

Hawai‘i Reef Restoration Monitoring Guide

F. Joseph Pollock, Gregory P. Asner, Ryan Carr, Eric Conklin, Courtney Couch, Daniel Demartini, Alexander Garcia, Mark Hixon, Kira Hughes, Brittany Huntington, Kim Falinski, Ryan Okano, Tom Oliver, Andrew A. Shantz, and Shannon Ruseborn

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Cover photo Top-down view of impacted Hawaiian coral reef. Photo credit: The Nature Conservancy.

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Executive Summary

Effective monitoring is vital to assess, refine, and adaptively manage coral reef restoration projects, but standardized monitoring protocols for restoration in Hawai‘i are currently lacking. This Hawai‘i Restoration Monitoring Guide fills this gap by outlining a standardized and readily implementable monitoring strategy. This abbreviated guide is based on the Coral Restoration Consortium’s Universal Metrics for Coral Reef Restoration—to ensure general comparability—and was developed in collaboration with the Hawai‘i Reef Restoration Science Team—to ensure suitability for the unique ecological and environmental context of Hawai‘i. The plan provides both high-tech and low-tech options to quantify each restoration metric to maximize inclusivity and adaptability without sacrificing comparability. For example, photogrammetric technologies can be used to create indelible snapshots of reefs for in silico (i.e., at a computer on dry land) assessment or monitoring can be conducted entirely in situ using visual assessments. Both approaches monitor the same set of selected metrics to quantify restoration progress, identify challenges early, and compare restoration outcomes across the state and the globe.

Monitoring Rationale

Why implement coral reef restoration?

Coral reefs are central to Hawai‘i’s economy, identity, and way of life, but they are under increasing threat. Hawaiian reefs are valued at over $33 billion (Bishop et al., 2011), support more than $10 million in nearshore fisheries each year (McCoy et al., 2018), and provide flood protection to people and property valued at more than $836 million annually (Storlazzi et al., 2019). The natural bounty of Hawaiian reefs has sustained the islands' communities for generations, and sophisticated traditional resource management approaches have historically protected the islands’ reefs and nearshore fisheries.

Unfortunately, the combined pressures of a growing population, heavy usage, and warming oceans have taken a significant toll on Hawai‘i’s coral reefs. Some reef areas have experienced 60% reductions in live coral cover in recent decades and some reef fish populations have fallen as much as 75% from historic levels (Birkeland & Friedlander, 2001; Minton et al., 2012).

Mass bleaching events in 2014/15 and 2019 caused coral bleaching across the Hawaiian archipelago (Couch et al., 2017; Rosinski et al., 2017; Winston et al., 2022). The 2015 event resulted in extensive coral mortality, for example, coral cover was reduced by up to 50% on surveyed reefs on west Hawai‘i Island (Kramer et al., 2016). These losses threaten Hawai‘i’s culture, economy, food security, and coastal resilience.

While small-scale reef restoration in Hawai‘i has been ongoing for the last decade, the dramatic decline of Hawaiian reefs has prompted scientists and reef managers to explore more scalable reef restoration approaches by outplanting corals onto degraded reefs. As the frequency and intensity of bleaching, disease, and storm events continues to hinder natural processes of recovery, restoration has emerged as an opportunity to catalyze reef rehabilitation and bolster resilience.

Why monitor coral reef restoration?

Reef restoration takes place within a myriad of different contexts and conditions—the goals of restoration projects differ, and what works in one location may not work in another. Therefore, effective monitoring is essential to determine if projects are making progress towards their goals and to identify and address challenges before they compound into program failure (NAS et al., 2019). Evaluating the success of restoration programs requires consistent monitoring of carefully chosen metrics to quantify progress towards clearly articulated goals and objectives. While there is no exhaustive list of every metric that should be monitored for every project, standardized and comparable metrics to evaluate restoration projects are critical for evaluating efficiency, cross-geography learning, and adaptive management (Goergen et al., 2020; Huntington et al., 2024).

