT, Alvarez-Noriega M, Alvarez-Romero JG, Anderson KD, Baird AH, et al. (2017) Global warming and recurrent mass bleaching of corals. Nature 543:373–377

Iacona GD, Sutherland WJ, Mappin B, Adams VM, Arnessworth PR, Coleman T, et al. (2018) Standardized reporting of the costs of management interventions for biodiversity conservation. Conservation Biology 32: 979–988

IPCC (Intergovernmental Panel on Climate Change) (2018) Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. IPCC, Geneva, Switzerland

Lindahl U (2003) Coral reef rehabilitation through transplantation of staghorn corals: effects of artificial stabilization and mechanical damages. Coral Reefs 22:217–223

McDonald T, Gann G, Jonson J, Dixon K (2016) International standards for the practice of ecological restoration—including principles and key concepts. Society for Ecological Restoration, Washington D.C.

Milner-Gulland EJ, Fisher M, Browne S, Redford K, Spencer M, Sutherland W (2010) Do we need to develop a more relevant conservation literature? Oryx 44:1–2

Montoya-May PH, Smit KP, Burt AJ, Frias-Torres S (2016) Large-scale coral reef restoration could assist natural recovery in Seychelles, Indian Ocean. Nature Conservation 16:1–17

Van MH Opper, Gates RD, Blackall LL, Cantin N, Chakravarti LJ, Chan WY, et al. (2017) Shifting paradigms in restoration of the world’s coral reefs. Global Change Biology 23:4675–4688

Page CA, Muller EM, Vaughan DE (2018) Microfragmenting for the successful restoration of slow growing massive corals. Ecological Engineering 123:86–94

Perrow M, Davy A (2002) Handbook of ecological restoration. Cambridge University Press, Cambridge, United Kingdom

Rinkevich B (1995) Restoration strategies for coral reefs damaged by recreational activities: the use of sexual and asexual recruits. Restoration Ecology 3:241–251

Rinkevich B (2000) Steps towards the evaluation of coral reef restoration by using small branch fragments. Marine Biology 136:807–812

Rinkevich B (2005) Conservation of coral reefs through active restoration measures: recent approaches and last decade progress. Environmental Science & Technology 39:4333–4342

Rinkevich B (2008) Management of coral reefs: we have gone wrong when neglecting active reef restoration. Marine Pollution Bulletin 56:1821–1824

Rinkevich B (2014) Rebuilding coral reefs: does active reef restoration lead to sustainable reefs? Current Opinion in Environmental Sustainability 7:28–36

Rinkevich B (2015a) Climate change and active reef restoration—ways of constructing the “reefs of tomorrow”. Journal of Marine Science and Engineering 3:111–127

Rinkevich B (2015b) Novel tradable instruments in the conservation of coral reefs, based on the coral gardening concept for reef restoration. Journal of Environmental Management 162:199–205

Ruiz-Jaen MC, Mitchell Aide T (2005) Restoration success: how is it being measured? Restoration Ecology 13:569–577

SER (Society for Ecological Restoration) (2004) The SER primer on ecological restoration. SER, Tucson, Arizona

Shaver EC, Silliman BR (2017) Time to cash in on positive interactions for coral restoration. PeerJ 5:20

Sunderland T, Sunderland-Groves J, Shanley P, Campbell B (2009) Bridging the gap: how can information access and exchange between conservation biologists and field practitioners be improved for better conservation outcomes? Biotropica 41:549–554

The World Bank (2019a) World development indicators. “World Bank list of economies (June 2018)”. The World Bank Group, Washington D.C. https://datahelpdesk.worldbank.org/knowledgebase/articles/906519 (accessed 08 Apr 2019)

The World Bank (2019b) World development indicators. “Consumer price index (2010 = 100)”. The World Bank Group, Washington D.C. https://data.worldbank.org/indicator/FP.CPI.TOTL (accessed 19 Apr 2019)

The World Bank (2019c) World development indicators. “GDP per capita, PPP (current international $)”. The World Bank Group, Washington D.C. https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD (accessed 19 Apr 2019)

Van Diggelen R, Grootjans AP, Harris JA (2001) Ecological restoration: state of the art or state of the science? Restoration Ecology 9:115–118

Wortley L, Hero J-M, Howes M (2013) Evaluating ecological restoration success: a review of the literature. Restoration Ecology 21:537–543

Yap HT (2000) The case for restoration of tropical coastal ecosystems. Ocean & Coastal Management 43:841–851

Supporting Information

The following information may be found in the online version of this article:

Appendix S1: Contains a description and a table (Table S1) on the broader attributes adopted from McDonald et al. (2016).

Table S1: All variables measured in the restoration projects reviewed and grouped under sub-attributes and attributes.

Received: 23 December, 2018; First decision: 4 March, 2019; Revised: 11 May, 2019; Accepted: 11 May, 2019; First published online: 17 June, 2019