frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 10 June 2024
DOI 10.3389/fmars.2024.1404336

OPEN ACCESS

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RECEIVED 20 March 2024
ACCEPTED 20 May 2024
PUBLISHED 10 June 2024

CITATION
Schopmeyer S, Galvan V, Hernandez-Delgado EA, Nava G, D'Alessandro M, Carne L, Goergen E, Viehman S, Moulding A and Lirman D (2024) An evaluation tool for assessing coral restoration efforts.
Front. Mar. Sci. 11:1404336.
doi: 10.3389/fmars.2024.1404336

An evaluation tool for assessing coral restoration efforts

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The ever-increasing need for coral restoration as a tool available to mitigate reef declines and aid in the recovery of lost ecosystem services requires improving restoration performance over time through an adaptive management framework to evaluate the status of restoration programs using uniform, consistent metrics. An evaluation tool, presented herein, allows restoration practitioners and managers to self-evaluate the robustness of each project and identify successful metrics, those metrics that need special attention, and changes to restoration strategies that can improve performance and aid recovery. This tool is designed to allow programs to track the progress of each key metric over time to assist in improving upon successes and learning from failures. The metrics within this restoration evaluation tool focus on published best-management practices and have resulted from extensive research conducted by restoration experts over the past 20 years. Common metrics of growth and survival are included, in addition to parameters vital to the operational success of restoration programs, such as coral reproduction, recruitment of associated reef taxa, increasing habitat for reef fisheries, and improving overall reef habitat. Five Caribbean restoration programs, each with at least 15 years of restoration experience, are presented as case studies. Each program was evaluated based on six restoration categories including: field-based nurseries, outplantings, programmatic management, education and outreach, event-driven restoration, and socioeconomic restoration. Category-specific metrics were scored with a binary scoring system and summarized using a stop-light indicator framework, where the resulting color/score indicates the operations tatus of the different program components (Scores >75% = green/successful; 50–74.9% = light green > yellow > orange/intermediate; <49.9% = red/sub-optimal). Composite scores may be used to evaluate individual projects, overall restoration programs, or even large-scale state of regional restoration plans. Overall, four of the five programs scored >75% indicating most of these programs are performing well, are versatile, well managed, and sustainable. Outside of environmental factors and large-scale

disturbance events, many programs described resource limitations, including funding and staffing, as reasons for scoring low on some metrics. A holistic evaluation rubric incorporated into programmatic self-assessment can ensure that restoration projects and programs are working towards success and sustainability.

KEYWORDS

coral restoration, restoration outcomes, restoration metrics, evaluation criteria, adaptive management

1 Introduction

Efforts to mitigate declining coral populations around the world have led to the proliferation of coral propagation and outplanting programs (Boström-Einarsson et al., 2020). Tied to this expansion, there is an increasing need for uniform, consistent guidelines and benchmarks to ascertain the operational status of restoration efforts that are implemented with variable levels of expertise and a wide range of programmatic goals (e.g., population enhancement, event-driven restoration, education, enhanced livelihoods). The application of a robust set of consistent performance metrics is crucial to develop and support an adaptive management system based on participatory monitoring and stakeholder engagement where actions can be taken to mitigate and remediate issues, such as disease outbreaks, prior to these threatening the long-term viability of the restoration efforts (Beeden et al., 2012; Anthony et al., 2015; Gann et al., 2019; Goergen et al., 2020). However, the availability of monitoring data and success criteria is limited, and lack of consistent guidelines, and the inability to compare coral restoration results to an undisturbed, pristine reference or control system, can lead to criticism of restoration programs. Monitoring and evaluation plans exist for many types of ecosystems and programs (e.g., Society for Ecological Restoration Recovery Wheel (www.seraustralasia.com/wheel/index), the U.S. Florida Everglades RECOVER program (www.evergladesrestoration.gov, saj.usace.army.mil/Missions/Environmental/Ecosystem-Restoration/RECOVER/RECOVER-Performance-Measures/), Great Barrier Reef water quality (www.reefplan.qld.gov.au), Reef Health (www.blueprojectatlantic.org; www.healthyreefs.org), seagrass communities (U.S. state programs: Texas www.texasseagrass.org, Florida https://ocean.floridamarine.org/fknms_wqpp/seagrass.htm, https://floridadep.gov/rcp/rcp/content/mapping-and-monitoring-seagrass-communities, www.seagrasswatch.org), and oyster reef restoration (Baggett et al., 2015)). However, few widely approved status metrics exist presently for coral restoration. Over the past decade, high survival coupled with fast growth of corals has fostered the creation of genotypically diverse nursery stocks, and currently, tens of thousands of corals are propagated and outplanted onto degraded reefs on a yearly basis in Florida alone (Ware et al., 2020; van Woesik et al., 2021). As a result of this substantial increase in the abundance, biomass, and overall footprint of restored corals, regional benchmarks of operational success have been suggested (Schopmeyer et al., 2017), but methods for holistically evaluating restoration programs to promote self-assessment of restoration practices and the design of adaptive strategies to improve performance have not been created.