Monitoring Approach

Goergen et al. (2020) present a set of universal metrics that could be measured for all reef restoration projects globally. The monitoring approach detailed below provides a straightforward, efficient, and statistically robust method for collecting these Universal Metrics that can be implemented in nearly any reef restoration project. These metrics and timeframe are intended to provide general considerations rather than a prescriptive plan. In some cases, additional metrics will be needed to assess progress towards your project objectives. For example, if your restoration goal is to increase habitat complexity for reef fish, you may need to add a measurement of structural complexity. Consider discussing your goals, planned metrics, and methods to analyze them with scientists or other technical experts before monitoring begins.

Before, After, Control, and Impact (BACI) experimental design

To accurately quantify the impacts of restoration efforts, it is important to collect pre- and post-restoration data at intervention and control sites. Such “Before, After, Control, and Impact” (BACI) experimental designs allow powerful statistical comparisons to quantify the true impact of restoration (Green, 1979). While beyond the requirements of most permits, a robust BACI design is the gold standard for assessing the efficacy of reef restoration and should be developed before restoration activities commence.

The “before” component of the BACI design requires that monitoring efforts begin at all sites—including control sites—prior to the restoration intervention. These pre-restoration surveys provide metrics on baseline conditions relative to which change over time can be quantified. Monitoring timing, frequency, and duration should be consistent across all sites both prior to and “after” the initiation of restoration.

Inclusion of “control” sites allows analyses to account for natural variability in and perturbations to the broader reef system (e.g., bleaching, storms) over time. Control sites are defined as nearby sites with biotic and abiotic conditions comparable to those of the restoration (i.e., “impact”) sites as possible. Reef surveys, local knowledge, and online tools like the Reef Restoration Mapping Tool (ReefRestoration.TNC.org) can help characterize restoration sites and identify controls sites with similar conditions (e.g., anthropogenic impacts, benthic community composition, depth, habitat complexity, and live coral cover).

Control sites should be approximately the same size as restoration (i.e., “impact”) sites and ideally contain wild colonies of the same species as those being restored. Identifying comparable control sites may be difficult depending on the type of reef that is being restored and extent of damage that has necessitated restoration. In addition, monitoring control sites may not be logistically or financially feasible for some reef restoration practitioners. Given these challenges, we recommend that restoration practitioners consult with state, federal, NGO, and academic partners conducting long-term monitoring in Hawai‘i, as these established programs may help identify control sites and/or provide “before” and “after” control data. These agencies may also be able to provide the statistical expertise to analyze and interpret BACI results, which may not

always be straightforward. For more details on BACI designs for reef restoration, see Goergen et al. (2020) and Huntington et al. (2024).

Monitoring phases and timeframe

The BACI design dictates that all the following phases be conducted as consistently as possible at both replicate control sites and replicate restoration ("impact") sites. The "pre-implementation" phase refers to the "before" component of the BACI design, whereas the other phases (e.g., short-, mid-, and long-term monitoring) comprise the "after" component. Although specific timing will depend on project goals and metrics used to track success, restoration monitoring can be generally broken into five phases:

- **Pre-implementation (i.e., "before") surveys conducted prior to outplanting** establish a baseline for all subsequent monitoring. These surveys should be conducted at both the planned restoration sites and paired control sites discussed above.
- **Reconnaissance surveys at restoration sites (within two weeks of outplanting)** provide initial qualitative surveys to identify immediate problems (e.g., transport, handling, or predation issues) for rapid course correction.
- **Short-term (i.e., implementation) monitoring (one year or less)** largely addresses how well the initial restoration was designed and executed, with particular focus on assessing the effectiveness of site selection and outplanting approaches on outplant survival.
- **Mid-term (i.e., effectiveness) monitoring (two to five years**) begins to quantify success of the restoration project relative to its stated goals and objectives. The effectiveness monitoring phase should clarify if the selected restoration approaches are allowing the outplants to grow and thrive (e.g., high survivorship and low tissue loss and damage) as well as indicators that restoration is moving towards meeting project specific goals (e.g., impacts on the local fish and invertebrate communities, reef accretion rates, structural complexity). At this phase, annual coral monitoring should be sufficient.
- **Long-term (i.e., impact) monitoring (five years and beyond)** assesses the impact of the restoration activities on the broader ecosystem once the outplants have had time to settle, grow, and influence the wider reefscape. Note, assessing wider reefscape changes may require additional metrics (e.g., coral cover and structural complexity), which are not included in the universal metrics below. At this phase, biennial monitoring should be sufficient.

