Assessment of Reef Restoration Techniques in West Hawai‘i

Technical Report

Bryant Grady[1], Mikayla Barnwell[1], Julia Rose[1], Evans Humphreys[1], Eric Conklin[1], and F. Joseph Pollock[1]

[1]The Nature Conservancy, Hawai‘i and Palmyra, Honolulu, HI

The Nature Conservancy
Hawai‘i and Palmyra

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Abstract

The Kanu Koʻa Initiative, a community-based coral restoration program, evaluated four coral restoration techniques at two environmentally distinct sites along the west coast of Hawaiʻi Island: Kahuwai Bay and Kealakekua Bay. This systematic comparison assessed direct reattachment of whole *Porites lobata* colonies, direct outplanting of *P. lobata* fragment arrays, nursery-grown *P. lobata* fragments, and direct outplanting of *Pocillopora meandrina*. Structure-from-Motion photogrammetry and in-water surveys over approximately one year revealed significant site-specific differences in restoration outcomes. At Kahuwai Bay, survival rates reached 100% for fragmented arrays and 94% for directly reattached *P. lobata* colonies, while Kealakekua Bay showed lower rates (60-70%). Statistical analyses revealed that time on the reef negatively affected survival at Kealakekua Bay but positively influenced growth at both sites. *Pocillopora meandrina* exhibited the highest growth rates and lowest survival at both sites. A cost-benefit analysis identified direct reattachment of whole *P. lobata* colonies as the most cost-effective technique at both sites, costing only 6% as much per colony as the most expensive technique, nursery-grown arrays. This research provides practical guidance for optimizing reef restoration success in Hawaiʻi and beyond and underscores the importance of tailoring restoration strategies to the local context. These findings contribute to a growing scientific foundation for coral reef restoration in Hawai'i and offer valuable insights for practitioners seeking to enhance reef resilience while maximizing the benefit of their restoration investment.

Introduction

Coral reefs are among the most biologically diverse and economically valuable ecosystems on Earth, providing essential habitat for marine species, coastal protection, food security and economic opportunities for millions of people worldwide. In Hawaiʻi, coral reefs hold particular significance, contributing over $2 billion in value to the state economy each year through tourism, fisheries and coastal protection (Grafeld et al. 2017; Reguero et al. 2019; Spalding et al. 2017) . Beyond their economic importance, Hawaiian reefs represent vital cultural resources that have sustained indigenous communities for centuries.

However, Hawaiian coral reef ecosystems face unprecedented threats. Over recent decades, these reefs have experienced significant degradation due to multiple stressors, including ocean warming, coastal development, land-based pollution and fishing pressure. The 2014-2015 and 2019 mass bleaching events resulted in substantial coral mortality across the Hawaiian archipelago, with some areas experiencing up to 50% reductions in coral cover (Rodgers et al. 2017; Winston et al. 2022l). As the frequency and intensity of thermal stress events increase, natural recovery processes are increasingly challenged, necessitating more active intervention approaches.

Coral reef restoration has emerged as an important complementary strategy to passive conservation efforts, particularly in areas where reefs have experienced acute or chronic degradation. Restoration techniques aim to enhance reef recovery by increasing coral cover, preserving genetic diversity and promoting ecosystem function. While restoration science has advanced significantly in recent decades, most methodological development and empirical evidence comes from the Caribbean region (Boström-Einarsson et al. 2020), where reef ecosystems, coral species, growth rates, and environmental conditions differ considerably from those in Hawaiʻi and the broader Pacific.

The ecological and environmental context of Hawaiian reefs necessitates region-specific testing and adaptation of restoration approaches. Hawaiian reefs are dominated by slow-growing massive corals like *Porites* species, rather than the branching *Acropora* species common in Caribbean restoration. Additionally, Hawaiian reefs experience different oceanographic conditions, including seasonal high-energy wave events, variable water quality influenced by volcanic substrate and distinct herbivore communities. These factors significantly influence the effectiveness of various restoration techniques and highlight the need for Hawaiʻi-specific protocols.

The Kanu Ko'a (*planting coral*) Initiative has responded to this need by implementing and robustly evaluating multiple restoration techniques across two ecologically distinct sites along the west coast of Hawaiʻi Island (West Hawaiʻi). This community-driven project aims to develop practical, effective restoration methodologies tailored to Hawaiian reefs while simultaneously building local capacity for reef stewardship. The initiative embraces both traditional ecological knowledge and modern scientific approaches to create culturally grounded, scientifically rigorous restoration protocols.

This study addresses two primary research questions:

- How effective are different coral restoration techniques at enhancing outplanted coral survival and growth across different reef environments in Hawaiʻi?
- How do restoration outcomes vary across geographies and among coral species and colony sizes?

The findings from this research will directly inform scaled-up restoration efforts planned for Kealakekua Bay and other priority sites identified in the statewide Hawaiʻi Makai Restoration Action Plan. Additionally, by documenting cost-effectiveness and labor requirements of different restoration approaches, this study provides practical guidance for practitioners working with limited resources. Ultimately, this work contributes to the broader goal of enhancing reef resilience while supporting the communities that depend on healthy reef ecosystems.

Materials and Methods

Site Selection

This restoration project in West Hawaiʻi focuses on two primary sites: Kahuwai Bay in Kaupūlehu and Kealakekua Bay in Kealakekua (Figure 1; interactive digital maps here). Focal Geographic Area selection was guided by the statewide Makai Restoration Action Planning Process (link), and specific restoration and control sites were selected with input from community members and partner organizations. The two sites differ significantly in marine environments and adjacent terrestrial and anthropogenic influences. Kahuwai Bay is largely undeveloped, apart from a few larger resorts directly on the coastal region. These resorts include golf courses and significant landscaping but utilize sewage treatment plants. There are minimal inputs from onsite sewage disposal systems (OSDS) or nutrient inputs from higher inland areas.

In contrast, Kealakekua Bay has a higher population density along the coast and inland, with various nutrient inputs from cesspools and other OSDS. Additionally, Kealakekua Bay experiences higher sedimentation from actively eroding cliffs. Both Kahuwai Bay and Kealakekua Bay are located within protected areas, Kealakekua Bay being a Marine Life Conservation District (MLCD) and Kahuwai Bay falling within a Marine Reserve. However, fish biomass, particularly herbivores and resource fish, varied greatly between the sites, with Kahuwai Bay generally having a higher abundance and biomass of fish compared to Kealakekua Bay.