Recent reviews of restoration ecology within reefs highlight that current metrics used to evaluate the effectiveness of restoration concentrate on the corals' biological response to outplanting (e.g., growth and survival). Most (65%) coral restoration monitoring studies focus on the performance of individual colonies (i.e., growth and survival) while an additional 35% of studies combine these indicators with only a limited number of other ecological factors such as recruitment, competition, and predation (Hein et al., 2017; Boström-Einarsson et al., 2020). Although growth and survival metrics are useful to assess individual colony performance, such metrics may be insufficient to fully characterize and assess the effectiveness of the methods used by restoration programs (Hein et al., 2017; Goergen et al., 2020; Viehman et al., 2023). As suggested in recent studies, published data are often biased towards only reporting high survival, and researchers, practitioners, and managers may avoid reporting failed restoration projects due to concerns about losing permits or funding and/or propagating a negative public perception of coral restoration (Bayraktarov et al., 2020; Boström-Einarsson et al., 2020). As a result, few published studies attempt to evaluate the overall performance of restoration beyond coral survival and growth. While increasing the abundance and size of outplanted corals is the proximate outcome of coral restoration, restoration success needs to be evaluated holistically and include other key metrics such as coral reproduction, genetic diversity, recruitment of corals and associated reef organisms (e.g., fish, invertebrates, megafauna), and improvement to overall reef habitat (e.g., shelter, rugosity, shoreline protection, carbonate production). As such, the restoration community would benefit from having a set of metrics linked to specific operational restoration goals, best management practices, and reef-scale properties to evaluate the performance of their programs within an adaptive management and restoration framework (Wapnick and McCarthy, 2006; Hein et al., 2017; Vardi et al., 2021).

Here, we describe an assessment tool based on the stop-light indicator framework that captures status information of a wide range of potential coral restoration project components and goals. Similar assessment strategies are effectively used in status reports for coral reefs in the US (Towle et al., 2022) and Caribbean (https://

www.healthyreefs.org/cms/wp-content/uploads/2022/12/2022-Report-Card-MAR.pdf) and for the USA Florida Everglades restoration (https://www.evergladesrestoration.gov/progress-report-1). This restoration evaluation tool follows metrics related to the recovery goals, objectives and criteria outlined in the Recovery Plan for Elkhorn and Staghorn Corals (NMFS, 2015) which are also applicable to additional species now listed under the US Endangered Species Act (NOAA Commerce Document, 2014). Metrics related to specific goals set forth by the Recovery Plan include protecting genetic diversity and increasing the abundance and spatial distribution of coral populations throughout their geographical ranges (Supplementary Table S1). This restoration evaluation tool also addresses adaptive management needs to inform conservation and to develop restoration plans to include metrics focusing on multiple and/or regional restoration objectives and strategies. Unlike the Ecological Recovery Wheel presented by Gann et al. (2019) designed to evaluate and track ecosystem recovery in comparison to baseline conditions using broader ecological categories, operational metrics established within this evaluation tool break down those categories into more specific field-based and procedural metrics based on best management practices and restoration-based research conducted by experts in the field of coral propagation and outplanting (Table 1).

A recent review by Suggett et al. (2024) highlighted the need to avoid conflating ecological restoration (the process of assisting reef recovery) with restoration ecology (the science behind ecological restoration). Moreover, the authors suggest that some of the recent criticism that has surfaced against reef restoration in the face of large-scale, climate-driven coral declines (e.g., Hughes et al., 2023), is due to the flawed extrapolation of small-scale restoration outcomes to predictions of the success of ecological restoration. Nevertheless, the first step in expanding restoration projects to meaningful ecological scales is to be able to assess and improve the operational status of these projects. The intent of this evaluation

TABLE 1 Evaluation Tool categories and metrics.

Metric #	Field-based Nursery Metrics	Outplanting Metrics	Program Management Metrics	Education and Outreach Metrics	Event-driven Restoration Metrics	Socioeconomic Goal-based Restoration Metrics
1	Nurseries are established based on published best practices or approved guidelines	Outplant sites are established based on published, best practices or approved guidelines	Program has successful scores from nursery and outplanting level metrics (> 75%)	Volunteers and/or stakeholders are included in local restoration activities	Benthic surveys are conducted post-event to determine: 1) the extent of the damage to the reef structure and ecological function, and 2) if coral restoration through triage or outplanting is feasible	Engage local stakeholders in reef conservation and management
2	Environmental parameters are measured at nursery locations (e.g., water temperature, light, current, sedimentation, nutrients, dissolved oxygen)	Outplant site contains/has historical presence of outplanted species	Programs are increasing functional capacity of the region by deploying multiple projects strategically to mitigate threats from large-scale disturbances (e.g., hurricanes, disease outbreaks, bleaching events)	Volunteers/participants have an increased awareness about the status of coral reefs and the need for coral restoration after participation in project/program	Event-driven restoration is monitored according to metrics outlined in published best practices or approved guidelines	Enhance recreational opportunities
3	Nursery contains multiple species	Sites are surveyed for reef community structure and species abundance prior to outplanting	Programs are increasing functional capacity of the region by deploying projects strategically to enhance spatial coverage of restoration efforts (e.g., increase local coral abundance, expand current population coverage, increase community education/ involvement)	Corals outplanted as part of educational, stewardship, or capacity building restoration programs have similar condition and survival to other local restoration programs		Provide meaningful employment opportunities and income generation

(Continued)

