Study Design and Analytical Guidance for Assessing Restoration Success following Vessel Groundings on Coral Reefs

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Cover photo: A large, outplanted *Pocillopora grandis* colony hosting a vibrant reef fish community at the M/V *Vogetrader* vessel grounding site in O'ahu, Hawai'i.
Photo credit: NOAA Fisheries. Photographer: Courtney Couch.

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How to use this document

Target audience

This guide aims to educate organizations—including natural resource agencies—on the proper study design and analytical framework to implement when a vessel runs aground on a coral reef to enable evaluating restoration success over time. It is imperative for resource management agencies who are entrusted with restoring the resource to pre-grounding conditions to understand study design considerations before taking restoration actions. This guide aims to better equip these managers to address the question: *Did the restoration actions successfully meet the restoration goals?*

What this guide offers

There are several published guides outlining comprehensive response strategies to a grounded vessel on a coral reef and highlighting techniques to conduct damage assessments. Additionally, coral reef restoration guides continue to grow in number, offering clear guidance on best practices for restoring ecological function on coral reefs damaged from acute disturbances. These existing resources provide valuable information on the process of removing vessels from the reef and a range of restoration approaches. However, existing guides do not address the appropriate study design and analytical framework needed to evaluate restoration success. Following a vessel grounding, a key component of the restoration plan should be long-term monitoring as it will be used to evaluate the success of the restoration. Robustly evaluating the success of restoration efforts years to decades after a grounding requires a well-thought out statistical study design and comprehensive analytical framework at the outset.

> This guide offers practical guidance on the survey design and analytical frameworks to implement during restoration following a vessel grounding.

This guide provides a brief overview of the grounding response, discusses overlooked study design considerations, and details the appropriate analytical framework to be used when conducting restoration interventions. We include a case study of a vessel grounding in O‘ahu, Hawai‘i highlighting lessons learned over the project duration. Lastly, we compiled the available vessel grounding response guides along with select guides on coral reef restoration into the *Further Reading* section to ensure these existing resources are easily accessible.

What this guide is not

Each vessel grounding is different and the ensuing response and restoration will have different goals. Therefore, this guide does not:

1. dictate the roles and responsibilities for agencies and/or responsible parties following a grounding;
2. address issues of risk or liability;
3. prescribe recommendations for restoration interventions, or
4. prescribe specific methods appropriate for restoration interventions.

Overview of the vessel grounding response

Following a vessel grounding, the damage assessment and restoration process consists of three general phases: assess, restore, and evaluate for success. The specific pathway through which vessel groundings are assessed and remediated can follow a variety of trajectories based on the severity of the grounding, legal mandates, and logistical capacity. In this section, we briefly outline the general pathway (Figure 1) and define common terminology used throughout this guide. There are numerous legal authorities governing the planning, response, and damage assessment relative to coral impacts from groundings, which are beyond the scope of this guide. For more information regarding the federal, state, or other local authorities and their legal authorities, please see the U.S. Coral Reef Task Force Handbook on Coral Reef Impacts: Avoidance, Minimization, Compensatory Mitigation, and Restoration (2016) and the Ship Grounding of Coral Reefs Technical Information Paper (International Tanker Owners Pollution Federation, 2021).

We have three focus areas in this guide including:

1. establishing a clear study design and collecting robust baseline data from which to evaluate restoration during the “Impact Assessment”;
2. reviewing overlooked issues (e.g., when to consider active versus passive restoration, setting clear restoration targets, or addressing shifting baselines at control sites) to consider when developing a “Restoration Plan”; and
3. defining the analytical framework to evaluate restoration success during “Long-term Monitoring.”