Monitoring approach and metrics

In situ surveys

Historically, in situ surveys have been the most common approach to restoration monitoring. During these surveys, monitoring teams collect measurements while in the water, typically while snorkeling or scuba diving. Metrics are typically quantified using flexible tapes to measure the restoration footprint and colony size and visual assessments to estimate percent mortality. We advise also taking photographs of the

colonies from multiple angles as a visual record. Hand-drawn maps, GPS points, and/or colony tags may help relocate individual colonies in future surveys. While in situ surveys allow restoration practitioners to exit the water with data, they require a considerable amount of in-water time and are prone to observer error.

Benthic community photomosaics

Structure-from-Motion (SfM) photogrammetry is a powerful tool for reef restoration monitoring, providing permanent visual archives of reef sites that can be assessed at multiple scales (Box 1). SfM is a type of photogrammetric analysis of overlapping digital photographs that enables precise, accurate, and comprehensive benthic compositional and three-dimensional structural measurements (Ferrari et al., 2017; Lange & Perry, 2020). SfM involves taking several hundred to several thousand overlapping underwater photographs of coral reef monitoring sites from different perspectives. Photogrammetry software is then used to match features between adjacent images to generate three-dimensional models of the reef and stitch the photos together into very accurate and highly detailed photomosaics. The resulting products allow users to assess the reef in silico (i.e., at a computer on dry land) and quantify changes in reef structure as well as demography, community composition, and many other metrics and parameters. Importantly, SfM provides indelible snapshots of the reef at specific moments that can be compared over time (e.g., BACI analysis).

While all of the universal metrics discussed in this guide can be monitored with in situ assessments, SfM provides a powerful tool to efficiently survey large restoration areas and thousands of colonies. SfM offers high precision and enables efficient underwater image collection, especially over large areas, which can significantly reduce in-water time. However, it's important to understand that there are tradeoffs to this approach.

The primary challenge with SfM lies in the high computational and annotation time required to convert images into detailed photomosaics and extract metrics of interest. Currently, data generation in silico is not readily automated. It requires human annotators trained in specialized software, which can be a time-consuming process until more automated procedures become widely available. For some metrics, particularly those not requiring fine-scale precision in measurement, traditional in situ methods may still be more effective, especially for small-scale projects where site access and in-water time are not limiting factors. The choice between SfM and in situ methods should be based on project scale, available resources, and specific metric requirements. It is important to note that SfM is not always the better option compared to traditional in situ methods.

Due to the technical nature of SfM planning, collection, analysis and curation, we suggest referring to the large-area imaging guide prepared by Edwards et al. (2023) as a complement to this plan. This guide provides detailed information on SfM methodologies and considerations, which can help practitioners make informed decisions about when and how to implement this technology in their restoration monitoring efforts.

The high cost, specialized equipment and technical expertise required for SfM imaging and data curation, backup, and analysis may make this high-tech approach infeasible for some restoration programs. To maximize inclusivity and adaptability without sacrificing comparability, low-tech, in situ assessment approaches are presented for each metric that are comparable with those assessed in silico.

Box 1. Photogrammetry and ex situ assessment

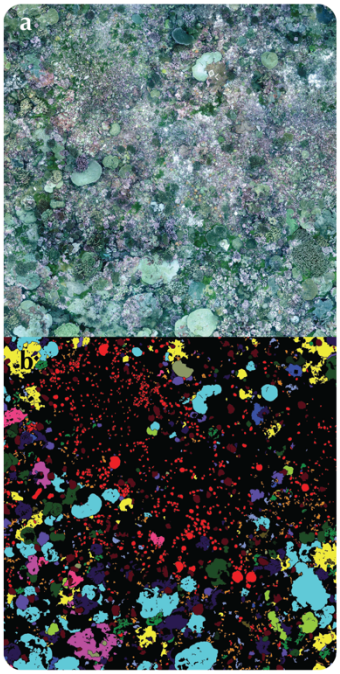
Box 1. Photogrammetry and *ex situ* assessment

Photogrammetry for reef monitoring

Photogrammetry is an increasingly important technique for monitoring coral reefs. The process involves taking hundreds or thousands of overlapping underwater photographs of monitoring sites from different perspectives. Specialized software then matches features across the images to generate highly detailed two-dimensional photomosaics (Box 1.1.a.) and/or three-dimensional digital surface models. Photomosaics can be used to derive reef-, population- and colony-level metrics, including colony taxon (Box 1.1.b), size and percent live tissue, and three-dimensional models allow precise spatial measurements of habitat features, like structural complexity and colony volume. Importantly, photogrammetry data collected at the same sites over time can serve as large-scale archives for monitoring reef change.