TABLE 1 Continued

Metric #	Field-based Nursery Metrics	Outplanting Metrics	Program Management Metrics	Education and Outreach Metrics	Event-driven Restoration Metrics	Socioeconomic Goal-based Restoration Metrics
4	Nursery contains a high degree of genotypic diversity	Environmental parameters are measured at outplant sites to demonstrate that large changes in parameters over short periods of time do not occur (e.g., minimum measurement of water temperature required, but may also include light, current, sedimentation, dissolved oxygen, turbidity)	Program has genotypic redundancy (exchange of genotypes among all projects) within nurseries and outplant sites	The satisfaction of reef-users to coral reef conditions or their experience on coral reefs is increased after restoration activities		Support young professionals in their scientific training and development
5	Nursery corals have a high degree of putative genotypic diversity (or assumed putative genotypes based on physical separation of collection sites)	Restored Reef Areal Dimension (RRAD) is measured at each outplant site	Program has defined goal(s) and clear metrics of success based on published best management practices and guides (e.g., number of nursery or outplanted corals, evidence of sexual reproduction)	Program has established an outreach and community engagement strategy that includes volunteer training standards		Promote local youth involvement in the sciences
6	Nursery tracks genotype provenance (e.g., source location, date, depth, number of corals)	Restored footprint or area (RRAD) shows no net decrease over time from original project area	Program has a strategic plan for restoration goals and objectives linked to coral recovery plans			
7	Nursery tracks genotype through time (e.g., maps, tags, propagation structure, etc.)	Outplant sites contain multiple outplanted species	Program goals support wider conservation, management (marine protected/conservation areas, no-take zones, etc), and restoration actions			
8	Nursery exhibits high coral survivorship (per species)	Outplants contain a high degree of putative genotypic diversity per restoration site (or assumed putative genotypes based on physical separation of collection sites)	Program's restoration efforts can be scaled up as needed			
9	Nursery exhibits low prevalence of colony partial mortality	Outplants exhibit positive growth (all species) and/or increases in abundance (branching species)	Program's restoration efforts can be scaled down as needed			
10	Nursery exhibits net coral growth (e.g., total linear extension, size class, maximum diameter or length, volume)	Outplants are tracked (tagged, photographed, mapped, marked) and monitored for 1st year after outplanting (or time required by funding/permits)	Program has appropriate exit strategies for nursery stock/monitoring			
11	Nursery exhibits low prevalence of disease and/or disease within nursery is mitigated	Representative photos are taken prior to, after, and during each monitoring event to document changes to overall abundance, coral cover, and/or reef structure	Program has a response plan to minimize and address stress/ disturbance events			

(Continued)

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TABLE 1 Continued

Metric #	Field-based Nursery Metrics	Outplanting Metrics	Program Management Metrics	Education and Outreach Metrics	Event-driven Restoration Metrics	Socioeconomic Goal-based Restoration Metrics
12	Nursery exhibits low impact of coral predators	Outplants exhibit high coral survivorship within 1st year resulting in positive change in abundance of each outplanted species at outplant site over time	Programs have a monitoring plan that includes recommended data, methods and frequency outlined within published best practices or approved guidelines			
13	Nursery exhibits limited competition by algae and other competitors (e.g., hydroids, sponges, damselfish)	Outplants maintain a high percent of live tissue per coral (outside of acute events) during 1st year	Program includes long-term monitoring to determine success/ ecological function			
14	Nursery provides a sustainable source of healthy coral outplants that are outplanted on a regular basis to prevent overgrowth/ breakage/mortality of corals	Outplants exhibit low tissue loss (< 5% of outplants) from bleaching	Program shows financial robustness and stability			
15	Nursery visits/ maintenance based on published best practices or approved guidelines (minimum quarterly and immediately following stress/ disturbance events (disease, bleaching, storms))	Outplants exhibit low prevalence (<10%) of disease within the 1st year (outside of acute events)	Program can be managed and maintained by the staff and/or locally available resources			
16	Nursery dimensions (area) and structure census (#) are available	Outplants exhibit low abundance and impacts of coral predators	Programs communicate/ collaborate with broader regional coral restoration community (e.g., create regional restoration plan, share ideas, information, data, successes/failures)			
17	Nursery can be easily expanded/ reduced if needed	Outplants exhibit limited competition by algae and other competitors (e.g., hydroids, sponges, damselfish)				
18	Nursery has a disturbance response plan	Outplants experience low levels of physical damage (unnatural colony fragmentation, breakage, and/ or dislodgement)				

(Continued)

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TABLE 1 Continued

Metric #	Field-based Nursery Metrics	Outplanting Metrics	Program Management Metrics	Education and Outreach Metrics	Event-driven Restoration Metrics	Socioeconomic Goal-based Restoration Metrics
19	Nursery has a disease mitigation plan (removal, banding, quarantine)	Outplants reach sexual maturity				
20		Outplants increase reef height/rugosity of site (branching species only for first five years)				
21		Outplants improve ecological value of reef and provides improved habitat for reef fish				
22		Outplants improve ecological value of reef and provides improved habitat for non-corallivorous invertebrates				
23		Outplants exhibit high annual coral survivorship/abundance during years 2–5				
24		Outplants exhibit high coral survivorship/abundance >5 years				
25		Benthic composition of outplant sites is surveyed long-term (>5 years) and outplant species exhibit positive change in abundance (may include recruitment of outplant species at restoration site) and growth as compared to baseline surveys				
26		Increased monitoring during times of stress (storms, disease events, coral bleaching, etc) or after impact events (coastal construction, dredging projects, ship groundings)				
27		Disease mitigation plan or prevention measures for outplants is established (removal, banding, antibiotic paste)				

tool is to improve restoration performance at the project level, to promote the design of adaptive strategies, and to encourage communication among local, regional, and global restoration partners to increase the likelihood of success through the self-evaluation of restoration metrics and results. The detailed scores for each metric in the evaluation tool can be used to determine which components or projects need special attention and additional resources as well as identify the need for rapid remediation. To track the progress of each metric over time, the evaluation can be repeated after changes are made to improve upon metrics with low scores or at scheduled intervals (i.e., annually). In addition, the tool and metrics may be updated to include changes in benchmarks, updates in coral restoration methods and techniques, and other strategies such as land-based nurseries as part of an adaptive management and restoration framework. Metrics where scores are especially low should be targeted for improvement first. The tool is not intended to be used to discard projects or programs, as learning from failure can be as informative as instant success, and tools and performance metrics should always be adapted to local conditions and program goals. This restoration evaluation tool aims to advance the development of science-based benchmarks to achieve population and ecosystem-based recovery for coral reefs by

evaluating the current status of restoration techniques, outlining the positive attributes of productive projects and programs, and promoting the development of successful strategies to scale up the practice of restoration ecology to achieve the recovery of the valuable ecosystem services provided by coral reefs.

