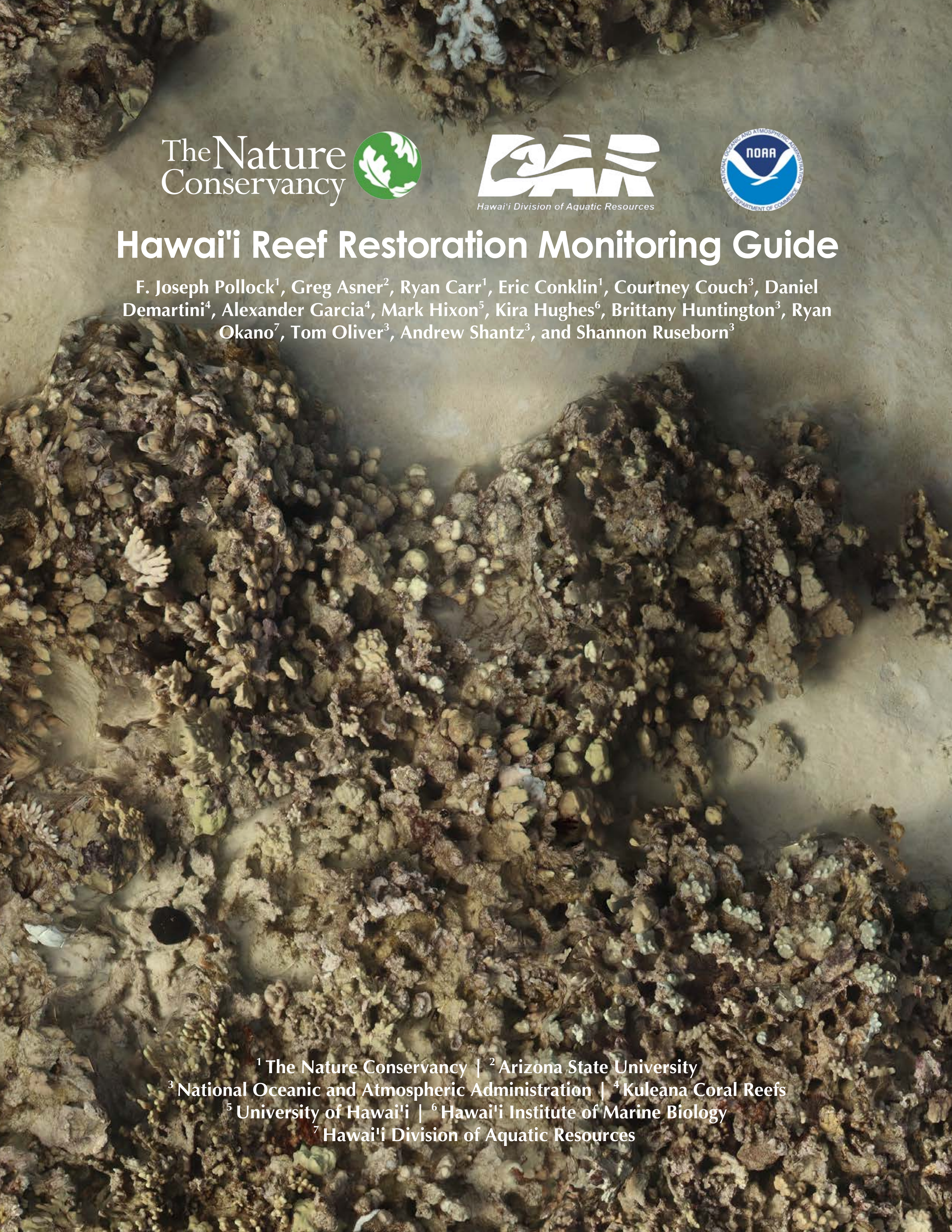

Hawai'i Reef Restoration Monitoring Guide

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Executive Summary

Effective monitoring is vital to assess, refine, and adaptively manage restoration projects, but standardized monitoring protocols for reef restoration in Hawai'i are currently lacking. The Hawai'i Restoration Monitoring Plan presented here fills this gap by outlining a standardized, easily implementable monitoring strategy. The plan is based on the Coral Restoration Consortium's Universal Metrics for Coral Reef Restoration - to ensure global comparability - and was developed in collaboration with the Hawai'i Coral Restoration Science Team - to ensure suitability for Hawai'i's unique ecological and cultural context. 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 utilized to create indelible snapshots of reefs for *in silico* assessment or monitoring can be conducted entirely *in situ*. Both approaches monitor the same set of carefully chosen 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 very 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 has 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 75% from historic levels (Birkeland and Friedlander 2001; Minton et al. 2012).

Back-to-back mass bleaching event in 2014/15 caused coral bleaching throughout the Hawaiian archipelago resulting in extensive coral mortality (Rosinski et al. 2017). Live coral cover was reduce by 50% on surveyed reefs in west Hawai'i (Kramer et al. 2016). These losses threaten Hawai'i's culture, economy, food security, and coastal resilience.

The dramatic decline of Hawaiian reefs has prompted scientists and reef managers to explore opportunities to complement threat reduction interventions with active reef restoration by transplanting 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?

Standardized and comparable metrics to evaluate restoration projects are critical for cross-geography learning, improvement, and adaptive management (Goergen et al. 2020). Evaluating the success of restoration programs requires consistent monitoring of carefully chosen metrics to quantify progress towards clearly articulated goals and objectives. Furthermore, effective monitoring allows challenges to be identified - and addressed - early before they compound into program failure.

Monitoring Approach

Goergen et al. (2020) present a set of Universal Metrics that should be measured for all reef restoration projects globally. These metrics allow consistent comparison among projects while supporting adaptive restoration project management. The monitoring approach detailed below provides a simple, efficient, and statistically robust approach for collecting these Universal Metrics that can be implemented in nearly any reef restoration project.