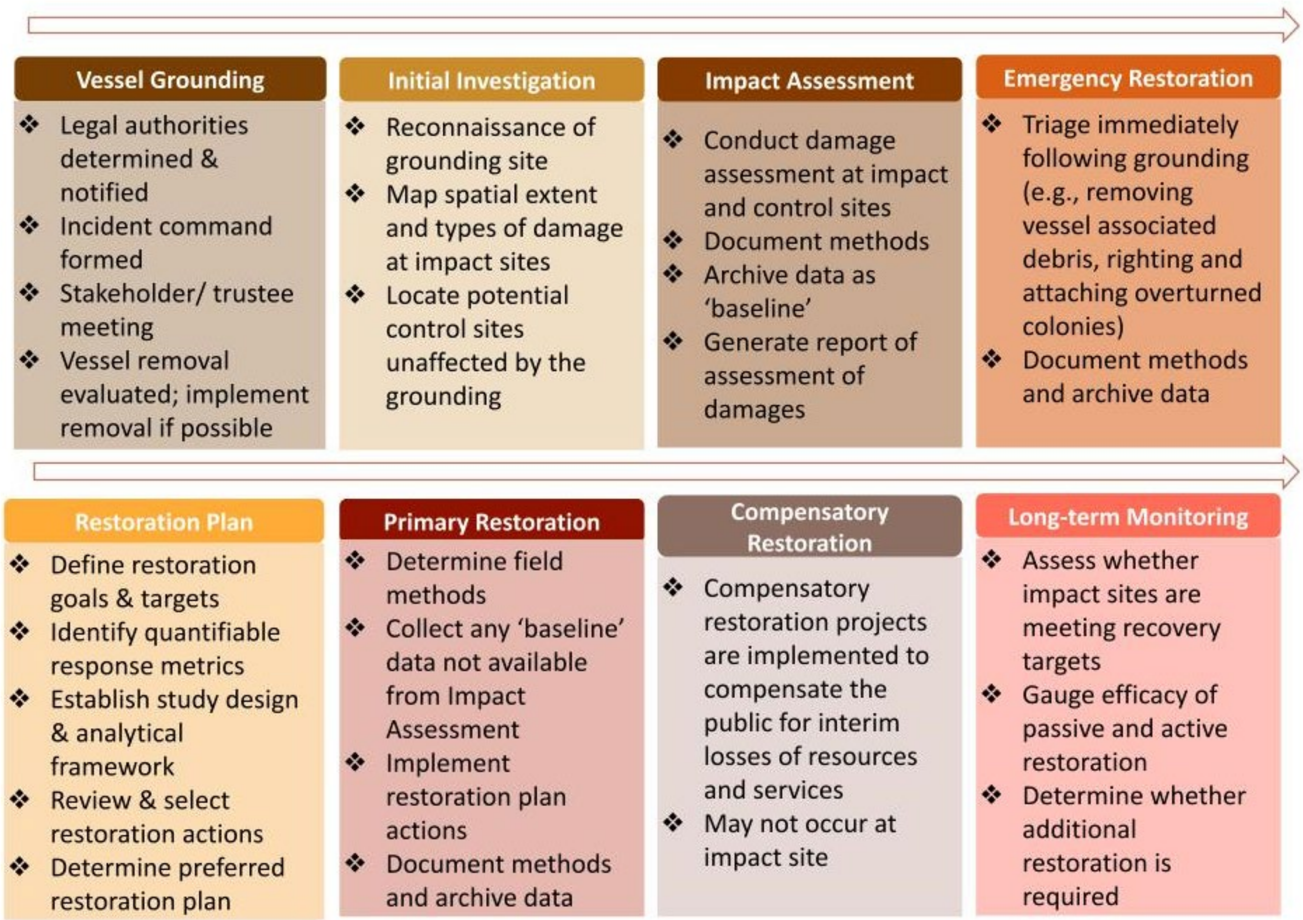


Figure 1. Outline of the vessel grounding impact assessment and subsequent restoration pathway, including key components to undertake during each phase.

For clarity on terminology used through this guidance document, we define emergency restoration, primary restoration, and compensatory restoration as follows:

Emergency restoration: refers to the actions intended to prevent further loss to the resource and/or minimize impacts of the grounding. These actions may closely follow the grounding, but sometimes occur quite a while after the initial grounding impact.

Examples include vessel debris removal, stabilizing large, dislodged, or overturned coral colonies or reef structure at the impact site. These actions should occur concurrently with the impact assessment or immediately after as they are time sensitive and are intended to reduce the overall impact. Data should be recorded on the location of emergency actions within the impact area, what methods were used, and the extent of the effort (e.g., number, size, and taxa of corals reattached)—especially if the emergency restoration actions impact metrics necessary to the long-term monitoring to evaluate restoration success.

Primary restoration: refers to the actions implemented at the grounding site to return the injured coral reef to return the injured coral reef to its pre-existing condition.

Primary restoration actions are generally designed to recover the impacted site to its pre-injury state, and are classified as either passive or active actions (defined below). The type and extent of the damage and resources available often determines what restoration actions are used.

Compensatory restoration: refers to the actions to compensate the public for the interim loss of the resource from the time the unplanned event (i.e., a vessel grounding) occurred until restoration is complete.

Compensatory restoration often does not occur at the impact site, and, therefore, can include a wide range of alternatives such as restoration of other associated habitats (e.g., invasive algal removal, enhancement of other coral reefs), prevention of future physical impacts (e.g., adding navigational markers, vessel navigation training), and education and outreach. Whether/when emergency or primary restoration are implemented will affect the interim loss of coral resources and, therefore, the amount of compensatory restoration needed.

Key points for managers

Restoration success following a grounding requires effective communication, coordination, and documentation considering the number of stakeholders involved and the long time scales of recovery.

Detailed documentation of the impact assessment methods and restoration methods (e.g., metadata, GPS coordinates, sampling design) are essential as long-term monitoring may not occur until several years after the impact assessment and restoration actions, and can be conducted by different parties.

The usability, rigor, statistical viability, and quality of the data collected during the impact assessment is integral to enable a thorough assessment of the restoration success over time.

The restoration targets need to be well-defined, explicit, and justified.

When determining primary restoration actions, pay close attention to whether a specific action and the scale of that action aligns with the project's restoration target(s).

A study design that includes both passive restoration alongside active restoration, paired with unaffected controls offers a robust design for assessing restoration success.

Often overlooked study design considerations

Selecting the appropriate reefs for restoration

"Not all areas can or should be restored." – Quigley et al., 2022

The type of habitat impacted and the severity of the impact is a practical consideration for restoring reefs following a vessel grounding. Large vessels can cause extensive impacts to the reef framework when they run aground. These physical impacts are acute and can be long-lasting given the slow pace at which coral reefs naturally accrete (Precht et al., 2001). Coral restoration can only be effective if the infrastructure is available and the capacity exists to achieve functional replacement (Quigley et al. 2022), which may not be feasible in areas where extensive framework stabilization is needed. Likewise, vessel groundings can occur in previously modified reef habitats, such as shipping channel cuts or harbor entrances where the impacts of the grounding further deteriorate the altered reef habitats. Thus, organizations planning and implementing coral reef restoration should carefully consider whether the grounding site is appropriate for reef restoration to succeed (Quigley et al. 2022), or whether compensatory restoration elsewhere would be a more effective effort. For example, a "no-action alternative" (e.g., natural recovery) is sometimes selected by trustees as the preferred primary restoration alternative at the impact site. Restoration at an alternate site is then used to compensate for lost resources from the vessel grounding.

When to consider passive versus active restoration?