2 Methods

This evaluation tool consists of a set of worksheets to evaluate new or existing coral restoration programs based on achievable goals and benchmarks established within the scientific literature and by restoration practitioners and managers. Metrics (n=74 in total) examine field-based nursery (n=19) and outplanting (n=27) practices, as well as other categories such as program management strategies (n=16), education and outreach (n=5), event-driven restoration (e.g., restoration following disease events, storms, or ship groundings; n=2), and restoration guided by socioeconomic goals (e.g., livelihood opportunities, tourism; n=5; Table 1). While programs may have other goals or components beyond the ones evaluated by this tool, we believe the framework proposed can be easily adopted and adapted to fulfill the needs of individual programs. Metrics to incorporate monitoring requirements by permitting and management agencies, as well as metrics to evaluate larger-scale restoration benefits, such as improved reef structure, sexual reproduction of outplants, and increased ecological habitat, were also utilized. Using a "lessons learned" perspective to incorporate data needs from practitioners, managers, and funding sources, coral restoration can be evaluated based on the strength and robustness of each project or program while also identifying specific metrics which may require action to improve performance. Metrics within this tool were also adapted based on goals of the Coral Restoration Consortium (CRC, www.crc.world) and utilize Universal and Goal-based Performance Metrics consistent with those presented in Goergen et al. (2020).

The restoration evaluation tool provides a simple, stop-light indicator framework that captures status or performance information of the wide range of potential project components and goals. Within this framework, metrics are rated using a simple binary score (0–1). Individual scores are aggregated based on the different project categories (e.g., field-based nursery, outplanting, management), as well as across all projects within a program to provide composite scores. Composite scores are calculated by adding the number of positive responses ("1s") and dividing by the total number of metrics within a project category. Composite scores may be evaluated at the project, program, or even region/country scale. Metrics are intended to be scored at the start of the project and at meaningful time intervals thereafter to track progress over time (minimum = annually). Guidance and rationale on the scoring procedure are provided for each metric based on published research and expert opinion (Supplementary Table S2).

Individual scores for each category assist in determining the overall performance of a project or program and in identifying which categories or individual metrics, if any, may require additional action to improve. For example, if a project scores high in the nursery category, but low in the outplanting category, individual metrics such as the number of genotypes outplanted at a site or the site selection based on presence of competitors can be changed. The composite scores are adjusted into a 1–100% scale, and the scores and the associated stoplight color scheme provide a quick overview of the status of each component (and progress) within and between projects. The resulting color/score indicates the status or performance of the coral restoration program components based on a suite of key metrics (e.g., survivorship, productivity, environmental parameters, genetic diversity, site selection, maintenance, monitoring, program management, and community and stakeholder engagement) outlined within the scientific literature, the Coral Reef Restoration Monitoring Guide (Goergen et al., 2020), and other Best Management Practice Guides and Manuals (https://www.crc.world/crc-resources; Edwards, 2010; Johnson et al., 2011; Baums et al., 2019). Relevant literature citations were provided for metrics to offer scientific support for the scoring scheme.

The stoplight color scheme is created via conditional formatting of composite scores with a graded color scale of red to green with a minimum of 50, a midpoint of 62.5 and a maximum of 75 (Figure 1). Scores represented by solid dark green are greater than 75% of the mean and are considered "successful" (Figure 1). Scores represented by hatched light green (65.0–74.9%), solid yellow (60.0–64.9%), and dotted orange (50.1–59.9%) are considered "intermediate" indicating that some adaptive management or changes in technique, methodology, or planning are needed to improve success. Finally, scores represented by striped red are less than 50.0% of the mean, are considered "sub-optimal", and highlight metrics or categories where

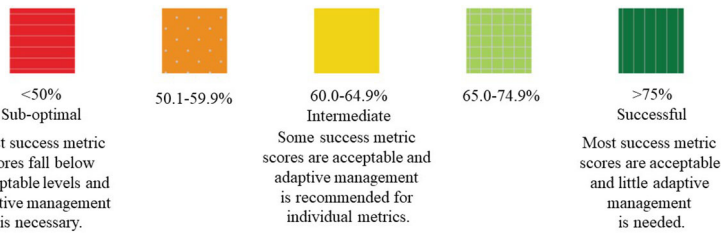

FIGURE 1
Composite scoring for restoration evaluation tool metrics and stoplight color coding 464 indicating the potential for restoration success [suboptimal = <50% (red with horizontal lines), 465 intermediate = 50.1–59.9% (dotted orange), 60.0–64.9% (solid yellow), 65.0–74.9% (hatched light 466 green), and successful = >75% (solid dark green)].

adaptive management must be adopted to fulfill project, program, or regional needs (e.g., population enhancement, research, mitigation, education, stakeholder livelihood, and community engagement). For example, if outplant survival is low due to predation by corallivores (<50% of the mean of other outplant sites and represented on the Programmatic Evaluation Tool as "red"), a program may decide to conduct predator removal at the outplant site, predator dilution or swamping (Shantz et al., 2011), or even abandon the restoration site and move outplanting efforts to a different site with lower natural predator prevalence. As another example, if a project receives a low score based on the genotypic diversity of outplants, then a project can increase propagation of additional genotypes, find additional locations for new collections, or consult with partner projects to exchange novel genotypes between nurseries.