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 restoration 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; Underwood 1994).

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 survey provide metrics on baseline condition 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 perturbations to the broader reef system (e.g., bleaching, storms, etc.) over time. Control sites should be selected with biotic and abiotic conditions as 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).

Monitoring phases and timeframe

Restoration monitoring can be broadly broken into five phases:

- **Pre-implementation (i.e., baseline) surveys (prior to outplanting)** establishes a baseline for all subsequent monitoring.
- **Initial (i.e., quick check) surveys (within two weeks of outplanting)** 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. At this phase, quarterly monitoring should be sufficient.
- **Mid-term (i.e., effectiveness) monitoring (one 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 allowed the outplants to grow and thrive (e.g., high survivorship and low tissue loss and damage). At this phase, annual 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. At this phase, biennial monitoring should be sufficient.

Monitoring tools

Benthic community photomosaics

Photomosaics are a powerful tool for reef restoration monitoring, providing permanent visual archives of reef sites that can be assessed at multiple scales (Box 1). Photomosaics and Structure-from-Motion (SfM) is a type of photogrammetry analysis of overlapping (stereo) digital photography that enables precise, accurate, and comprehensive structural measurements. 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 and stitch the photos together into incredibly accurate and highly detailed photomosaics. Resulting photomosaics can then be assessed *in silico* (i.e., at a computer on dry land) to characterize demography, community composition, benthic structure, and many other metrics and parameters. Importantly photomosaics provide indelible snapshots of the reef at specific moments that can be compared over time (e.g., BACI analysis).

Benthic community photomosaics are the backbone upon which this monitoring plan is built. Due to the technical nature of photomosaic planning, collection, analysis, and curation, we have prepared a **Photomosaic Standard Operating Procedure** to complement this plan.

The high cost, specialized equipment, and technical expertise required for photomosaic imaging and analysis may make this high-tech approach unfeasible 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 perfectly comparable with those assessed *in silico*.