Restoration Plots

At each site, a before-after-control-impact (BACI) study design was implemented, including four focal restoration (i.e., impact) plots and four control plots. This experimental design was selected to measure the impact of the restoration intervention while simultaneously accounting for background reef change unrelated to the restoration work (Connor et al. 2016, Hughes et al. 2023, Goergen et al. 2020). Each plot measured approximately 10 meters by 10 meters. At each site, individual focal restoration and control plots were marked with permanent corner markers, which were drilled and epoxied into the reef. These markers included targets for our Structure-from-Motion (SfM) surveys, allowing us to align temporal surveys and track fine-scale changes in plots over time. The plots alternated between restoration and control and were spread across roughly 600 meters at each site (Figure 1; interactive digital maps here). Plot depths ranged from approximately 4.5 to 9 meters (15 to 30 feet). Kahuwai Bay had higher coral cover, ranging from 40% to 65%, while Kealakekua Bay had lower coral cover, ranging from 10% to 30%. The structural integrity of the reef at Kahuwai Bay was significantly more intact compared to Kealakekua Bay.

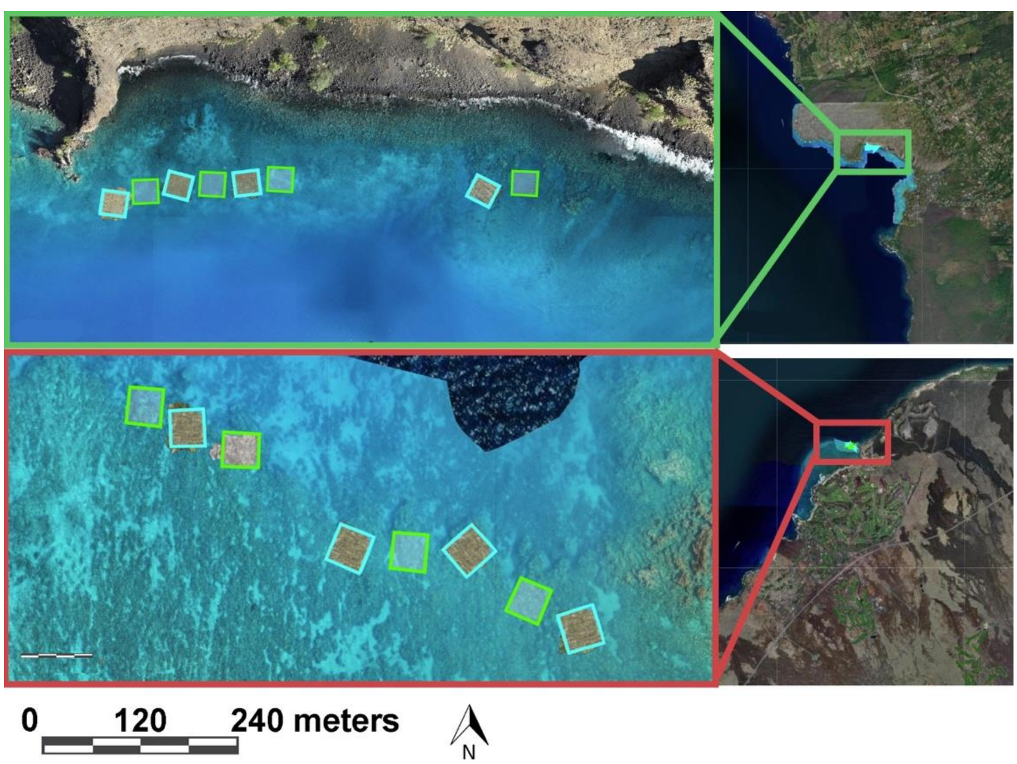

Figure 1. Map showing restoration sites: Kealakekua Bay (green) and Kahuwai Bay (red). Restoration plots (blue) and control plots (green) alternate within 600-meter spans at each site. An interactive version of this map can be found here.

The success of the following restoration techniques were evaluated at each site:

- direct reattachment of whole *Porites lobata* colonies (i.e., colony reattachment),
- direct outplanting of *Porites lobata* fragment arrays (i.e., fragment arrays),
- nursery-grown *Porites lobata* fragments (i.e., nursery fragments) and
- direct outplanting of *Pocillopora meandrina* (i.e., *Pocillopora* outplants).

The number of replicates per technique was standardized within each restoration plot as follows (Table 1):

- twelve directly reattached *Porites lobata* colonies,
- six directly outplanted *Porites lobata* fragment arrays,
- six nursery-grown *Porites lobata* fragment arrays, and
- twelve directly outplanted *Pocillopora meandrina*.

Applying the methods consistently across the replicate restoration plots allowed for a rigorous comparison of the effectiveness of the different restoration techniques.

Table 1. Summary of Restoration Methods and Number of Arrays/Colonies per Plot, Location, and Across the Study.

Restoration Method	Replicates per Plot	Total per Site	Total Across Study
Direct reattachment of *Porites lobata* colonies (i.e., colony reattachment)	12 colonies	48 colonies	96 colonies
Direct outplanting of *Porites lobata* fragments (i.e., fragment arrays)	6 arrays	24 arrays	48 arrays
Nursery-grown *Porites lobata* fragments (i.e., nursery fragments)	6 arrays	24 arrays	48 arrays
Direct outplanting of *Pocillopora meandrina* (i.e., Pocillopora outplants)	12 colonies	48 colonies	96 colonies

Coral Collection and Restoration Methods

All corals used in this study were collected as corals of opportunity. These corals were found detached from the reef substrate, either dislodged and mobile, moving/rolling on the benthos, or had been overturned due to swell and broken off. It is unlikely they would have survived in this state. Under Division of Aquatic Resources Permit Number 2024-03, these corals were collected and data were recorded on species, health condition, collection site, depth, and date of collection. The collection dates varied depending on the restoration techniques used, and coral size varied across species and methods tested. Parent colonies for direct outplanting of *Porites lobata* (i.e., fragment arrays) and nursery-grown *Porites lobata* fragments (i.e., nursery fragments) had shared tissue (i.e., one parent colony donated tissue to both treatments) to investigate the influence of genotype on outcome across techniques. All corals were planted haphazardly throughout each plot, ensuring no coral was placed within 30 cm of another established or outplanted coral. Areas of flat or convex substrate were prioritized, while also assessing the structural integrity of the substrate to ensure that prevent breakage or shifting during major swell events would be unlikely.