In 2021, the evaluation tool was distributed to five coral restoration programs, each with at least 15 years of field-based nursery and outplanting experience around the Caribbean, including Oceanus, A.C. in Quintana Roo, Mexico (MX); the Grupo Puntacana Foundation in Punta Cana, Dominican Republic (DR); the University of Miami (FL), in Miami, Florida, USA; Sociedad Ambiente Marino in Culebra, Puerto Rico, USA (PR); and Fragments of Hope in Placencia, Belize (BE). Each program was asked to provide one score for each metric regardless of the number of projects (e.g., nurseries, outplant sites, etc.) that have been or currently are managed by the program. Therefore, a metric would receive a score of "1" if all nurseries meet the criteria and a score of "0" if even one nursery did not meet the criteria for that metric. Additionally, programs were asked to provide scores for all metrics even if the metric was not an overarching goal of the program (e.g., education and outreach, enhancing recreational opportunities, etc.). While scoring a "0" for some metrics based on the whole rather than individual examples may reduce the overall score for the program, the intent within these case studies was to show the versatility of the tool and how it may be used to identify metrics that may require changes, adaptive management, or additional steps to increase success. Programs provided comments for potential reasons for scoring a metric as "0" (e.g., nurseries do not contain multiple species as funding is only available for one species, outplant mortality was high due to storm damage, a nursery has low genotypic diversity as the nursery was only recently installed). The scores were tallied for each category (e.g., nursery, outplanting, management, education/outreach, event driven restoration, and socioeconomic restoration) and averaged for a composite score for each case study (e.g., MX, DR, FL, PR, and BE). Each program used as a case study has been conducting coral restoration (propagation and outplanting) for at least 15 years, using similar methodologies for rearing and outplanting corals, and similar monitoring designs to evaluate their efforts. To account for potential differences in methodologies or coral restoration strategies, each program was asked to provide explanations of why they scored a metric as a "0" and those responses were considered by the authors when analyzing the composite score for each program.

3 Results

Mean scores from case studies ranged between 68.4 and 94.7% for field-based nurseries and between 44.4 and 85.2% for outplanting (Table 2). Composite scores (i.e., mean scores of field-based nurseries and outplanting combined) for each case study ranged between 56.4 and 86.3% with four out of five programs scoring >75%. When composite scores were calculated to include management, education and outreach, event-driven restoration, and socioeconomic categories, scores were greater than 75% for four out of five programs (Figure 2), with scores ranging from 63.2 to 93.3% (mean 81.0%) among programs. Overall, the restoration category with the highest score among programs was "education and outreach" (92.0%) while the lowest

TABLE 2 Color-coded composite scores for six restoration metric categories from five case studies [Mexico (MX), Dominican Republic (DR), Florida (FL), Puerto Rico (PR), and Belize (BE)].

Category	MX	DR	FL	PR	BE	Mean Category Score
Nursery	73.7	68.4	94.7	73.7	84.2	78.9
Outplanting	81.5	44.4	77.8	85.2	81.5	74.1
Management	87.5	56.3	87.5	100.0	81.3	82.5
Education/Outreach	80.0	80.0	100.0	100.0	100.0	92.0
Event-driven	100.0	50.0	100.0	100.0	50.0	80.0
Socioeconomic	60.0	80.0	100.0	80.0	80.0	80.0
Mean Program Score	80.4	63.2	93.3	89.8	79.5	81.3

Colors indicate composite scores: striped red (<50%) = sub-optimal, dotted orange (50.1–59.9%), solid yellow (60.0–64.9%), and hatched light green (65.0–74.9%) = intermediate, and solid dark green (>75%) = successful.

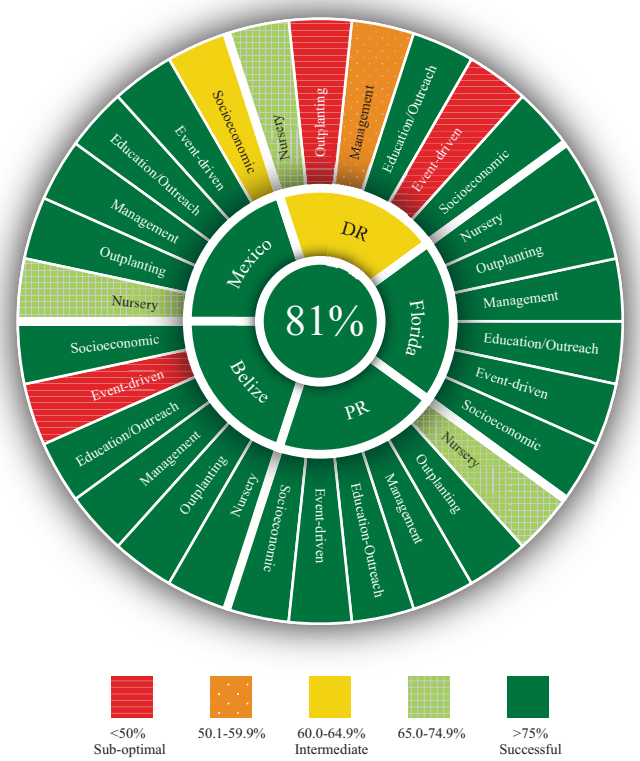

FIGURE 2
Color-coded scoring of six restoration categories (outer ring) for each of five case studies, composite scoring for each of five case studies [middle ring; Mexico (MX), Dominican Republic (DR), Florida (FL), Puerto Rico (PR), Belize (BE)], and the overall mean score of all case studies combined (center circle). Scores and color schemes represent suboptimal = <50% (red with horizontal lines), intermediate = 50.1–59.9% (dotted orange), 60.0–64.9% (solid yellow), 65.0–74.9% (hatched light green), and successful = >75% (solid dark green).

scored category was "outplanting" (74.1%). The category with the lowest variance (standard error) between programs was "nurseries" (75.8% ± 3.9) while the highest variance was within "event-driven restoration" (80.0% ± 12.2).