Box 1. Photomosaics and ex situ *assessment.*

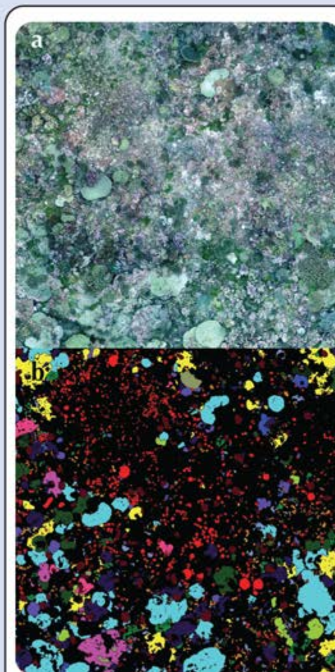
Box 1. Photomosaics and *ex situ* assessment

What are photomosaics?

Photomosaics and Structure from Motion (SfM) are large-scale photographic survey techniques that can be used to characterize the composition and complexity of benthic communities (Brainard et al. 2019b). The process involves taking hundreds, and in some cases thousands, of overlapping underwater photographs of coral reef monitoring sites from different perspectives. Photogrammetry software is then used to match features between adjacent images and stitch the photos together into accurate and highly detailed three dimensional digital surface models and photomosaics (Box 1.1.a.) . These high definition and larger scale photomosaics can provide consistent data on percent cover, species composition (Box 1.1.b.), and physiological health of corals, algae, and other benthic taxa. Furthermore, photomosaics and SfM collected over time can serve as large-scale archives for monitoring changes on reefs.

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 photomosaics (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).

Variables to be assessed and assessment method

Universal metrics

The universal metrics for reef restoration monitoring described by Goergen et al. (2020) are summarized in Figure A and Table A and briefly described below.

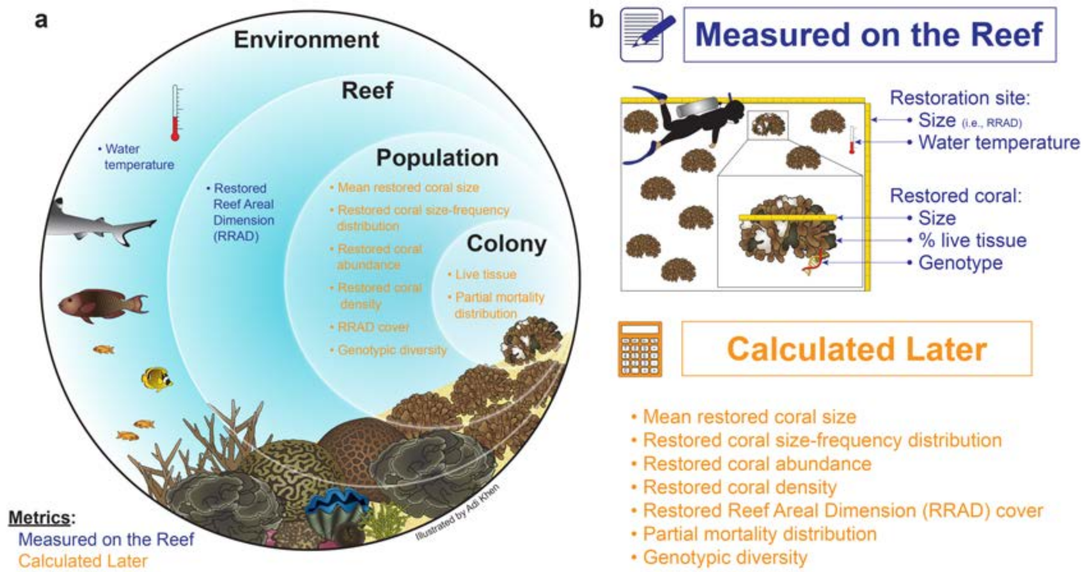


Figure A. Universal metrics for monitoring coral reef restoration.