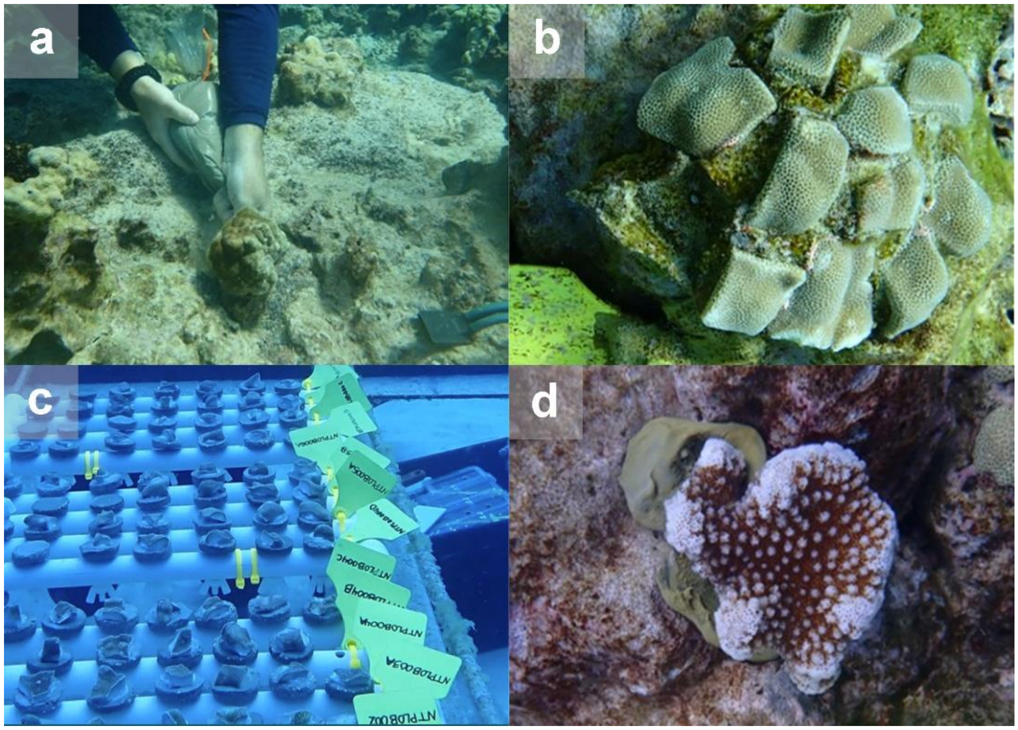

Figure 2. Photos of each restoration technique: a) direct reattachment of whole *Porites lobata* colonies (i.e., colony reattachment), b) direct outplanting of *Porites lobata* fragment arrays (i.e., fragment arrays), c) nursery-grown *Porites lobata* fragments (i.e., nursery fragments), and d) direct outplanting of *Pocillopora meandrina* (i.e., *Pocillopora* outplants).

Direct Reattachment of *Porites lobata*

Porites lobata colonies (mean size: 93 cm^2 ± 14.8 SE at Kahuwai Bay; 176 cm^2 ± 18.2 SE at Kealakekua Bay) were collected and immediately transported to their designated restoration plots, where they were cemented in place. Wire brushes were used to clean the reef substrate to ensure firm attachment. The cement mix, consisting of commercially available concrete mix, xanthan gum, and diatomaceous earth, was prepared on site, typically on the boat, and loaded into pipetting bags. A small portion of concrete was applied to the reef substrate to secure the corals directly to the plots. The concrete typically took 24 hours to set and harden, securing the corals.

Direct Outplanting of *Porites lobata* Fragment Arrays

Massive coral species like *Porites lobata* have slower growth rates than many other corals, making techniques such as micro-fragmentation potentially useful to promote more rapid growth (Page et al. 2018). In some cases, micro-fragmentation can help reduce the bottleneck of heightened mortality that occurs in juvenile corals (Forsman et al. 2015, Raymundo and Maypa 2004). To implement this technique, corals of opportunity were collected and placed in a temporary flow-through system that pumped fresh seawater into tanks. The corals were fragmented into 2-3 cm pieces, labeled, and prepared for outplanting back into the restoration plots within six hours of collection. The corals were outplanted onto the reef using epoxy after removing turf algae from the substrate with a wire brush. Each array consisted of 12 fragments spaced roughly 1.5 cm apart from each other, forming an array approximately 12 cm in diameter. Efforts were made to not cover living tissue with epoxy and epoxy was smoothed around and between the fragments as much as possible to promote rapid tissue sheeting as ridges or cracks in the epoxy skirt slow the pace of fusion of fragments into one colony.

Nursery-Grown *Porites lobata* Fragments

For nursery-grown *Porites lobata* fragments, each parent coral of opportunity that was fragmented for direct outplanting also had fragments placed on the nursery table. Seven fragments were secured onto individual mounting plugs and left on the nursery table for roughly six months to a year, or until they grew out and completely covered their plugs. Marine-grade super glue specifically designed for corals was used to secure these corals to the plugs. Once the corals had grown out, the same epoxy used for direct outplanting was used to secure nursery grown arrays to the reef. The mounting plugs were outplanted after removing turf algae from the substrate, forming a cluster array of 7 fragments, with each array roughly 12 cm in diameter (i.e., the same array size as the *P. lobata* direct outplanting technique). Nursery grown fragments were larger than their direct outplanting counterparts, necessitating fewer fragments per array (7) to reach the standard 12 cm diameter fragment array than with the direct outplanting technique (12 fragments).

Direct Outplanting of *Pocillopora meandrina*

Direct outplanting of *Pocillopora meandrina* involved locating corals of opportunity of this species. These corals were typically harder to find as corals of opportunity due to their weedy nature and tendency not to break off from living reef structures and survive for extended periods, unlike some *Porites* species. Larger *P. meandrina* colonies recovered were split into smaller portions, aiming for fragments of 10-12 cm. These corals were epoxied directly onto the reef after removing any turf algae from the substrate.

Monitoring

Detailed monitoring of the four restoration techniques was essential to evaluating their relative success. A rigorous Structure-from-Motion (SfM) photogrammetry methodology was implemented to track changes within experimental plots and quantify differences among restoration approaches over time. Prior to outplanting, baseline surveys of all plots were conducted. Subsequent monitoring included immediate post-outplanting surveys followed by quarterly assessments to track individual coral outplantings. The survey protocol followed standardized SfM procedures described in Greene et al. (in review), collecting hundreds to thousands of images of each restoration and control plot during initial and quarterly monitoring events. Photos were taken approximately 1 to 1.5 meters above the benthic substrate, with 70% overlap in both the X and Y directions. .

Image processing employed Agisoft Metashape (version 2.1.0) to generate high-resolution orthomosaics of the benthic surface. To enable precise temporal comparisons, ReefShape, an image processing pipeline developed by Will Greene (Perry Institute for Marine Science), was utilized that aligned imagery across multiple time points. This alignment enabled us to measure fine-scale changes in both overall benthic cover and individual outplanted corals throughout the study. Following temporal alignment, orthomosaics were exported to ArcGIS Pro (version 3.2.0) for detailed spatial analysis. Within each mosaic, individual outplanted corals were digitized as polygon shapefiles at each time point, documenting their shape, area, perimeter, survival status, and extent of partial mortality. The geometry of each polygon was calculated to obtain surface area information for each individual coral at all monitoring timepoints.