The composite score across programs for metrics within the nursery category (n=19) was 78.9% (Supplementary Figure S1). All programs scored high on several nursery metrics (numbered based on Metric # within the Evaluation Tool): 1) nurseries established based on published, best practices or approved guidelines, 4) nurseries contain a high degree of genotypic diversity, 10) nurseries exhibit net coral growth, 11) nurseries exhibit low prevalence of disease and/or disease within nursery is mitigated, 12) nurseries exhibit low impact of coral predators, 14) nurseries provide a sustainable source of corals that are regularly outplanted, and 17) nurseries can be easily expanded/reduced if necessary. Nursery metrics that received the lowest scores (≤40%) were: 9) nurseries exhibit low prevalence of partial mortality, and 13) nurseries exhibit limited competition by algae and other competitors. Scores were low for metrics such as partial mortality of corals within nurseries due to disease events or a lack of nursery maintenance. Competition by biofouling organisms, especially algae, was high also due to lack of nursery maintenance.

The composite score across programs for outplanting metrics was 74.1% (Supplementary Figure S2). All programs reported high values for the following outplanting metrics: 1) outplant sites are established based on published, best practices or approved guidelines, 2) outplant sites contains or has a historical presence of the outplanted species, 3) outplant sites are surveyed for reef community structure and species abundance prior to outplanting, 7) outplant sites contain multiple outplanted species, 8) outplants contain a high degree of putative genotypic diversity per restoration site, 9) outplants exhibit positive growth (all species) and/or increases in abundance (branching species), 18) outplants experience low levels of physical damage, and 23) outplants exhibit high annual survivorship/abundance during years 2–5 (Figure 2). Three outplanting metrics received scores <40%: 16) outplants exhibit low abundance and impacts from coral predators, 17) outplants exhibit limited competition by algae and other competitors, and 22) outplants improve the ecological value of the reef and provides improved habitat for non-corallivorous invertebrates. Scores were low for some metrics as conditions were spatially and temporally variable between restoration locations, and site maintenance and ecological surveys were not conducted at each location.

The composite score for program management metrics was 82.5% (Supplementary Figure S3) and all programs scored high for the following five metrics: 2) programs are increasing functional capacity of the region by deploying multiple projects strategically to

mitigate threats from large-scale disturbances, 3) programs are increasing functional capacity of the region by deploying projects strategically to enhance spatial coverage of restoration efforts (e.g., increase local coral, expand current population coverage, increase community education/involvement), 5) program has defined goal (s) and clear metrics of success based on published best management practices and guides, 7) program goals support wider conservation, management, and restoration actions, and 9) program restoration efforts can be scaled down as needed (Figure 2). Although no metrics received scores <60%, metrics associated with strategic planning for restoration goals and objectives, response planning to minimize and address stress events, and monitoring of restoration activities scored the lowest. Scores were low for these metrics as some programs do not have standardized or formal plans for overall restoration goals or emergency scenarios and monitoring is limited due to staffing or funding resources.

All programs used as case studies incorporate education and outreach components into their restoration plans resulting in the highest scores recorded for all the metrics evaluated (92.0 ± 4.9; Supplementary Figure S4). The only metric scoring <100% was due to some programs not having methods or survey instruments to evaluate increased awareness among volunteer participants within restoration activities. Both metrics associated with event-driven restoration scored 80% (Supplementary Figure S5), indicating that although some restoration programs are involved in restoring coral communities and monitoring due to damage from acute stress, not all programs have the capacity to conduct such activities effectively due to logistics or funding. For socioeconomic restoration metrics, the composite score was also 80.0% (Supplementary Figure S6), and all programs scored high for two metrics: 1) local stakeholders are engaged in reef conservation and management, and 3) restoration activities provide meaningful employment opportunities and income generation. Only one socioeconomic metric received scores <80%, restoration activities enhance recreational activities, as three out of five of the programs focus their restoration activities on population enhancement and ecological services rather than tourism and recreation.

4 Discussion

As coral propagation and outplanting efforts expand on a global scale, the need has increased for the development of regional restoration benchmarks and metrics for determining the status and performance of restoration programs. In addition, efforts have been made to standardize monitoring protocols to allow for quantitative evaluation of restoration projects and provide metrics of programmatic operational success beyond basic coral growth and survivorship (Schopmeyer et al., 2017; Goergen et al., 2020). The restoration evaluation tool described here provides detailed metrics and a scoring scheme based on published literature and expertise to assess the status of coral restoration projects and programs with a wide range of programmatic goals (e.g., population enhancement, education, enhanced livelihoods). More developed projects and programs can serve as the benchmarks against which newer projects can be assessed and serve as baselines for developing additional metrics and benchmarks (Schopmeyer et al., 2017).

Utilizing case studies from coral restoration projects around the Caribbean, we quantified the status of five restoration programs, compared metrics between programs, and evaluated differences among them. Using the scoring scheme outlined in this study, four of the five programs scored >75% overall indicating most of these well-established programs are performing well and are versatile, well managed, and sustainable. However, this tool is designed to evaluate methods and outcomes, identify specific metrics that do not meet current benchmarks or follow best practices, and inform programs on potential operational deficiencies. Therefore, a composite score of >75% can still indicate that some aspects of each program are below expectations and that implementing adaptative management actions may increase productivity and future restoration success.