Passive restoration: allows for natural recovery after the grounded vessel and associated vessel debris have been removed

Active restoration: employs restoration techniques such as coral outplanting, coral rubble removal, substrate stabilization, and herbivore management to bolster recovery

Natural recovery should be supported where possible (Quigley et al. 2022). For some sites, this may consist entirely of passive restoration. This means the grounding sites are left to recover naturally after the vessel and associated debris is removed since the impacts were minimal, the reef framework is primarily intact, and coral recruitment is deemed sufficiently high enough to support recovery without further interventions. For example, given sufficient recovery time at the *M/V Vogetrader* grounding in Hawaiʻi (see *Case Study: M/V Vogetrader* section), passive restoration will likely suffice in restoring some impact sites to a pre-disturbance state, if that state is characterized by low density, small sized corals, and the impacts from the grounding were mild or minimal (i.e., mild scouring or scraping of the reef framework). Baseline data—such as the abundance of coral recruits and juveniles, and the availability of stable substrate—collected at both the impact and control sites during the impact assessment can offer insight into the recovery potential of the impact site and predicted recovery timelines under a passive restoration approach. It is worth noting that the time it takes the coral reef to recover represents lost ecosystem services—such as habitat provisioning, coastal protection, food provisioning—until full recovery is achieved. Those lost ecosystem services of the resource represent a debt that must be recovered in the passive approach when full recovery is achieved.

However, passive restoration may not be sufficient for reefs with more extensive coral communities and/or those that experienced severe impacts. For example, in the case of the M/V *Wellwood* grounding in the Florida Keys, the grounding pulverized the reef spur and groove habitat. This unrestored reef framework stabilized into a low-relief, hard-bottom community far different from that of the pre-injury habitat characterized by topographic complexity (reviewed by Precht et al. 2001). Thus, active restoration techniques, such as substrate stabilization or outplanting of coral colonies, may be necessary for vessel grounding sites to recover to their former state. This is particularly true when unstable substrate is the primary condition preventing reef regrowth (Fox et al., 2019). In this scenario, coral rubble removal and/or substrate stabilization can be first implemented to improve the survival of the subsequent coral outplants and corals naturally recruiting to the impact area.

Establishing clear targets for restoration success

The goal of primary restoration following vessel groundings is to restore reefs to a pre-disturbance state. Restoration targets are used to establish how restoration success will be defined and often relate to ecosystem services and functions provided by the reef itself. Organizations planning and implementing coral reef restoration following a vessel grounding should establish restoration targets that adhere to the following best practices.

- The restoration targets need to be explicit and justified; targets can range from recovery of coral community composition to more functional/ecosystem service based targets, such as restoring habitat provisioning and coastal protection.
- The targets need to have a well-defined and realistic timeframe given coral growth rates, natural recruitment levels, and available logistical resources.
- The targets should be able to be evaluated with a few well-selected quantifiable metrics.
- The appropriate study design and analytical framework needs to be established to evaluate the quantifiable metrics in support of meeting the restoration targets.

Once targets are established, organizations should select quantifiable metrics (e.g., coral cover, structural complexity, rubble cover) that clearly align with the restoration targets. Metrics should be unambiguous, clearly defined, and easy to evaluate in the field (Prach et al., 2019). For example, colony size is a common metric in support of a restoration target to restore “coral community structure.” However, colony size can be measured in a myriad of ways. Thus, clear definitions on how to assess colony boundaries and account for partial mortality to ensure the method of distinguishing one colony from the next can be repeated in future monitoring are required. Additionally, Prach et al. (2019) recommend monitoring two to four, well-selected metrics that align with the restoration target over a single metric or numerous metrics to avoid over reliance on one metric or analytical and logistical failures caused by too many. The restoration proposals are usually created by the responsible party and the regulatory authority then determines appropriateness or compliance. Thus, a successful process depends upon the common understanding of all parties involved of the restoration target(s) identified, and the appropriateness of the quantifiable metrics selected to evaluate replacement of lost resources through time.

Lastly, when determining restoration targets and the quantifiable metrics by which they will be assessed, attention needs to be placed on the study design and analytical framework used. A before-after-control-impact (BACI) design is a commonly used analytical framework for assessing restoration success (Chevalier et al., 2018, Smokorowski and Randall, 2017). We recommend coupling a BACI framework with a study design that includes passive restoration sites alongside active restoration sites, which are paired with unaffected control sites. Greater detail on BACI and the recommended study design can be found in the *Analytical Framework Recommendations* section of this guide**.**

Considering restoration targets under shifting baselines

Globally, coral communities are under increased threat due to the combined effects of climate change and local environmental stressors. As a result, many coral reef communities are experiencing declines that are unrelated to vessel groundings. This creates a shifting baseline where the likelihood of restoring a grounding site to pre-grounding levels (an often cited goal of many vessel grounding restoration plans) may be impractical under contemporary reef conditions. In other words, restoration may never achieve pre-grounding baseline conditions. Given shifting baselines, what are practical considerations for those responsible with implementing restoration? It is not reasonable to decrease the damage compensation value simply because coral reefs are declining globally. However, it does complicate the objective of how to evaluate restoration success using long-term monitoring data if the control sites are declining over time.

We suggest using an adaptive management approach leveraging the best available science to assess the rate of contemporary decline for a given reef or coastline in the vicinity of the grounding site to inform realistic recovery targets when analyzing long-term monitoring data (Viehman et al., 2009). For example, if declines at control sites are predicted over time (e.g., due to local and global stressors), recovery targets can be adapted to align with the current state of the resource, rather than the state of the resource at the time of the grounding.

Analytical framework recommendations

Employ a before-after-control-impact (BACI) analytical design

The ability to assess restoration success relies on having an appropriate study design tailored to the goals of the project. Restoration practitioners typically use a BACI study design to assess the success of restoration actions, where the restoration is the 'impact' being assessed. We also recommend a BACI framework for assessing the success of restoration following a vessel grounding. The BACI design was originally conceived as a tool for measuring environmental impacts or disturbance. For this use, a BACI design consists of surveying an impact site and an unaffected control site before the environmental impact occurs and again after the impact (Stewart-Oaten et al., 1986). The BACI design's main strength is allowing the practitioner to assess how the impact site is changing over time compared to unaffected control sites.

When applying a BACI design to assess restoration success after a vessel grounding, "impact" refers to restoration sites—not the damage from the grounding itself—and "control" refers to sites unaffected by the disturbance.