Analysis

Restoration success was evaluated using two primary metrics: survival and growth. For survival analysis, the post-outplanting persistence of each coral was documented and compared across techniques. Growth was also assessed to determine which techniques and sites supported not only coral survival but also colony expansion. Growth was quantified using two complementary approaches: cumulative change in surface area (cm^2) and percent change in surface area relative to initial colony size, calculated as:

$$Percent\ Change\ =\ \left(\frac{Final\ Surface\ Area\ -\ Initial\ Surface\ Area}{Initial\ Surface\ Area}\right)\ x\ 100$$

This dual analytical approach was necessary as absolute surface area measurements favor larger colonies that can contribute greater absolute growth due to exponential growth patterns. In contrast, percent change metrics provide insight into growth efficiency relative to initial size. Together, these metrics offer a comprehensive understanding of each technique's contribution to reef restoration outcomes, with absolute measurements informing total habitat added and relative measurements clarifying habitat added relative to initial outplant size.

To investigate the factors influencing coral survival, a generalized linear mixed model (GLMM) with a binomial distribution and logit link function was employed. The model specified coral survival as a binary response variable (1 for survival, 0 for non-survival), with days on the reef and restoration technique as fixed predictors. An interaction term was included to assess whether the effect of days on reef varied by technique. Given the hierarchical structure of the data, with multiple observations nested within plots, plot was included as a random intercept to account for potential variability in survival probabilities across different plots. This approach allowed for control of plot-specific effects and focus on the fixed effects of interest.

Although all restoration techniques were initially considered, nursery-grown *Porites lobata* fragments were ultimately excluded since these corals did not have enough time to be grown on the tables and outplanted for a sufficient length of time to be included in this analysis. The final model focused on three restoration techniques:

- direct reattachment of whole *Porites lobata* colonies (i.e., colony reattachment),
- direct outplanting of *Porites lobata* fragment arrays (i.e., fragment arrays), and
- direct outplanting of *Pocillopora meandrina* (i.e., *Pocillopora* outplants).

Effect coding was employed for the restoration technique variable to compare each technique against the overall mean effect, rather than a specific reference category. Model fitting was performed using the glmer function from the lme4 package in R, with maximum likelihood estimation via the Laplace approximation. Model convergence was assessed, and potential issues with identifiability were addressed by examining the eigenvalues and rescaling variables as necessary. The final model was selected based on the Akaike Information Criterion (AIC), with lower AIC values indicating better model fit.

Cost-Benefit Analysis of Coral Restoration Techniques

To evaluate the cost-effectiveness of different coral restoration techniques a comprehensive cost-benefit analysis framework was developed. This framework incorporated multiple factors, including implementation costs, average survival, human input time, and equipment costs for each restoration method. The analysis focused on four techniques:

- direct reattachment of whole *Porites lobata* colonies (i.e., colony reattachment),
- direct outplanting of *Porites lobata* fragment arrays (i.e., fragment arrays),
- nursery-grown *Porites lobata* fragments (i.e., nursery fragments) and
- direct outplanting of *Pocillopora meandrina* (i.e., *Pocillopora* outplants).

Data were collected on all relevant variables for each restoration technique to comprehensively assess their cost-benefit ratios. The following index equation was used:

The following Benefit Index (*BI*) equation was used:

$$BI = \frac{(Average\ Survival \text{ x } K\ )}{Total\ Cost}$$

$$Total\ Cost = \Big(\big((n)personal \text{ x } (n)days\big) \text{ x Personel Cost}\Big) + Equipment\ Cost(Material\ Costs)$$

Where *K* is a constant factor that was chosen to make the benefit index more interpretable. In this case K=10,000, which will scale the benefit index up by 10,000 times. *Average Survival* was also normalized by dividing by 100 to create a value between 0 and 1. This equation quantifies the benefit derived from each restoration technique relative to its total cost. By incorporating both survival and growth probabilities, the analysis assesses the overall effectiveness of each method in promoting coral restoration.

The framework also included an equation for potential additional colonies that could be outplanted if the resources put into the less efficient techniques was instead applied to the more efficient techniques (i.e., marginal cost/colonies); the number of additional corals that could have been outplanted in a given restoration technique given the resources of the most expensive technique:

$$Marginal\ Colonies = \frac{(Cost\ Saved \times Average\ Survival)}{Cost\ Per\ Coral}$$

Where:

$$Cost\ Saved = \max(Human\ Input\ Time) - Human\ Input\ Time$$

This comprehensive approach supports data-driven decision-making about the most effective and efficient coral restoration methods, with appropriate emphasis on the human input time requirements of each technique.

Results

Evaluation of four coral restoration techniques across two sites in West Hawaiʻi revealed significant site and technique specific differences in coral survival and growth. After approximately one year of monitoring, survival rates were consistently higher at Kahuwai Bay than Kealakekua Bay across all restoration techniques. Survival was highest for directly reattached large *Porites lobata* colonies (i.e., colony reattachment) and fragmented arrays of *P. lobata* (i.e., fragment arrays). Directly outplanted *Pocillopora meandrina* (i.e., *Pocillopora* outplants) showed substantially lower survival, with field observations in Kealakekua Bay documenting crown-of-thorns starfish (*Acanthaster planci*) predation as a contributing factor. Outplant growth rates differed substantially among locations and techniques. Survival of fragments reared on nursery tables (i.e., nursery fragments) varied greatly between sites, with much higher survival noted at Kealakekua Bay, though, importantly, these fragments had not yet been outplanted. Though there was high mortality of the *P. meandrina* colonies, those colonies that did survive had the highest growth rates at both locations. *P. lobata* that were directly reattached to the reef as large colonies generally increased in size at Kahuwai Bay, but not Kealakekua Bay. *P. lobata* that were fragmented and then outplanted in arrays had high variability in growth, but after 1 year had not generally increased in size at either site. All restoration techniques exhibited seasonal growth patterns with peak expansion during summer months (June-August).

Table 2. Mean area (cm²), standard error, number out-planted, and survival percentage by restoration technique for Kahuwai Bay and Kealakekua Bay at time of outplanting and at the most recent monitoring time point. Restoration techniques: direct outplanting of *Porites lobata* fragment arrays (i.e., fragment arrays), direct outplanting of *Pocillopora meandrina* (i.e., *Pocillopora* outplants), and direct reattachment of whole *Porites lobata* colonies (i.e., colony reattachment),.