In situ vs *ex situ* assessment

Coral reef monitoring data has traditionally been collected *in situ* by highly trained research divers. The need for skilled staff with the experience to accurately and rapidly collect benthic data combined with the requirement that these divers spend extended periods of time underwater on SCUBA presents significant financial and logistical challenges, particularly in remote locations (Page et al. 2017). *Ex situ* assessment of benthic photogrammetry products (i.e., at a computer on dry land) has the potential to mitigate these challenges and increase survey efficiency by a) reducing the amount of time divers are required to spend underwater by relocating the bulk of benthic assessments from the field to the lab and b) providing a permanent visual record of reef status and condition (Lirman et al. 2007). Instead of requiring expert staff to travel to remote locations, they can assess digital images shared over the cloud from almost anywhere on earth. The permanent visual record that photomosaics provide also allows analyses of criteria that may not have even been considered when the monitoring program was originally established.



Box 1.1. Sample a) raw and b) digitized 100 m² photomosaic plots. Each color in the digitized mosaic (b) corresponds to a distinct coral taxon. Adapted from Edwards et al. (2017).

Universal metrics

The universal metrics that should be collected for all reef restoration projects were described by Goergen et al. (2020), are summarized in Figure 1 and Table 1, and briefly described below. While all universal metrics are valuable for assessing restoration success, not all of them need to be directly measured. We have carefully differentiated between metrics that must be measured versus those that can be calculated (i.e., derived) later than these measurements. This distinction helps focus limited time and resources on collecting this relatively small subset of metrics. Metrics that must be measured include water temperature, restoration footprint, coral size, genotypic composition, and live tissue percentage. Other metrics, such as size-frequency distribution, abundance, density, percent cover, and partial mortality distribution, can be

derived from these field measurements. This approach streamlines data collection while still providing comprehensive information about restoration outcomes. Figure 1 illustrates this differentiation, with measured metrics shown in blue and derived metrics later shown in green.

While the universal metrics focus on restored corals within restoration (i.e., “impact”) sites as previously mentioned, wild colonies of a similar species composition should ideally be monitored within “control” sites to provide context for how the restored colonies are faring relative to their wild counterparts (see “Before, After, Control, and Impact (BACI) experimental design” section above).