Universal metrics enable consistent evaluation of reef restoration success and should be collected on all coral 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 calculated (**orange** text) from a small subset of metrics measured "on the reef" (**blue** text) either in person or *in silico*.

Table A. 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 (HoBo)	Real time temperature logging (e.g., Aqualink buoy)
Reef	Area where corals were planted and extent of reef impacted	Restored Reef Areal Dimension (RRAD)	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-frequency distribution	%: percentage of restored coral colonies per species by size class	Derived	Derived from mean restored colony size (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	#/m2: number of restored coral colonies divided by RRAD area	Derived	Derived from restored coral abundance and RRAD (i.e. restored coral abundance / RRAD)	
		Restored Reef Areal Dimension (RRAD) cover	%: percentage of RRAD occupied by restored coral colonies	Derived	Derived from mean restored colony size, restored coral abundance, and RRAD (i.e., [mean restored colony size * restored coral abundance] / RRAD)	
		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	Live tissue	%: mean percent live tissue per restored coral colony	Measured	UW visual estimate of % live tissue	*In silico* measurement from SfM
		Partial mortality distribution	%: percentage of restored coral colonies in each percent % mortality class	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 rate and disease and bleaching prevalence (Clausen and Roth 1975; Highsmith 1979; Douglas 2003; Jones et al. 2004).

In this monitoring plan, water temperature data will be collected for each restoration and control site using *in situ* (e.g., HOBO or similar) temperature loggers programmed to collect data hourly. Where possible, satellite connected Aqualink smart buoys will also be used to provide real time temperature data.

Reef-level: Restored Reef Areal Dimension (RRAD)

Restored Reef Areal Dimension (RRAD) quantifies the overall reef area where corals are planted and measures how they spread over time. This metric is useful for reporting project size in a standardized way. RRAD helps capture changes in restoration footprint over time due to processes such as coral death (potentially resulting in a smaller RRAD) or, alternatively, breakage and reattachment of branching corals (potentially expanding the size of the RRAD).

In this monitoring plan, RRAD is quantified from time series photomosaics. If photomosaics are not available, *in situ* distance and angle measurements can be used.

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 size**: mean restored coral size (maximum diameter) by species in cm;
- **restored coral size-frequency distribution**: percentage of restored corals per species by size class;
- **restored coral abundance**: number of restored corals by species;
- **restored coral density**: number of restored corals divided by RRAD area in number per m^2;
- **RRAD percent cover**: percentage of RRAD occupied by restored corals; and
- **genotypic diversity**: number of unique genets per species at each restoration site

Apart from genotypic diversity, all population-level metrics can be calculated using RRAD (see above) and size measurements for each restored colony (Figure A, Table A). In this monitoring plan, per-restored-colony size measurements are collected from time series photomosaics. If photomosaics are not available, *in situ* identification and measurements of individual tagged colonies can be used.

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

In this monitoring plan, geographic distance among donor colonies will be used as a proxy for genetic diversity. Each donor colony will be treated and tracked as a separate genotype and efforts will be made not to collect multiple donors from the same genet (i.e., a minimum distance between collected donor colonies will be established). Where possible, genetic sequencing will be used to confirm lack of clonality and, to the degree possible, genetic relatedness.

Colony-level: live tissue and partial mortality distribution

Colony-level metrics quantify the amount of live tissue on restored corals, including:

- **live tissue**: mean percent live tissue per restored coral and
- **partial mortality distribution**: percentage of restored corals in each percent mortality tranche (i.e., 0%; 1–25%; 26–50%; 51–75%; 76–99%; or 100%)

All colony-level metrics can be calculated using % live tissue measurements from each restored colony (Figure A, Table A). In this monitoring plan, % live tissue measurements are collected from individual restored colonies using time series photomosaics. If photomosaics are not available, % live tissue measurements can be collected from individual tagged colonies *in situ*.

Closing remarks

This monitoring guide was developed in collaboration with the Hawai'i Coral 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.