Location	Restoration Technique	Mean Outplant Size (cm²)	SE	Mean End Size (cm²)	SE	Replicates Outplanted (n)	Replicates Surviving (n)	Survival (%)
Kahuwai Bay	Fragment arrays	39	3.0	42	4.8	24	24	100
	Pocillopora outplants	28	2.0	21	3.9	48	23	48
	Colony reattachment	93	14.8	119	14.8	48	45	94
Kealake...	Fragment arrays	47	3.2	41	5.6	25	15	60

	Pocillopora outplants	15	1.4	20	3.3	48	13	27
	Colony reattachment	176	18.2	145	15.6	49	31	63

Survival Patterns

Survival was higher at Kahuwai Bay across all restoration techniques than at Kealakekua Bay, except for fragments held on the nursery table. At Kahuwai Bay, survival was remarkably high for both directly outplanted *P. lobata* arrays (100% survival throughout the study) and large reattached *P. lobata* colonies (94% survival) (Figure 3; Table 2). At Kealakekua, these outplanting techniques had the highest survival rates, but were substantially lower than at Kahuwai Bay (*P. lobata* array survival = 60%; *P. lobata* large colony reattachment survival = 63%; Figure 3; Table 2). Across both locations, directly outplanted *P. meandrina* had the lowest relative survival (48% survival at Kahuwai Bay, 27% survival at Kealakekua Bay; Table 2; Figures 3). Field observations noted active predation by the crown-of-thorns starfish (*Acanthaster planci*) on *P. meandrina* outplants, which likely contributed to their low survival rates. In contrast to the general trend, fragments reared on nursery tables had much higher survival at Kealakekua Bay (83% survival) than at Kahuwai Bay (33% survival), though it is important to note these corals had not yet faced the challenges of outplanting in Kealakekua Bay. Higher survival in Kealakekua may also be attributed to adaptive management of the nursery table. Enhanced coral tray designs and regular cleaning of the table of were incorporated into Kealakekua's table in an effort to try and increase retention of individual fragments as a result of the mortality that occurred at the Kahuwai table.

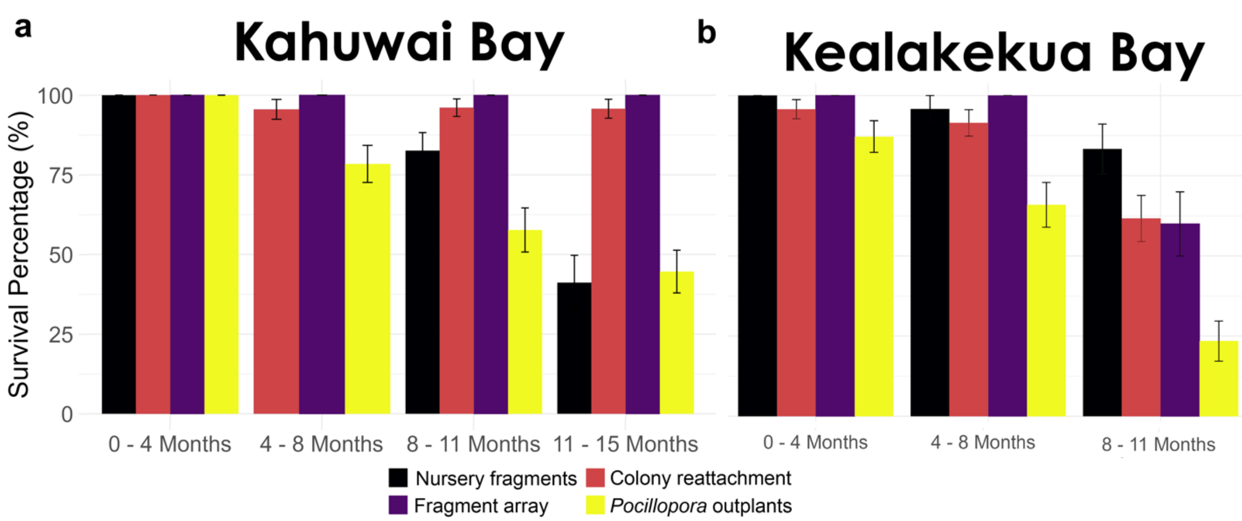

Figure 3. Survival percentage (Y-axis) over time points in truncated months (X-axis) for four restoration techniques in a) Kahuwai Bay and b) Kealakekua Bay.

Statistical analysis using generalized linear mixed models (GLMMs) underscore these findings (Figure 4). At Kahuwai Bay, the high intercept value (Estimate = 4.6908, $p < 0.001$) indicates strong baseline survival probability, while the days on reef had no significant effect on survival (Estimate = -0.0058, $p = 0.149$). This indicates that outplants at Kahuwai Bay maintained high survival regardless of time since outplanting, demonstrating favorable conditions for outplant persistence in the bay. In contrast, at Kealakekua Bay days on reef had a significant negative effect on survival probability (Estimate = -0.0187, $p < 0.001$), reflecting the challenges that outplants face at this location. Survival rates were significantly different between restoration techniques at both sites (Kahuwai: Estimate = -1.9769, $p = 0.0343$; Kealakekua: Estimate = -2.1351, $p < 0.001$), with *P. meandrina* outplants showing consistently lower survival than other techniques. The interaction between days on reef and technique was not statistically significant at either site (Kahuwai: $p = 0.2775$; Kealakekua: $p = 0.112$), indicating that the time-dependent survival patterns were similar across techniques within each site. The random effect of plot showed considerable variability at both locations (Variance: Kahuwai = 0.6727; Kealakekua = 0.6863), highlighting the importance of local reef conditions on outplant survival even within a focal geographic area in determining outplant success.