With good alignment between parties involved in impact assessments and restoration efforts, the impact assessments will ideally generate the "before restoration action" data from which restoration success can be measured.

An alternative approach that we do not advocate using is a direct comparison of the control and impact sites with no temporal component. The control-impact (CI) comparison may free the practitioner from relying on "before" data collected prior to the restoration actions. However, a CI comparison cannot attribute any observed differences or successful convergence between the restored impact site and the control site to the restoration actions definitively (Smokorowski and Randall, 2017). Moreover, a before-after (BA) analysis of the restoration site alone is of little value in evaluating restoration success without control sites to contextualize temporal change from natural variation. Thus, both CI and BA analyses on their own should be avoided.

Under the BACI analytical framework, the main statistic of interest is a significant interaction effect between the factors time (BA) and treatment (CI) that signifies a restoration-induced change compared to natural variation.

This interactive effect is frequently generated using a fully crossed, two-factor analysis of variance (ANOVA) statistical test.

The original concept of the BACI design assumes that control and impact sites are similar before the environmental perturbation.

> When applying the BACI design to restoration following a vessel grounding, it is important to keep in mind that the restoration actions are the perturbation being assessed, not the impact of the vessel grounding itself.

Thus before the restoration actions begin, the coral reefs at the unimpacted “control” sites are at a different state than the “impact” sites where the grounding occurred and restoration is to take place. These control sites represent the desired state of the impact sites after the restoration actions are complete. Additionally, the classic BACI design assumes that temporal changes at the control sites should be smaller than the impact sites (Underwood, 1992). However, the coral communities in control sites can decline over time for reasons unassociated with the grounding (see *Considering restoration targets under shifting baselines* section). This potentially violates a primary BACI assumption that temporal changes resulting from the restoration impact should be larger than temporal changes at control sites.

Improvements on the classic BACI model have been suggested over the years, such as paired sampling designs and measuring progressive change overtime. However, these approaches are unlikely to be applicable in a vessel grounding context in which spatial replication is absent (e.g., a single vessel grounding, not multiple) and frequent temporal monitoring to assess progressive change is often limited by funding. Yet, despite these limitations, the simple BACI study design is still favored to employ following a single vessel grounding to evaluate restoration success. A BACI design is well understood in the restoration community and can be achieved without intense temporal or paired sampling. We offer the following additional suggestions—which are compiled from scientific literature—to improve the use of a BACI design after a vessel grounding.

Move beyond a significant interactive effect

Significant interactions between treatment (e.g., restored vs control sites) and time (e.g., before vs after restoration) can arise for a variety of reasons, such as larger temporal changes at the control sites compared to restored sites as corals decline from local and global stress. As a result, a significant interaction between time and treatment alone is not sufficient to determine whether restoration following a vessel grounding was successful in returning the impacted reef to pre-grounding conditions. Chevalier et al. (2019) coined two additional metrics that, when coupled with the BACI contrasts, aid in better understanding how restoration and control sites are changing over time: CI-divergence and CI-contribution (see Box 1).

Box 1. Calculating measures of impact for BACI designs

BACI contrasts $= (\mu_{IA} - \mu_{IB}) - (\mu_{CA} - \mu_{CB})$	Where μ represents the mean response (e.g., coral density) for each treatment (*I* = restored sites; *C* = control sites) and time (*A* = after; *B* = before).
CI-contribution $= \lvert\mu_{IA} - \mu_{IB}\rvert - (\mu_{CA} - \mu_{CB})$	Defined as absolute value of change at impact sites minus control sites. In other words, how much larger is the temporal change at restored sites compared to control sites.
CI-divergence $= \lvert\mu_{IA} - \mu_{CA}\rvert - \lvert\mu_{IB} - \mu_{CB}\rvert$	Defined as how similar impact and control sites are after restoration compared to before restoration. In other words, how much did the impact sites converge towards the control sites over time.

Adapted from Chevalier et al. 2019

The CI-divergence and CI-contribution metrics are useful to quantify

1. how impact sites become more similar to control sites after restoration, and
2. when large changes occur in the control sites due to natural reef degradation over time.

While these metrics are not formal statistical tests, they are simple calculations that are useful to help quantify how the impact sites are changing relative to control sites over time.

Apply a "gold standard" study design

Passive restoration sites can play an important role in a restoration study design. By definition, both passive and active sites are impacted by the grounding and share a similar starting point prior to restoration implementation. However, only active impact sites are subject to restoration intervention, while the passive impact sites are left undisturbed.

> The gold standard is a study design that includes both passive and active restoration impact sites alongside unaffected controls. This is the strongest design for assessing the success of restoration actions (Figure 2).

Without passive impact sites, one may be able to demonstrate that active impact sites recovered to levels found at the unaffected controls, but they cannot definitively attribute this recovery to the active restoration techniques used (Chapman, 1999). Unfortunately, most vessel grounding restoration projects do not employ these comparisons of active and passive restoration sites, either due to inadequate study designs or lack of knowledge. By using active restoration in some impacted areas and passive restoration in others, one can better assess the benefits of specific active interventions to aid in successful recovery (Chapman, 1999). Thus, we advocate for the use of both passive and active restoration when engaging in a vessel grounding project at the time of restoration planning (Figure 2).