Within the nursery category, two out of the five programs scored >75%. Most programs scored well in best nursery practices such as high genotypic diversity, good survivorship, positive growth, low disease prevalence, and good nursery management and planning. For metrics with scores <60%, programs indicated that limitations in staffing and financial support resulted in low nursery maintenance which contributed to increased partial mortality, competition with algae and damselfishes, and the ability to repair and recover nursery resources after storms. Higher scoring programs are programs associated with local universities which may contribute to overall nursery success as resources and staffing may be more readily available and sustainable. On the other hand, the remaining programs are run by not-for-profit organizations which often face resource and staffing limitations that may limit their ability to conduct consistent nursery maintenance.

In general, programs scored the lowest in the outplanting category. As in the nursery category, programs scored well based on genetic diversity and growth. Low scores were provided for metrics such as one-year survival, impacts of coral predators, and competition at the outplant site. It is important to note that many conditions, including overgrowth, competition, and predation, cannot be controlled by restoration operators on the reef as easily as they are within nurseries, and therefore it is not unexpected that many programs scored lower on these outplanting metrics than within the nursery category. Additionally, the impact of such conditions may be a factor of outplant density where scores are low during the first couple of outplanting attempts but may increase over time as outplants outgrow competitors or dilute the number of predators. Also, the three programs with higher mortality, predation, and competition are located in regions where fishing pressure may be higher, resulting in a lack of grazers to help maintain healthy reefs. Therefore, coral restoration projects may consider conducting restoration efforts within marine protected areas or working together with fishery programs to improve conditions on a reef or on an ecosystem scale. As mentioned previously, each program provided scores for restoration activities as a whole, meaning that the scores presented here may be lower

than if individual nursery or outplanting projects were scored independently. Based on the self-reporting from the programs in this study, metrics were scored as "0" because of one or two examples, projects, or sites where survival was low, or competition was high, suggesting that the majority of their outplants did well. But projects that continue to score low on outplanting components over time should investigate alternative outplanting methodologies or site locations, as well as site maintenance, to improve their success. Most other "0"s, provided for ecosystem service-type metrics, were the result of lack of monitoring as many programs must prioritize nursery maintenance and outplanting over monitoring when faced with limited staff or funding. Many programs were obliged to score low for long-term success metrics, such as environmental monitoring at outplant sites, outplants reaching sexual maturity, improved benthic habitat for coral associated organisms, and enhanced benthic composition, as they do not currently monitor these metrics or lack the funding to monitor long-term. Currently, most outplanting permits only require basic monitoring for up to 12 months and the lack of consistent funding to finance long-term monitoring can result in the paucity of outplant or ecosystem level success data beyond the initial year (Boström-Einarsson et al., 2020).

Four out of five programs scored above 80% within the program management category indicating that many programs are successful at utilizing management strategies focused on project persistence, threat avoidance, and overall ecosystem conservation. The highest scored metrics related to the program's ability to enhance the spatial coverage of their restoration efforts, increase the functional capacity of projects to strategically mitigate threats against large-scale disturbances such as storms and disease outbreaks, and support wider conservation, management, and restoration actions. Additionally, four of the five programs received a composite score > 80% from combined field-based nurseries and outplanting metrics suggesting programs are properly managing their active restoration strategies and methodologies. However, programs did score "0"s for management metrics such as basing their restoration goals and objectives on coral recovery plans and developing response plans to minimize and address disturbance events. Also, programs indicated that project monitoring did not include the data, methods, and frequency outlined in monitoring guides, which is indicative of low scores from the outplanting category. Such metrics could be easily rectified with the creation of program/project plans which address recovery goals and response planning, as well as developing and implementing standardized monitoring plans. Over time, scores for such metrics should improve as the projects and programs continue to develop and expand their capacity.

All five case studies include education and outreach as important goals of their program, resulting in this category having the highest composite score. Only one metric was below 100% as two programs do not have methods in place to evaluate volunteer and stakeholder awareness about coral reefs and restoration after participation in restoration activities. The creation of a survey to gauge the impact of projects on participant's views related to the need to protect and restore coral reefs would be a simple solution and easily facilitated through digital survey platforms. As many programs utilize volunteers and local stakeholders as part of their workforce, it is essential to develop and implement metrics to assess engagement strategies and volunteer training standards as well as the condition and survival of corals outplanted by education and outreach projects compared to those outplanted by restoration practitioners. Therefore, the value of restoration to both the reefs and to the local community are evaluated within the tool.

The ability of the different programs to respond to acute disturbances by conducting event-driven restoration was highly variable. Only two metrics currently exist within the tool that focus on evaluating the extent of the damage caused by an event like a storm, ship grounding, or disease outbreak, determining if coral restoration through triage or outplanting is feasible, and monitoring of post-event outplanting based on metrics outlined within this tool and other restoration and monitoring guides to determine the need for and success of event driven restoration. Some well-funded and established programs have the potential to respond to such events, but others lack such capacity. In regular use of this tool, programs would only use this section if event-driven restoration was a focus of restoration activities, and additional metrics may be created to better assess the need for and success of such restoration.