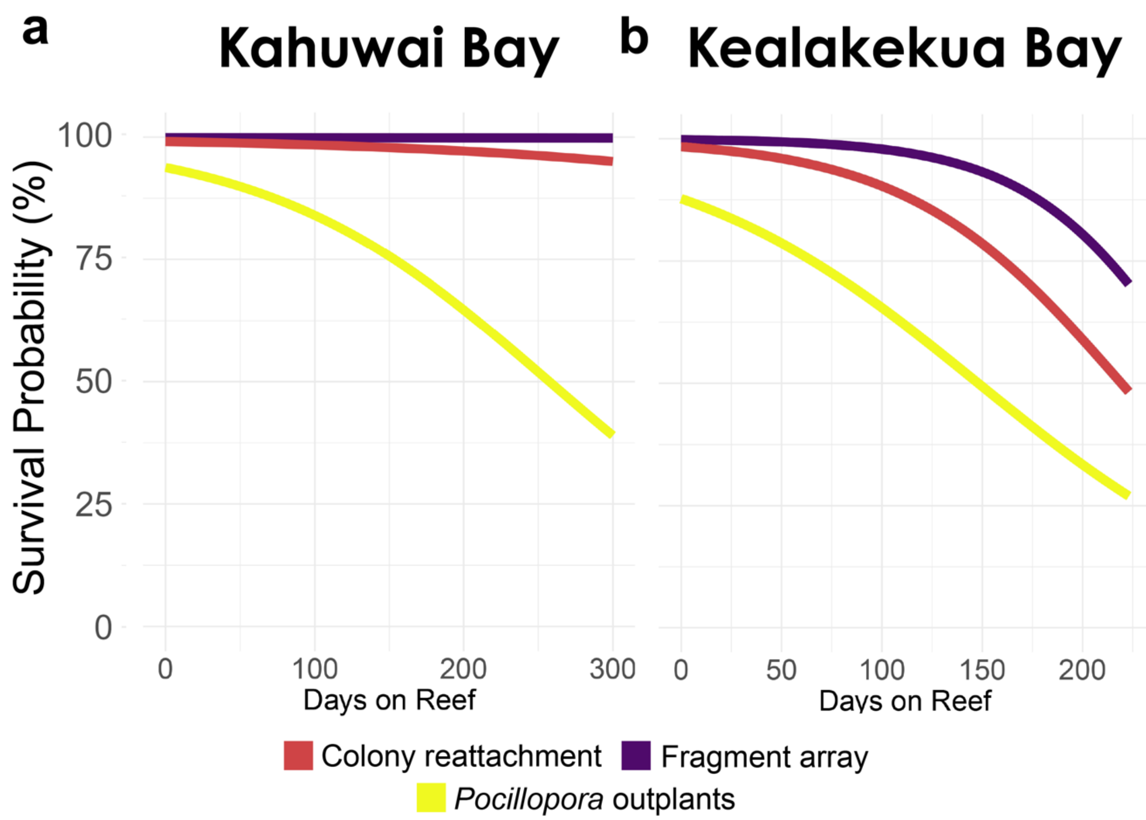

Figure 4. Generalized linear mixed effects models assessing the effect of days on reef on the probability of survival for a) Kahuwai Bay and b) Kealakekua Bay for three restoration techniques: fragmented direct cluster out-planting, large colony reattachment, and *P. meandrina* out-planting at Kealakekua Bay.

Growth Patterns

Growth patterns, measured as both cumulative change (cm^2) and percent change in surface area, displayed considerable variability among restoration techniques and sites. Colonies of *P. meandrina* that survived after roughly one-year post-outplanting exhibited the highest growth rates at both Kahuwai Bay and Kealakekua Bay (Figures 5). Growth rates for this technique in Kealakekua were particularly high, with colonies growing an additional 60% of their original starting size after only 300 days (Figure 5). In contrast, direct reattachment of *P. lobata* increased in size considerably at Kahuwai Bay, but not at Kealakekua Bay, indicating site-specific factors influencing their growth. Fragmented *P. lobata* colonies outplanted in arrays did not show much growth at either site. This technique in particular exhibited a "one step forward, two steps back" growth pattern. While these colonies initially showed growth and fusion, they subsequently experienced partial mortality. As a result, after nearly a year, surviving fragment arrays merely changed shape without a net increase or decrease in size (Figure 5).

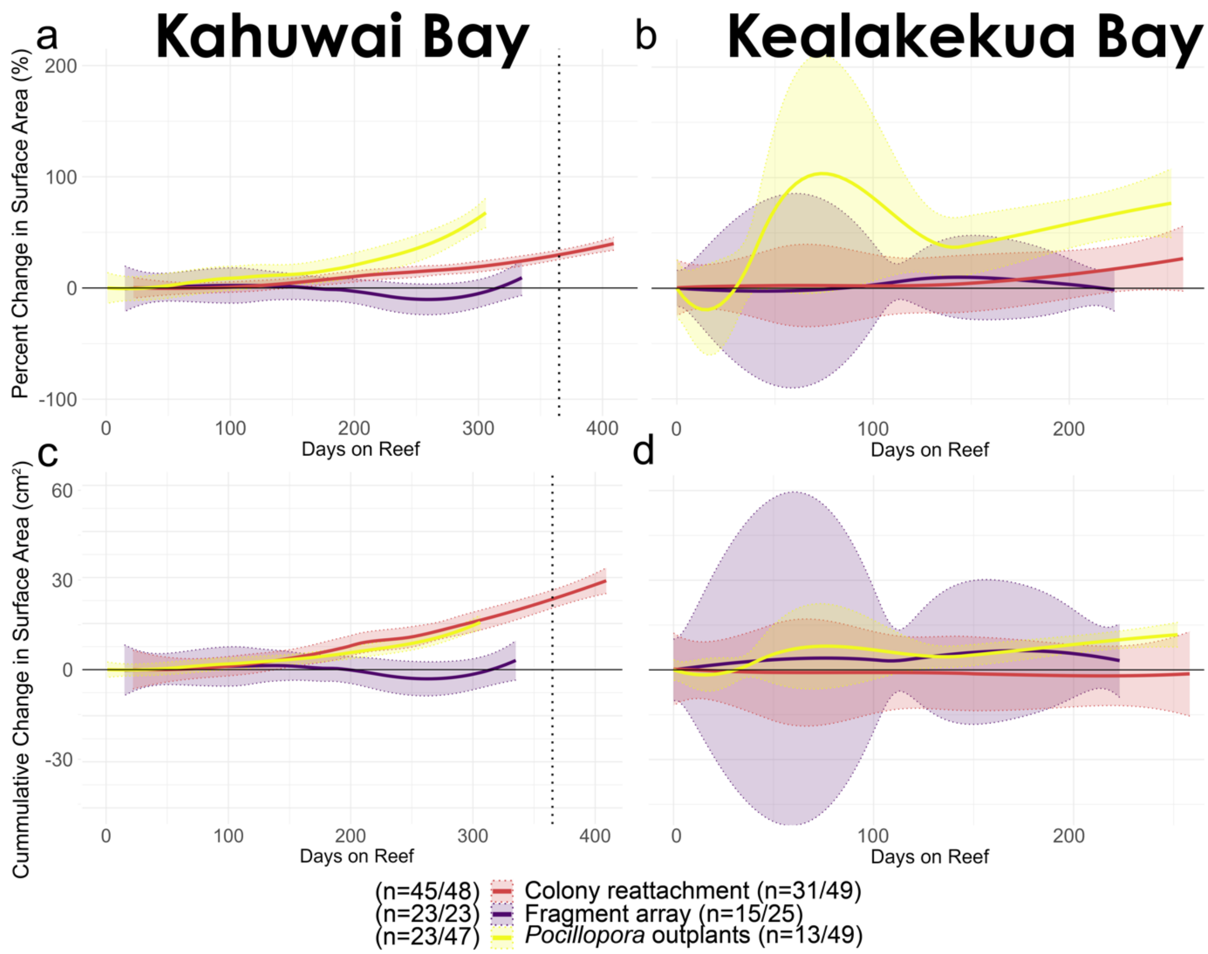

Figure 5. (a & b) Percent change from starting size, and (c & d) average cumulative change in surface area (cm²) over days on the reef for three restoration techniques: fragmented direct cluster out-plantings, large colony reattachment, and *P. meandrina* direct out-planting in Kahuwai Bay (a & c) and Kealakekua Bay (b & d). Shading represents standard error, and thedotted black line represents the 365-day mark.