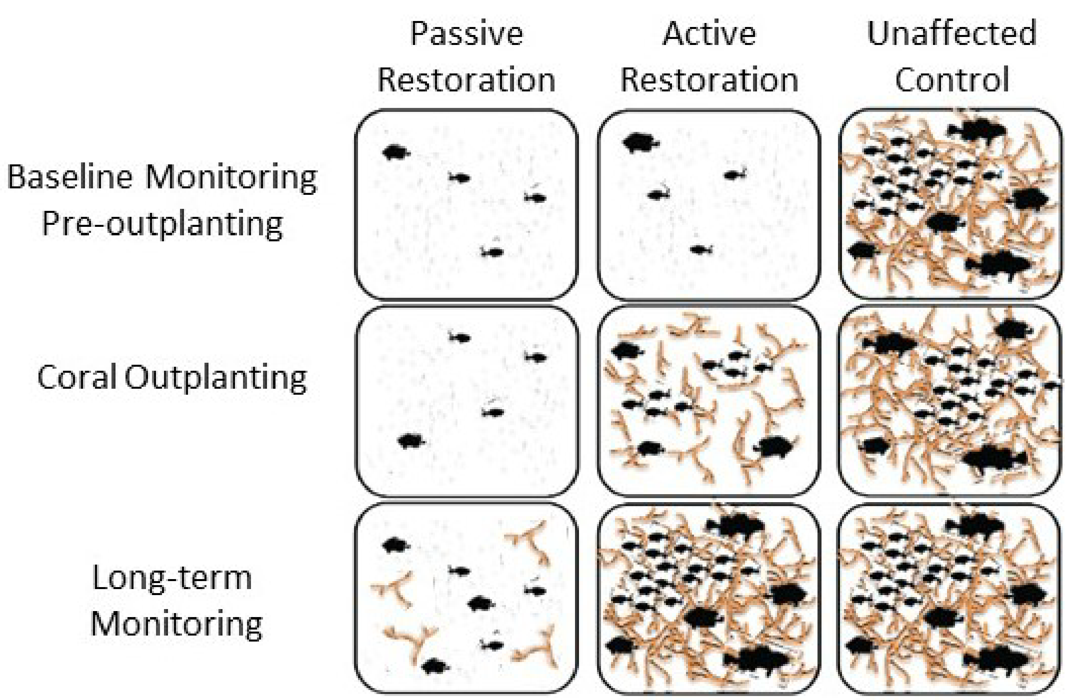


Figure 2. Example of a restoration study design that incorporates both passive and active restoration actions at impact sites alongside unaffected control sites to better assess the efficacy of active restoration actions, such as coral outplanting over time (adapted from Goergen et al., 2020).

During the long-term monitoring phase of the restoration process, the following analytical comparisons can be made under a BACI framework.

1. Compare temporal change at the active restoration impact site to the passive impact site. If temporal change at the active site exceeds those at the passive site, the active restoration techniques were successful in boosting or accelerating recovery trajectories.
2. Compare the active restoration sites to unaffected control sites. Evaluate if the restoration was successful in recovering the impact areas to unaffected control conditions at baseline monitoring levels (and/or long-term monitoring levels if control sites have changed over time).

Monitoring restoration success at varying points of engagement

Organizations involved in responding to and monitoring the impacts of vessel groundings have a variety of responsibilities. We outline the following best practices for organizations and agencies engaging with a vessel grounding at different stages of the restoration project (Figure 3).

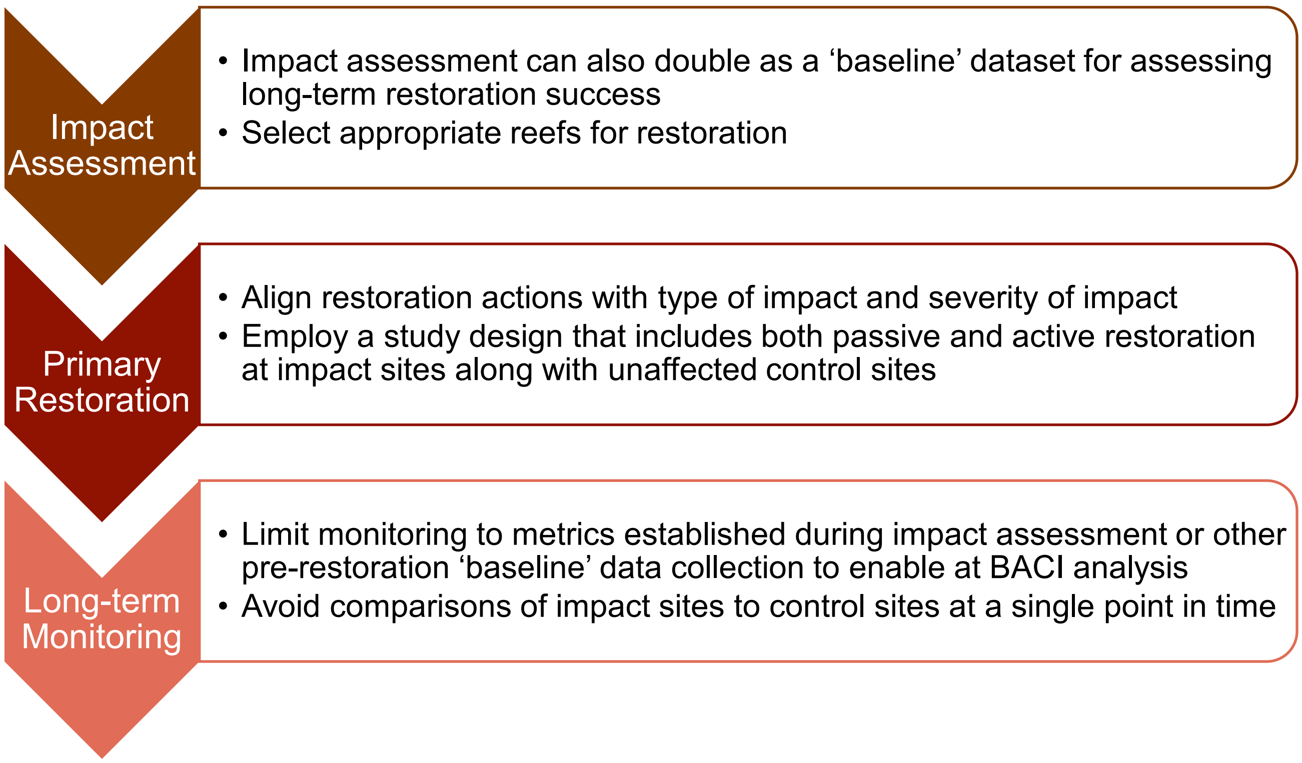


Figure 3. Key considerations for engaging with a vessel grounding restoration project at three distinct stages in the project lifespan: time of initial impact, implementing primary restoration, and conducting long-term monitoring of the restoration.