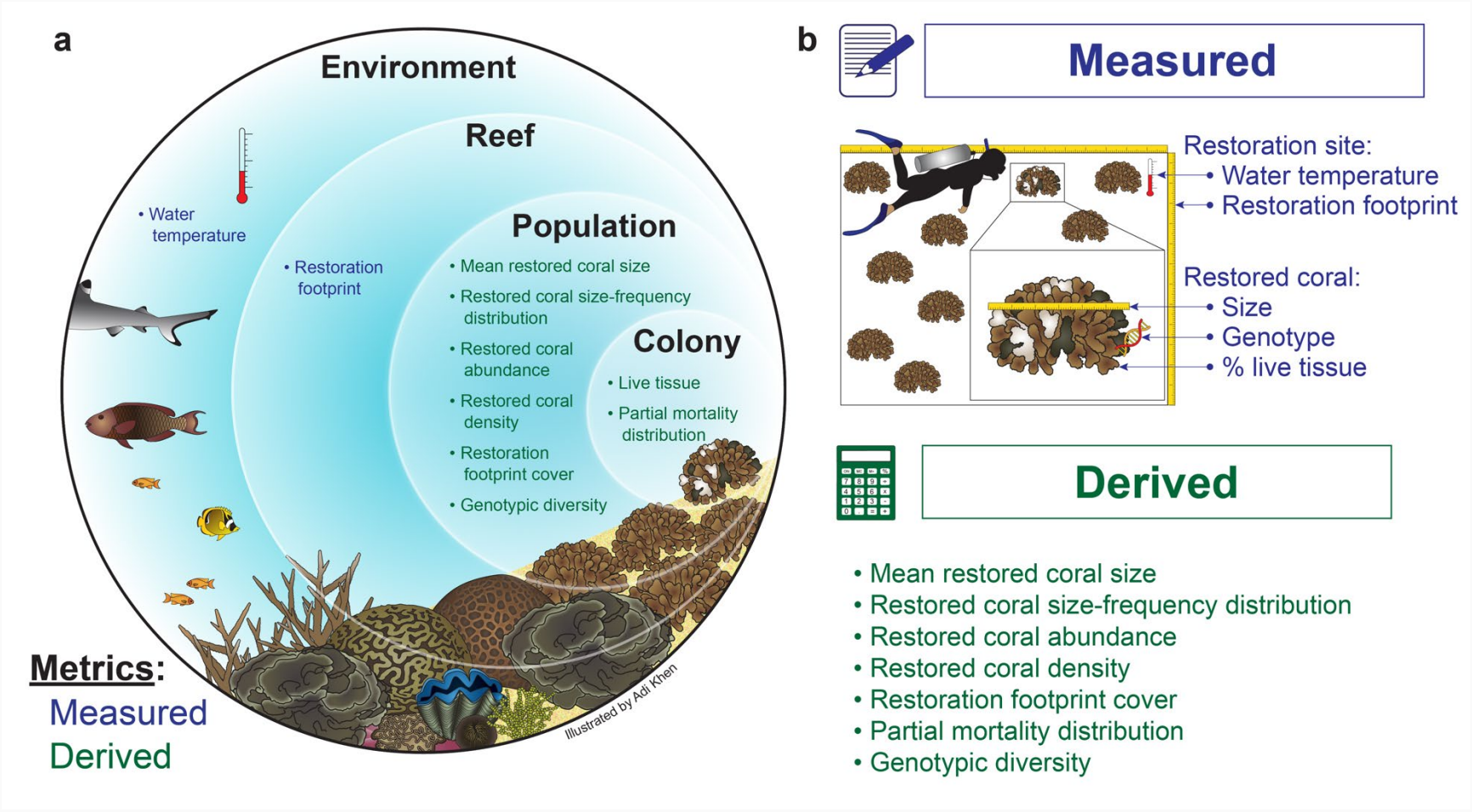


Figure 1 Universal metrics for monitoring coral reef restoration. Universal metrics enable consistent evaluation of reef restoration success and should be collected on all reef restoration projects. (a) These metrics evaluate restoration at different scales (i.e., environment, reef, population, and colony), providing data on the size, growth, condition, and diversity of restored corals and water temperature and dimensions of the restoration site. (b) Many of the recommended universal metrics can be derived (green text) from a small subset of metrics measured (blue text) either in person or in silico.

Table 1 Summary of universal restoration metrics. Adapted from Goergen et al. (2020).

Scale	Brief description of metric	Metric	Unit	Measured or derived?	Low-tech	High-tech
Environment	Reporting of the water temperature of restoration sites	Water temperature	°C: maximum, minimum, and monthly mean temperature at each restoration site	Measured	In situ temperature loggers (e.g., HOBO data loggers)	Real time temperature logging (e.g., Aqualink buoy)
Reef	Area where corals were outplanted	Restoration footprint	m^2: surface area of restoration site (planar projection)	Measured	In situ distance & angle measurements to construct polygon	Outline from aerial imagery (drone or satellite); SfM Outline; GPS points around area, overlaid in a google map style analysis.
Population	Measurement of the genotypic composition and distribution of size classes of restored corals	Mean restored coral size	cm^2: mean restored coral colony size by species (planar projection)	Measured	In situ identification & measurements of individual colonies	In situ measurement from SfM
		Restored coral size-	%: percentage of restored coral	Derived	Derived from mean restored colony size	