Statistical analysis using GLMMs provided additional insights into growth dynamics (Figure 6). At Kahuwai Bay, days on reef had a significant positive effect on growth probability (Estimate = 0.0090, $p < 0.001$), indicating that the more time outplants spent on the reef the larger they grew. However, restoration technique did not significantly affect growth at this site (Estimate = -0.0335, $p = 0.890$), suggesting that site conditions, rather than restoration technique, were the primary driver of growth patterns at Kahuwai Bay. The interaction between days on reef and restoration technique was not significant (p = 0.391), indicating that all techniques followed similar growth trajectories over time. The random effect of plot showed moderate variability (Variance = 0.4078), reflecting some heterogeneity in growth conditions across among plots within the bay. At Kealakekua Bay, days on reef also had a significant positive effect on growth probability (Estimate = 0.0038, p = 0.0011), but the effect was less pronounced than at Kahuwai Bay. Unlike at Kahuwai Bay, restoration technique significantly influenced growth at Kealakekua Bay (Estimate = 0.5343, p = 0.0223). The marginally significant interaction between days on reef and technique (p = 0.0699) suggests that growth trajectories may diverge somewhat among techniques over time at this site. Interestingly, the random effect of plot showed no variability (Variance = 0), indicating relatively consistent growth conditions across plots at Kealakekua Bay despite the variable survival rates observed.

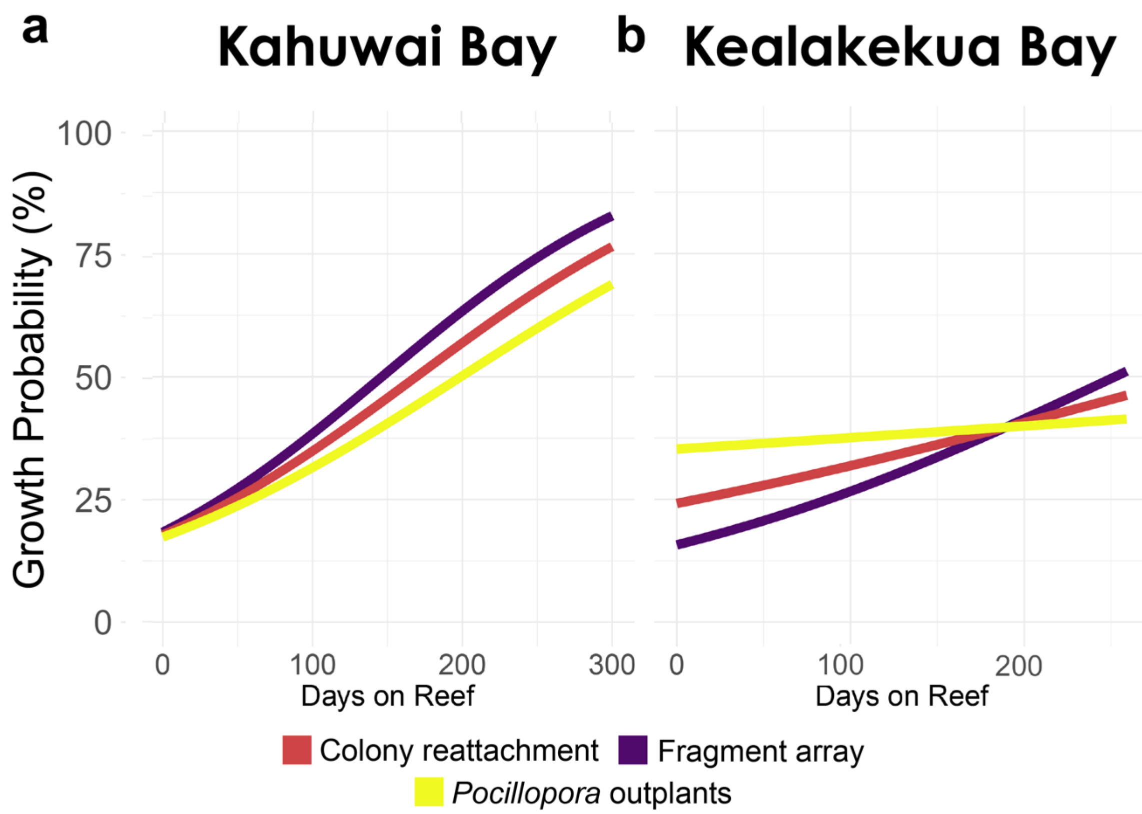

Figure 6. Generalized linear mixed effects models of probability of survival (left Y-axis) and probability of growth (right Y-axis) plotted against days on the reef (X-axis) for three restoration techniques: fragmented direct cluster out-planting, large colony reattachment, and *P. meandrina* out-planting at Kealakekua Bay.

Seasonal growth patterns were evident across all restoration techniques at both sites, with peak expansion occurring during summer months (June-August) (Figures S1 & S2). This seasonal trend suggests that environmental factors (e.g., temperature and light availability) during these months are particularly favorable for coral growth.

Cost-Benefit Analysis of Coral Restoration Techniques

The cost per restored coral varied substantially across restoration techniques. Direct outplanting techniques - direct outplanting of *Pocillopora meandrina* and direct reattachment of *Porites lobata* colonies - were the most cost-effective at $163 per coral. In contrast, directly outplanted fragment arrays and nursery-grown fragments were considerably more expensive at $1,280 and $2,759 per coral, respectively (Table 3).

Table 3. Cost summaries of materials, implementation, manpower, days need to implement, operation costs, cost per 24 corals, and cost per individual coral. Restoration techniques: direct outplanting of *Porites lobata* fragment arrays (i.e., fragment arrays), direct outplanting of *Pocillopora meandrina* (i.e., *Pocillopora* outplants), direct reattachment of whole *Porites lobata* colonies (i.e., colony reattachment), and nursery-grown *Porites lobata* fragments (i.e., nursery fragments). *All 10 people are not needed across all 25 days and has been accounted for in Total Cost.