Literature Cited

Baums IB (2008) A restoration genetics guide for coral reef conservation. Molecular Ecology 17:2796-2811

Baums IB, Baker AC, Davies SW, Grottoli AG, Kenkel CD, Kitchen SA, Kuffner IB, LaJeunesse TC, Matz MV, Miller MW (2019) Considerations for maximizing the adaptive potential of restored coral populations in the western Atlantic. Ecological Applications 29:e01978

Birkeland C, Friedlander AM (2001) The importance of refuges for reef fish replenishment in Hawai'i. Hawaii Audubon Society

Bishop RC, Chapman DJ, Kanninen BJ, Krosnick JA, Leeworthy VR, Meade NF (2011) Total economic value for protecting and restoring Hawaiian coral reef ecosystems final report. NOAA Technical Memorandum CRCP CRCP 16

Clausen C, Roth A (1975) Effect of temperature and temperature adaptation on calcification rate in the hermatypic coral *Pocillopora damicornis*. Marine Biology 33:93-100

Douglas A (2003) Coral bleaching: how and why? Marine Pollution Bulletin 46:385-392

Drury C, Schopmeyer S, Goergen E, Bartels E, Nedimyer K, Johnson M, Maxwell K, Galvan V, Manfrino C, Lirman D (2017) Genomic patterns in Acropora cervicornis show extensive population structure and variable genetic diversity. Ecology and Evolution 7:6188-6200

Goergen EA, Schopmeyer S, Moulding AL, Moura A, Kramer P, Viehman TS (2020) Coral reef restoration monitoring guide: Methods to evaluate restoration success from local to ecosystem scales. NOAA Technical Memorandum NOS NCCOS 279

Green RH (1979) Sampling design and statistical methods for environmental biologists. John Wiley & Sons, United Kingdom

Highsmith RC (1979) Coral growth rates and environmental control of density banding. Journal of Experimental Marine Biology and Ecology 37:105-125

Jones RJ, Bowyer J, Hoegh-Guldberg O, Blackall LL (2004) Dynamics of a temperature-related coral disease outbreak. Marine Ecology Progress Series 281:63-77

Kramer K, Cotton S, Lamson M, Walsh W (2016) Bleaching and catastrophic mortality of reef-building corals along west Hawai'i Island: findings and future directions. Proceedings of the 13th International Coral Reef Symposium:219-230

Lirman D, Gracias NR, Gintert BE, Gleason ACR, Reid RP, Negahdaripour S, Kramer P (2007) Development and application of a video-mosaic survey technology to document the status of coral reef communities. Environmental Monitoring and Assessment 125:59-73

McCoy KS, Williams ID, Friedlander AM, Ma H, Teneva L, Kittinger JN (2018) Estimating nearshore coral reef-associated fisheries production from the main Hawaiian Islands. PLOS One 13:e0195840

Minton D, Conklin E, Weiant P, Wiggins C (2012) 40 years of decline on Puako's coral reefs: A review of historical and current data (1970–2010) Nature Conservancy 43

Page CA, Field SN, Pollock FJ, Lamb JB, Shedrawi G, Wilson SK (2017) Assessing coral health and disease from digital photographs and *in situ* surveys. Environmental Monitoring and Assessment 189

Rosinski A, Gove J, Birkeland C, Gorospe K, White D, Oliver T, Conklin E, Walsh W, Williams I (2017) Coral bleaching recovery plan: identifying management responses to promote coral recovery in Hawai'i Hawai'i Department of Land and Natural Resources, Division of Aquatic Resources

Storlazzi CD, Reguero BG, Cole AD, Lowe E, Shope JB, Gibbs AE, Nickel BA, McCall RT, van Dongeren AR, Beck MW (2019) Rigorously valuing the role of U.S. coral reefs in coastal hazard risk reduction US Geological Survey 52

Underwood A (1994) On beyond BACI: sampling designs that might reliably detect environmental disturbances. Ecological Applications 4:3-15