		frequency distribution	colonies per species by size class		(i.e., number in size class / restored coral abundance)	
		Restored coral abundance	#: number of restored coral colonies by species	Derived	Derived from mean restored colony size (i.e., sum of colonies measured)	
		Restored coral density	#/m^2: number of restored coral colonies divided by restoration footprint	Derived	Derived from restored coral abundance and restoration footprint (i.e. restored coral abundance / restoration footprint)	
		Restoration footprint cover	%: percentage of restoration footprint occupied by restored coral colonies	Derived	Derived from mean restored colony size, restored coral abundance, and restoration footprint (i.e., [mean restored colony size x restored coral abundance] / restoration footprint)	
		Genotypic diversity	#: number of unique genets per species at each restoration site	Measured	Presumed genotypes based on minimum geographic collection distance	Genetic sequencing
Colony	Estimate of the amount of live tissue on restored corals and tracking of	Live tissue	%: mean percent live tissue per restored coral colony, with note of colonies lost to dislodgement	Measured	UW visual estimate of % live tissue and colony presence/absence	In silico measurement from SfM

	colonies lost to dislodgement	Partial mortality distribution	%: percentage of restored coral colonies in each percent mortality class, and percentage lost to dislodgment.	Derived	Derived from live tissue and restored coral abundance (i.e., number in % mortality class / restored coral abundance)

Environmental: water temperature

Water temperature is an important and easily obtained environmental metric with implications for coral growth rates and the prevalence of disease and bleaching (Clausen & Roth, 1975; Douglas, 2003; Harvell et al., 2007; Highsmith, 1979; Jones et al., 2004).

In this monitoring plan, we recommend that water temperature data are collected for each restoration and control site, using temperature loggers deployed at each site and programmed to collect data hourly (e.g., HOBO or similar). Where possible, satellite-connected Aqualink smart buoys can also be used to provide real time temperature data. The NOAA Coral Reef Watch program (https://coralreefwatch.noaa.gov/main/) can also provide information on sea surface temperatures at restoration sites as well forecast potential bleaching conditions to help plan additional monitoring and interventions (Foo & Asner, 2020).

Water quality plays a crucial role in coral reef health and restoration success. While temperature is the only required universal water quality metric, monitoring additional parameters can provide valuable insights into local environmental conditions. Box 2 outlines the importance of conducting a desktop scoping assessment of existing water quality information before beginning restoration work and suggests additional parameters to monitor if resources allow. Thoughtful consideration of water quality can significantly enhance restoration planning, implementation, and long-term success.

Box 2. Water quality monitoring

Box 2. Water quality monitoring

Importance of water quality data

Water quality is a critical factor influencing coral reef health and restoration success. While temperature is the only universal water quality metric required for all restoration projects, monitoring additional water quality parameters can provide valuable insights into local environmental conditions and potential stressors.

Water quality monitoring approaches

Before beginning restoration work, a desktop scoping assessment of existing water quality information should be conducted. This process helps build awareness of potential threats and identifies valuable data sources for ongoing monitoring. Key steps include:

- Reviewing existing water quality data from government agencies, academic institutions and community monitoring programs.
- Consulting local experts and stakeholders to understand historical and current water quality issues (see Table 2).
- Identifying gaps in available data that may be relevant to your restoration project.

If resources allow, consider monitoring these additional parameters:

- **Dissolved oxygen**: Measures the amount of oxygen gas dissolved in seawater, which is essential for respiration.
- **Photosynthetically Active Radiation (PAR)**: Measures light levels essential for coral growth and photosynthesis.
- **Salinity**: Indicates freshwater input and potentially land-based pollution sources.
- **Turf algae cover**: Indicates substrate availability for coral recruitment and potential competition with corals.

When possible, existing monitoring programs or partnerships should be leveraged to collect water quality data. This collaborative approach maximizes resources and contributes to broader coastal management efforts.

Reef-level: restoration footprint

Restoration footprint measures the contiguous reef area over which corals are outplanted. Restoration footprint differs slightly from the Restored Reef Areal Dimension (RRAD) metric presented in Goergen et al. (2020). Both measure the two-dimensional reef area encompassing all outplants using the shortest contiguous boundary (i.e., the restoration footprint). However, while RRAD changes over time as corals die or spread, restoration footprint remains consistent over time. Restoration footprint can be calculated from SfM imagery or measured in situ using distances and compass bearings.