Restoration based on "Socioeconomic" goals was important for some programs included in this study. In general, programs focused on the ability of their activities to engage local stakeholders in reef conservation, provide meaningful employment and income generation, and support young professionals and local youth in their scientific development. As with education and outreach, many programs utilize local stakeholders, students, or volunteers to conduct restoration activities and value the opportunity to prepare the next generation of restoration practitioners and reef conservationists. Programs included as case studies here, in particular those located in Mexico, Belize, and the Dominican Republic, also focus on improving the livelihoods of local stakeholders, in particular those where restoration projects were designed to employ local fishermen as restoration practitioners to provide income in areas with severely overfished populations. One metric, enhancing recreational opportunities, ranked low among the programs. As Hein et al. (2019) explains, without proper management, reef-dependent tourism economies are not necessarily sustainable and may also create negative environmental impacts. Many restoration practitioners consider the vulnerability of outplant sites to visitation as outweighing that of the potential benefit to tourism and, therefore, do not focus on restoration that enhances recreational opportunities. However, outside of programs included in this study, many are located near popular tourist resorts and dive sites thus allowing for easy access to sites for restoration activities. Therefore, including additional metrics within the evaluation tool related to restoration to provide coastal protection, ecotourism, capacity building, and reef-user satisfaction may elucidate the socioeconomic benefits and risks of coral restoration and assist in determining how to build collaborative partnerships with local communities to increase restoration success without creating negative impacts.

As benchmarks for restoration success develop over time, the tool may be updated to reflect the most recent data, metrics, and guidelines. Metrics which are more appropriate for specific regions can be added to the tool as the information becomes available. For example, benchmarks for coral growth in Florida may not best represent productivity in the Dominican Republic due to widely different environments and disturbance drivers. As such, care should be taken when comparing results between projects, programs and/or regions to ensure that scores based on location-specific results do not lead to incorrect conclusions. This also reinforces the need for consistent and standardized monitoring to improve comparisons such as those suggested by Goergen et al. (2020). Adding or dividing some metrics to obtain more detailed and accurate scoring may be appropriate over time, so maintaining the evaluation tool as a living document will be essential to maintaining the utility and value of the tool. Finally, adaptation of the evaluation tool into an online platform similar to the database/dashboard created by Boström-Einarsson et al. (2020) would simplify data entry and reporting while also creating a common, user-friendly platform for restoration operators, managers, and scientists to discuss challenges and successes within the restoration community.

The program evaluation tool described here will benefit the coral restoration community, including practitioners and managers, by providing a systematic method for assessing the status of restoration projects and programs developed on set metrics linked to specific restoration goals and appropriate monitoring guidelines. This tool goes beyond just measuring outplant growth and survival and includes metrics to evaluate other components vital to the success of reef-scale restoration such as coral reproduction, recruitment of reef organisms to a restored site (e.g., corals, fish, invertebrates, and megafauna), increase in sustainability of reef fisheries, improvement to overall reef habitat (e.g., shelter, rugosity, shoreline protection), success and challenges in restoration performance, adaptability of techniques, and ensures that restoration projects and programs are sustainable. Additionally, the tool captures status information of a wide range of potential project components and goals, including key steps such as coral collection, nursery deployment and maintenance, coral monitoring, stakeholder involvement, funding sources, data sharing, education and outreach, and project sustainability that can be tracked over time, and identifies project components in need of immediate adaptive management. The metrics within this tool focus on best-management practices or results from restoration-based research conducted by experts in the field of coral propagation and outplanting and are designed to evaluate the strength and robustness of each project or program while also identifying specific metrics which may need adjustment or action to improve performance. Programs may not need to evaluate themselves across all categories or utilize all of the metrics for this tool to be useful. Ideally, programs can define their goals and then identify which metrics align to those goals and are to be evaluated routinely (monthly, quarterly, annually). As programs change their goals, they can add to or change the metrics being used to evaluate themselves. For example, this tool may be updated to include metrics for programs utilizing land-based nurseries. Finally, the intent of the tool is not to criticize any particular project or diminish the hard work of restoration practitioners and managers, as we can learn as much from shortcomings and failures as we can from instant success. This tool allows for self-critique of methodologies, techniques, and protocols to promote the design of adaptive strategies to improve performance and encourage communication between restoration partners (locally, regionally, or globally) to increase success. Therefore, this restoration evaluation tool will advance the development of science-based benchmarks to achieve population-based recovery for coral reefs by evaluating the status of restoration techniques, outlining the positive attributes of productive projects and programs, and promoting the development of successful strategies to achieve population-based recovery for corals and coral reefs.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

SS: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing. VG: Methodology, Resources, Writing – review & editing. EH-D: Methodology, Resources, Writing – review & editing. GN: Methodology, Resources, Writing – review & editing. MD'A: Methodology, Resources, Writing – review & editing. LC: Methodology, Resources, Writing – review & editing. EG: Conceptualization, Writing – review & editing. SV: Conceptualization, Writing – review & editing. AM: Conceptualization, Writing – review & editing. DL: Conceptualization, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. Funding for the initial version of this restoration evaluation tool was provided by Counterpart International and the Punta Cana Ecological Foundation. Travel to the 2018 Reef Futures symposium was provided by the Coral Restoration Consortium (CRC) for brainstorming concepts related to this tool and the CRC Monitoring Guide. The National Fish and Wildlife Foundation (Grant 66113) provided partial support to EH-D.

Acknowledgments

The authors would like to thank Austin Bowden-Kerby, Jake Kheel, Jessica Levy, Amelia Moura, and Rita Sellares for their contributions to the development of this restoration evaluation tool and edits to the manuscript. The authors also thank Jessica Pernell for creating the evaluation tool graphics.

Conflict of interest

Author VC was employed by company Iberostar Group.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling editor BR declared a past co-authorship with the author EAHD.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2024.1404336/full#supplementary-material

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