Monitoring design considerations at time of Impact Assessment

Ideal engagement would begin at the impact assessment stage where the parties tasked with designing and implementing restoration can conduct surveys to assess the extent of the damage. As discussed previously, these impact assessments may also generate baseline metrics from which restoration success can be measured. Attention should be placed on study design (see *Often Overlooked Study Design Considerations* and *Analytical Framework Recommendations* sections) including:

- quantifying both extent and severity of impacts across the vessel grounding impact site;
- carefully selecting unaffected control sites in the nearby area to match grounding

sites with respect to habitat type, depth, geomorphology, water quality, etc.;

- assessing available capacity including funding, boats/infrastructure, divers/taxonomic expertise, safety, etc. to develop actionable restoration targets; and
- ensuring baseline data is thoroughly collected and clearly documented on the relevant indicators (metrics) for each restoration target.

Monitoring design considerations at time of primary restoration

While less ideal than engaging at the time of the impact assessment, engaging at the time of primary restoration offers an important opportunity to influence the direction of the restoration study design.

> Primary restoration actions at the impact sites—including passive and/or active approaches—should align with the severity and extent of the impact as well as the overall project's goals.

Considering that coral reef restoration science is still in its infancy, incorporating hypothesis based elements into the study design can further develop knowledge of how to best restore reefs following a vessel grounding (Precht and Robbart, 2006). For example, pairing passive and active restoration actions at impact sites alongside unaffected control sites into the restoration plan can establish a compelling study design to assess both the effectiveness of specific active restoration actions and the success of the restoration project over the agreed upon monitoring period (Figure 2).

When determining which primary restoration actions to employ, pay close attention to whether the specific action and the scale of that action aligns with the project's restoration targets (Chapman, 1999). For example, if one of the restoration targets is to increase coral colony density at the site, the best approach may be to outplant high numbers of smaller coral colonies. In contrast, if the target is to reestablish habitat complexity and habitat provisioning to reef-associated fishes, the corals outplanted may be larger in size, spatially clustered, and incorporate diverse morphologies (Figure 4).

In both these examples, “baseline” data on the response metric (e.g., colony density, structural complexity, fish abundance) should be available prior to implementing the restoration action either from the impact assessment or as supplemental baseline data collected during the primary restoration phase. Additionally, the scale of monitoring should be carefully considered such that sample size (e.g., size of quadrat or transect) and units of replication (e.g., area surveyed) are sufficient to capture the active restoration effort. Lastly, methods should be sufficiently detailed and clearly documented to enable replication of methods at the time of long-term monitoring.

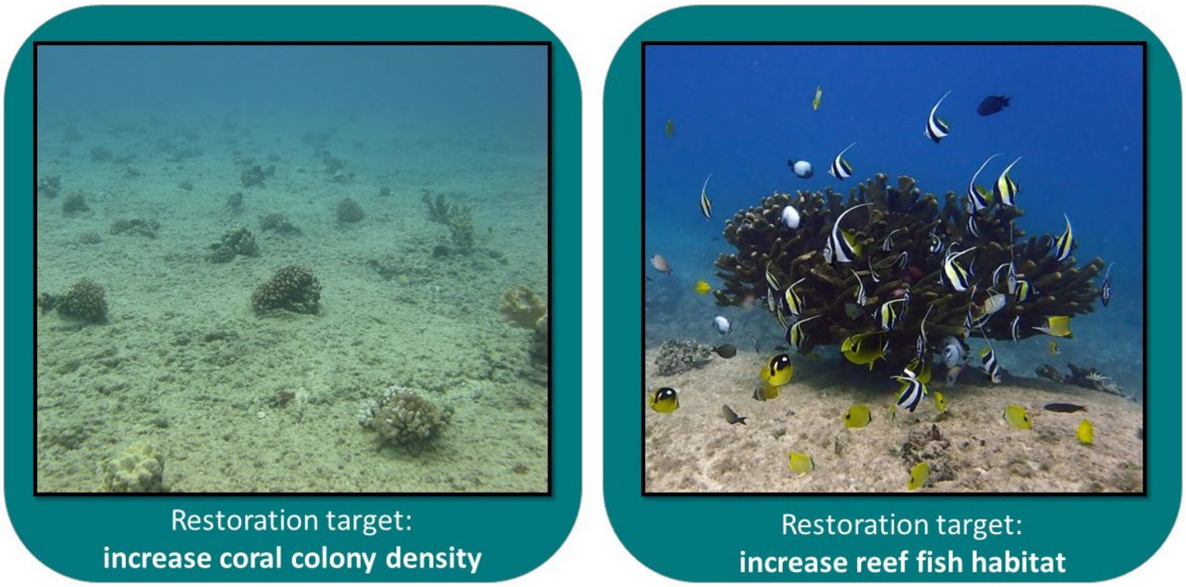


Figure 4. Coral outplanting designs can vary based on the restoration target identified. Left example depicts numerous small, coral outplants given the target of increasing coral density at the impact sites. Right example depicts outplanting large, branching coral morphologies given the target of increasing coral reef fish habitat. Photo credit: NOAA Fisheries. Photographer: Courtney Couch.

Monitoring design considerations at time of long-term monitoring

If engagement is unable to occur in an earlier stage (for example, many years after the ship grounding and associated restoration actions), the organization or agency tasked with long-term monitoring will be limited to the experimental design and historical data that were collected during the initial impact assessment and primary restoration stages. Nevertheless, long-term monitoring in the field of coral restoration science is still quite limited, which makes the long-term monitoring stipulated by most vessel groundings inherently informative. We continue to advocate for a BACI design to evaluate restoration success using the available baseline (before) data (e.g., collected during the impact assessment for the vessel grounding).