RRAD was developed to capture growth and reef-level expansion of coral taxa that rely on asexual fragmentation (e.g., *Acopora cervicornis*). In the main Hawaiian Islands, very few coral species (e.g., *Porites compressa*) reproduce via asexual fragmentation so colony breakage or displacement is not expected to provide meaningful contributions to many restored coral areas. Furthermore, redefining restoration areas throughout the project makes interpreting changes in area-based metrics like percent cover and coral density challenging and can hinder comparison with control sites in the BACI framework. Therefore, this monitoring plan suggests using restoration footprint instead of RRAD. For ease of measurements, the restored area should be clearly demarcated by physical landmarks or markers (e.g., pins, tags, nails) before the project begins and an equivalently sized area should be identified and monitored in control plots for

comparison. Within the restored area, RRAD can still be quantified at the site to understand changes in the distribution and spread of restored corals but metrics such as percent cover and restored colony density should be recorded based on the original restored area for the BACI design.

Population-level: coral size, size-frequency, abundance, density, cover, and genotype

Population-level metrics describe the demographics of the restored coral populations, including:

- **mean restored coral* colony size**: Mean restored coral colony size should be calculated from measurements of outplanted corals, either made in the field during surveys or calculated from SfM imagery. At minimum, the mean restored colony size should be reported as the maximum diameter by species in centimeters. Ideally, colonies can also be measured along their orthogonal diameter in the field to calculate colony area based on the equation for an ellipse or traced in photomosaics to provide a two-dimensional colony area.
- **restored coral* colony size-frequency distribution**: percentage of restored coral colonies per species by size class; corals should be classified into the following bins: <5 cm; 5–10; 11–20; 21–30; 31–40; 41–50; 51–75; 76–100; >100 cm.
- **restored coral* colony abundance**: number of restored corals by species.
- **restored coral* colony density**: number of restored corals divided by the restoration footprint. If several plots exist within the restored area, colony density should also be calculated at the plot level if applicable, in number per m^2.
- **restored coral* percent cover**: percentage of the restoration footprint and plot area when applicable occupied by restored corals. Percent cover can be calculated by summing the 2-dimensional measured area of all restored corals and dividing by the total area of the restoration footprint or plot.
- **genotypic diversity**: number of unique genets per species at each restoration site.

***** As defined by Goergen et al. (2020), a restored coral colony is defined as “one continuous skeletal unit, which has live tissue. Isolated tissue areas on one skeletal unit are considered part of one coral as long as the skeleton is continuous between the living tissue areas.” As previously mentioned, wild colonies in comparable "control" sites should also be monitored to provide context for restoration outcomes (i.e., BACI design).

Genotypic diversity is a measurement of the number of unique genotypes (genets) that are used for restoration per species. Repeated asexual propagation and outplanting of a small number of donor colonies has the potential to reduce genetic diversity which can negatively affect reef resilience (Baums, 2008; Baums et al., 2019; Drury et al., 2017). Therefore, it is important to track intra-specific diversity in reef restoration efforts.

Determining coral genotypes requires genetic testing that is rarely available for most reef restoration practitioners. Instead, many places like the Caribbean use distance

between donor colonies as a proxy for genetic diversity. However, in Hawai‘i, most reef restoration is conducted utilizing “corals of opportunity” (COO). COO are colonies or fragments of coral that have naturally (resulting from surge/water motion, storms, etc.) or unnaturally (resulting from boat- strikes/groundings, anthropogenic impact, etc.) been dislodged or unattached from the substrate and have a low chance of survival without human intervention. Asexual reproduction via fragmentation is uncommon for most Hawaiian coral species. Thus, unless COO fragments have clearly broken off from the same colony, for the purposes of this guide, we suggest considering each COO as a unique genotype. The only exception to this guidance is when collecting *Porites compressa* for restoration. Here, fragments of *P. compressa* collected from the same location should be considered a single genotype. Where possible, genetic sequencing should be used to confirm lack of clonality and, to the degree possible, genetic relatedness. Furthermore, nursery operations that involve collection and propagation of corals through fragmentation should carefully inventory the number of clonal fragments produced and track their origins, outplant locations, and numbers. Before outplanting, genotypic diversity and colony origins need to be carefully considered in the restoration plan.

Colony-lvel: live tissue and partial mortality distribution

Colony-level metrics quantify the presence and condition of restored coral colonies, including:

- **live tissue***: mean percent live tissue per restored coral colony and presence/absence of restored colonies.
- **partial mortality distribution**: percentage of restored coral colonies in each percent mortality interval (i.e., 0%; 1–25%; 26–50%; 51–75%; 76–99%; or 100%) and percentage lost to dislodgement.