A control-impact (C-I) design (where the restored area is compared to nearby control sites at the time of long-term monitoring only) should be avoided since it cannot meaningfully attribute differences observed between the control and the restored sites to the effects of the restoration itself. Thus, when conducting the long-term monitoring, one should adhere to the metrics, methods, and locations of restoration intervention implemented during the impact assessment and primary restoration (i.e. the “before data”). Likewise, the usability, rigor, statistical viability, and data quality of the “before data” collected during the impact assessment is paramount to enable a thorough assessment of the restoration success over time.

Case Study: M/V *Vogetrader*

Location

Southern channel entrance to Barbers Point Harbor on southwest Oahu, Hawai'i.

Impact

In 2010, the M/V *Vogetrader* ran aground on a shallow coral reef causing damage to 3,478 m^2 of coral habitat and resulting in the loss of over 100,000 coral colonies. The vessel impact area consisted of reef sites that differed in the severity of grounding impacts and habitat.

Restoration Targets

Recovery of coral species, size classes, and abundances to pre-impact conditions (NOAA DARP, 2017)

Primary Restoration Actions

Active restoration. In 2013, two active restoration approaches were implemented at specific locations within the *Vogetrader* impact area to accelerate reef recovery.

- Removal of 354 m^2 of coral rubble at the site.
- Reattaching 643 dislodged corals (sourced from in and adjacent to the impact area).

Passive restoration. The remainder of the *Vogetrader* impact area was designated for passive restoration with the expectation that coral reefs would naturally recover to a pre-grounding state in the absence of human intervention.

Challenges

- "Before data" from 2010 surveys limited to coral density, size, and community composition; no coral or rubble cover data.
- No GPS locations for 2010 control sites.
- Coral outplants were not tagged and lacked an experimental design to enable evaluating efficacy of outplants.
- Limited documentation of 2010 methods.

M/V Vogetrader grounded on a coral reef in Oahu, Hawai'i. Photo credit: U.S. Coast Guard.

Long-Term Monitoring

In 2022, field surveys were conducted at the *Vogetrader* impact sites and nearby control sites. The objectives of these surveys were to:

- evaluate temporal trends in coral density, size, and community composition 12-years post vessel grounding;
- quantify rubble persistence at the impact area;
- assess coral outplant survivorship and change in size over time 9 years after attachment.

Was Primary Restoration Successful to Recover the Reef?

Reef recovery varied spatially across the impact sites, likely driven by differences in the severity of grounding impacts and the coral communities present prior to the grounding.

- Minimal recovery occurred at impact sites directly adjacent to the shipping channel where the grounding destabilized reef framework.
- Both active and passive restoration impact sites recovered to present day control sites, though levels fell short of 2010 pre-grounding conditions (due to a shifting baseline at control sites over time).
- Recovery was most successful in reef habitats that experienced only superficial scarring from the grounding and low pre-grounding coral densities.

Divers surveying coral outplants in the impact area (top). Pocillopora grandis colony nine years after outplanting (bottom).

Lessons Learned for Primary Restoration

- Given sufficient time, passive restoration can likely restore reefs to pre-grounding conditions on marginal reef habitats (e.g. low coral cover) where impacts are less severe.
- Passive restoration is not sufficient in reef habitats that experienced extensive grounding impacts.
- Coral rubble appears to persist over a decade after the vessel grounding, likely affecting new coral recruitment and survival. Yet, the absence of

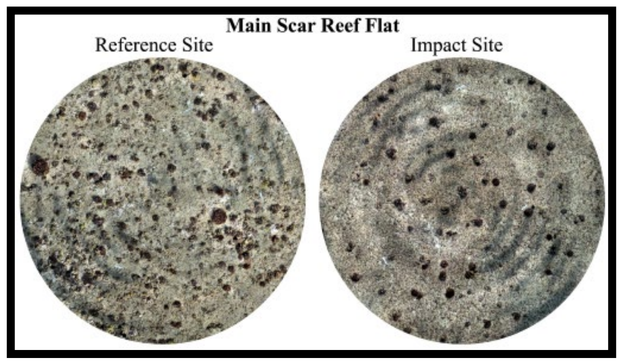
initial cover data and records of where the removal specifically occurred at the impact site limited our ability to assess the efficacy of the 2013 rubble removal efforts.

- Outplanting fewer, larger coral colonies did not improve coral density or size at the impact area, though secondary benefits, such as increased structure that attracted numerous reef fish, were observed.
- Restoration practitioners should carefully align the restoration action to the project's goals and metrics of success (e.g., increasing coral cover versus habitat complexity).

Recommendations

We recommend the following practices to improve future monitoring efforts.

- Record GPS coordinates for all sites (impact and control) with site photos to enable repeat sampling over time.
- Archive all raw data and metadata from the initial damage assessment.
- Provide thorough documentation of survey methods used to quantify restoration success.
- Carefully evaluate the experimental design that addresses restoration goals when selecting active and passive restoration actions at impact sites.
- Consider using structure from motion (SfM) approaches to assess recovery from vessel grounding damage. Photomosaics can be taken at time of impact and repeated over time at the same location to measure changes in structural complexity, benthic cover, and colony growth without requiring tagging colonies.



Structure from motion (SfM) photomosaics of the main scar reef flat reference (left) and impact (right) sites captured during the 2022 field surveys.

Further Reading

Table 1. Legal framework and guidance documents for damage assessments and subsequent restoration specific to vessel groundings in coral reef ecosystems.

Resource	Description
Damage assessment protocol and restoration of coral reefs injured by vessel groundings (Precht et al., 2000)	Guidance for emergency restoration, impact assessment, remediation, and restoration of coral damage caused by vessel grounding, including establishing a restoration plan.
Coral Reef Restoration: The Rehabilitation of an Ecosystem under Siege (Precht and Robbart, 2005)	Guidance for impact assessments, emergency restoration, restoration design following acute disturbance (including goal setting and success criteria), and long-term monitoring.
Ship Groundings on Coral Reefs: Technical Information Paper (2021)	Guidance on how to conduct an initial assessment, response strategies to reduce the severity of damage, and reviews options for active restoration approaches.
Rapid Response and Restoration for Coral Reef Injuries in Southeast Florida - Guidelines and Recommendations (Collier et al. 2007)	Technical guidance and recommendations for initiating a rapid response to grounding, primary restoration planning, and post-response assessments.
Improving scientific decision-making in the restoration of ship-grounding sites on coral reefs (Precht et al. 2001)	Reviews types of impacts from vessel groundings and the scope of restoration possibilities in relation to severity of impact and the ecological reef setting.
U.S. Coral Reef Task Force Handbook on Coral Reef Impacts: Avoidance, Minimization, Compensatory Mitigation, and Restoration (2016)	This handbook provides a general summary of current avoidance, minimization, compensatory mitigation, and restoration strategies that may help address physical damage resulting from vessel groundings.

Table 2. Selected coral reef restoration guides with practical application to implementing restoration in a vessel grounding (or acute impact) scenario.

Resource	Description
Coral Reef Restoration Monitoring Guide: Methods to evaluate restoration success from local to ecosystem scales (Goergen et al. 2020)	Excellent restoration guide to identify goal-based performance metrics to restore reef function and services, especially Chapter 9 on event driven physical impacts.
Coral reef restoration as a strategy to improve ecosystem services: A guide to coral restoration methods (Hein et al. 2020)	Report aims to assist practitioners, managers, and decision-makers in considering how and whether to undertake coral reef restoration. While not necessarily focused on acute-disturbances, Chapter 4 provides key recommendations on restoration methods.
Early warning and rapid response protocol: Actions to mitigate the impact of tropical cyclones on coral reefs (Zepeda-Centeno et al. 2019)	While focused on acute disturbance from storms, the guidance on rapid damage assessment, site prioritization, and detailed protocols for emergency restoration response, and secondary response are applicable to vessel groundings as well.

Literature Cited

Chapman M.G. (1999). I*mproving sampling designs for measuring restoration in aquatic habitats*. Journal Aquatic Ecosystem Stress Recovery, (6), 235–251

Chevalier M., Russell J.C., Knape J. (2019). *New measures for evaluation of environmental perturbations using Before‐After‐Control‐Impact analyses*. Ecological Applications, (29), e01838

Collier C., Dodge R.E., Gilliam D.S., Gracie K., Gregg L., Jaap W., Mastry M., Poulos N. (2007). Rapid Response and Restoration for Coral Reef Injuries in Southeast Florida: Guidelines and Recommendations.

Fox H.E., Harris J.L., Darling E.S., Ahmadia G.N., Estradivari, Razak T.B. (2019). Rebuilding coral reefs: success (and failure) 16 years after low-cost, low-tech restoration. Restoration Ecology, (27), 862-869

Goergen E.A., Schopmeyer S., Moulding A.L., Moura A., Viehman S. (2020). Coral reef restoration monitoring guide: Methods to evaluate restoration success from local to ecosystem scales.

Hein M.Y., McLeod I.M., Shaver E.C., Vardi T., Pioch S., Boström-Einarsson L., Ahmed M., Grimsditch G. (2020). Coral Reef Restoration as a strategy to improve ecosystem services –A guide to coral restoration methods.

International Tanker Owners Pollution Federation. (2021). Ship Groundings of Coral Reefs. Technical Information Paper. London, United Kingdom.

[NOAA DARP] NOAA Damage Assessment, Remediation, and Restoration Program. (2017). Final damage assessment and restoration plan and the NEPA evaluation for the February 5, 2010, M/V Vogetrader grounding at Kalaeloa, Barbers Point, Oahu. https://pub-data.diver.orr.noaa.gov/admin-record/6211/VT_Final%20DARP-NE%20%281%29.pdf

Prach K., Durigan G., Fennessy S., Overbeck G.E., Torezan J.M., Murphy S.D. (2019). A primer on choosing goals and indicators to evaluate ecological restoration success. Restoration Ecology, (27), 917–923

Precht W.F., Aronson R.B., Swanson D.W. (2001). Improving scientific decision-making in the restoration of ship-grounding sites on coral reefs. Bulletin Marine Science, (69), 1001–1012

Precht W.F., Deis D.R., Gelber A.R. (2000). Damage assessment protocol and restoration of coral reefs injured by vessel groundings. Proceedings 9th International Coral Reef Symposium, Bali, Indonesia 23-27 October 2000. (2), 7

Precht W.F., Robbart M. (2006). Coral Reef Restoration: The Rehabilitation of an Ecosystem under Siege. Coral Reef Restoration Handbook. Taylor & Francis Group, Boca Raton, Florida.

Quigley K.M., Hein M., Suggett D.J. (2022). Translating the 10 golden rules of reforestation for coral reef restoration. Conservation Biology, (36), e13890.

Smokorowski K.E., Randall R.G. (2017). Cautions on using the Before-After-Control-Impact design in environmental effects monitoring programs. FACETS, (2), 212–232

Stewart-Oaten A., Murdoch W.W., Parker K.R. (1986). Environmental Impact Assessment: “Pseudoreplication” in Time? Ecology, (67), 929–940

Underwood A.J. (1992). Beyond BACI: the detection of environmental impacts on populations in the real, but variable, world. Journal Experimental Marine Biology and Ecology, (161), 145–178

U.S. Coral Reef Task Force. (2016). Handbook on Coral Reef Impacts: Avoidance, Minimization, Compensatory Mitigation, and Restoration.

Viehman, S., Thur, S.M., & Piniak, G.A. (2009). Coral reef metrics and habitat equivalency analysis. Ocean & Coastal Management, 52(3–4), 181–188