  * On reefs exposed to high wave energy, colony loss due to dislodgement can be quite common. Data collection for this metric provides an opportunity to differentiate between colonies that have died in place, those suffering partial mortality, and those lost to dislodgement.

All colony-level metrics can be calculated using percentage live tissue measurements from each restored colony (Figure 1, Table 1). In this monitoring guide, percent live tissue measurements are collected from individual restored colonies using time series photomosaics. If SfM is not available or pragmatic, percent live tissue measurements can be collected from individual tagged colonies in situ.

Data collection for these colony-level metrics should allow differentiation between corals that have died in place (i.e., 0% live tissue, but still present), those that have experienced partial mortality, and those lost due to dislodgement (i.e., absent). This distinction is crucial in Hawaiian reefs, where colony dislodgement can be as significant as, or even more significant than, mortality in place. In the BACI design, it is important to track natural dislodgement and loss of colonies in control plots, which can be substantial during significant swell seasons.

In larger restoration projects, it may be more practical to subsample colony-level metrics. Determining the appropriate subsample size will depend on the overarching goals of the project but should accurately capture patterns in the restored population (Box 3).

Box 3. Subsampling and statistical power

Box 3. Subsampling and statistical power

The need for subsampling

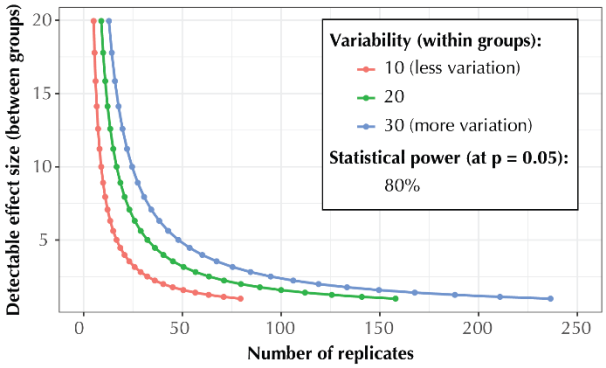
As restoration projects scale up, monitoring every coral outplant quickly becomes impractical. Subsampling (i.e., monitoring a representative subset of outplants) allows for efficient data collection while maintaining statistical validity. However, determining the optimal number of colonies to monitor can be a challenging endeavor. Power analysis helps balance the need for robust data with the practical constraints of time and budget.

Power analysis for optimal replication

Power analysis is a statistical tool that helps determine the minimum sample size needed to detect meaningful effects, balancing statistical rigor with available resources. Key factors affecting replication include:

- **Desired detectable effect size**: Larger differences between groups are easier to detect at lower sample sizes.
- **Variability**: Greater variability in responses within groups increases the sample size needed to detect an effect of a given magnitude.
- **Desired statistical power**: Typically, 80% or higher, this represents the probability of detecting an effect if it exists.

Box 2.1. illustrates how the number of replicates affects the detectable effect size under different levels of variability. To determine the optimal number of replicates (i.e., subsamples), an estimate of variability is typically obtained from a preliminary study or existing literature, which is then used for power analysis calculations (e.g., the "power.anova.test()" and "power.t.test()" in the free statistical software, R). Consultation with a statistician or reef monitoring expert (Appendix 1) can greatly streamline this process.



Box 3.1. Sampling power curves showing the relationship between number of replicates and detectable effect size. Lines represent different levels of variation within groups. More replicates allow detection of smaller effects, but with diminishing returns. Higher variation requires more replicates to detect the same effect size.

Closing Remarks

This monitoring guide was developed in collaboration with the Hawai‘i Reef Restoration Science Team—a consortium of scientists, reefs managers, and restoration practitioners working to maximize restoration success on Hawaiian reefs—and aims for consistency with global best practices while ensuring suitability for Hawai‘i’s unique ecological and cultural context. As the field of restoration matures and expands in Hawai‘i, the Pacific, and beyond, the metrics and monitoring approaches presented here will likely require iterative improvement and/or modification. Therefore, this guide is intended to be a living document that can and will be updated regularly to be as useful and relevant as possible to ensure effective restoration of Hawai‘i’s vitally important coral reefs.

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