Restoration Technique	Material Cost	Implementation Cost	People Needed	Days Needed	Cost per Day	Corals (n)	Total Cost	Cost per Coral
Fragment arrays	$4,900	$25,000	10	4	$600	24	$30,700	$1,280
***Pocillopora* outplants**	$1,200	$4,600	4	2	$600	48	$7,800	$163
Colony reattachment	$1,200	$4,600	4	2	$600	48	$7,800	$163
Nursery fragments	$59,700	$36,000	10*	25	$600	24	$66,198	$2,759

The benefit index analysis, which incorporated both implementation costs and survival rates, revealed clear differences in cost-effectiveness. Direct reattachment of *P. lobata* colonies had the highest benefit index at both sites (Kealakekua Bay: 0.81; Kahuwai Bay: 1.21), indicating the highest benefit relative to cost (Table 4). This method substantially outperformed all other techniques, with at least twice the benefit index of the next most effective technique, direct outplanting of *P. meandrina* (Kealakekua Bay: 0.35; Kahuwai Bay: 0.62). Direct outplanting of *P. lobata* arrays had the third lowest index. The most expensive technique, nursery-grown fragments, had the lowest benefit indices (Kealakekua Bay: 0.12; Kahuwai Bay: 0.06). Direct reattachment of *P. lobata* colonies demonstrated dramatically higher cost-effectiveness than nursery-grown fragments at both sites. At Kahuwai Bay, the benefit index for direct reattachment (1.21) was nearly 20 times higher than for the nursery table approach (0.06), while at Kealakekua Bay, direct reattachment (0.81) yielded nearly 7 times the benefit of nursery-grown fragments (0.06).

Table 4. Summary of Key Metrics: the cost per coral, normalized average survival, benefit index (BI), and marginal costs. Marginal costs represent the number of additional colonies that could have been outplanted using the resources from the cost-ineffective technique. The average survival rate is factored into this calculation, accounting for projected post-outplanting mortality.

Restoration Technique	Cost per Coral	Average Survival Kealakekua (%)	Average Survival Kahuwai (%)	Kealakekua *BI*	Kahuwai *BI*	Marginal Colonies Kealakekua	Marginal Colonies Kahuwai
Fragment arrays	$1,280	60	100	0.20	0.33	5	9

***Pocillopora* outplants**	$163	27	48	0.35	0.62	49	89
Colony reattachment	$163	63	94	0.81	1.21	116	174
Nursery fragments	$2,759	81	81	0.12	0.06	0	0

Analysis of marginal costs quantified the number of additional colonies that could be implemented if resources from less efficient restoration techniques were reallocated to more efficient ones (Table 4). For instance, if the resources allocated to the nursery table approach were redirected to direct reattachment of *P. lobata*, enough colonies could be outplanted so that an additional 116 colonies would survive at Kealakekua Bay and 174 at Kahuwai Bay; accounting for the respective survival probabilities at each site. These figures represent more than doubling the potential number of surviving colonies at Kealakekua Bay and nearly quadrupling them at Kahuwai Bay. The marginal gains for redirecting resources to other techniques were substantially lower, with *P. meandrina* outplanting yielding 49 and 89 additional colonies, and fragment arrays yielding only 5 and 9 additional colonies at Kealakekua and Kahuwai Bays, respectively. The lower efficiency of fragment arrays stems from their substantially higher per-coral costs and more complex implementation requirements, including longer outplanting times and necessary shore support teams. Although process improvements might marginally increase efficiency, the fundamental cost structure and logistical demands of this approach would continue to limit its cost-effectiveness compared to direct colony reattachment.

Although fragmented and nursery-grown corals are more expensive than direct outplanting, the nursery table could benefit from economies of scale. A tenfold increase in nursery capacity (from 24 to 240 arrays) would reduce per-coral rearing costs significantly - from $2,758.25 to approximately $275.82. However, the subsequent outplanting of these fragments would require substantial field effort, adding approximately $48,000 in implementation costs and resulting in a final per-coral cost of $475.82. Though more economical at scale, this approach would still be roughly three times more expensive than direct colony reattachment. The nursery approach does offer one notable advantage: a single coral of opportunity can be propagated into multiple outplant arrays, potentially addressing limited donor colony availability and/or allowing for propagation of corals with particular traits (e.g., thermal tolerance). Despite their higher costs, nursery approaches may offer valuable applications for rare or endemic coral species where the conservation value per colony significantly exceeds typical restoration costs.

Discussion

Key Findings

Our assessment of four coral restoration techniques across two West Hawaiʻi sites revealed that both restoration technique and site characteristics strongly influence restoration outcomes. Outplant growth and survival rates were generally higher at Kahuwai Bay than Kealakekua Bay. Direct reattachment of whole *Porites lobata* colonies emerged as the most successful technique at both sites, with high survival rates (94% at Kahuwai Bay, 63% at Kealakekua Bay) and the most favorable cost-effectiveness ratio. Direct outplanting of *P. lobata* fragment arrays showed high survival at Kahuwai Bay (100%) but moderate survival at Kealakekua Bay (60%), with minimal net growth over the study period. Despite high survival, this technique was approximately 7.9 times more expensive per coral than direct reattachment. Nursery-grown fragments represented the most resource-intensive approach - nearly 17 times more expensive than direct reattachment. Meanwhile, *Pocillopora meandrina* outplants exhibited the lowest survival (48% at Kahuwai Bay, 27% at Kealakekua Bay) but the highest growth rates when they survived. These findings underscore the importance of tailoring reef restoration approaches - and expectations - to the local context, and they identify direct reattachment as a practical, accessible restoration approach that can be readily implemented across Hawai‘i and beyond.

Whole Colony Reattachment: A Promising Restoration Technique

Direct reattachment of whole colonies performed consistently well across both study sites, highlighting the potential of this technique across diverse environmental conditions. This approach yielded high survival, moderate growth rates, and exceptional cost-effectiveness, making it potentially suitable as a primary restoration strategy for widespread implementation. Its resilience to site-specific factors likely stems from minimal handling stress, preserved colony integrity, and immediate stable attachment.

Fragment-based approaches showed greater sensitivity to environmental conditions. The difference in nursery table survival between sites (33% at Kahuwai Bay versus 83% at Kealakekua Bay) underscores the importance of site-specific pilot testing before scaling nursery-based approaches. Direct fragment arrays exhibited a "one step forward, two steps back" growth pattern, suggesting that energetic demands of recovery and attachment may limit their expansion during the first year post-outplanting.

Statistical modeling revealed that at Kahuwai Bay, time benefited growth ($p < 0.001$) without compromising survival, indicating favorable conditions for long-term restoration. In contrast, at Kealakekua Bay, time negatively impacted survival ($p < 0.001$), suggesting more challenging environmental conditions that may require technique refinement.

Optimizing Restoration Strategies and Investment

The State of Hawai‘i's Coral Ecological Value Assessment Tool (Division of Aquatic Resources 2017) provides an economic framing for this work. Whole colony reattachment demonstrated costs ($163 per coral) well below the state's assigned value for comparable coral colonies ($200-400), indicating positive return on investment. In contrast, fragment-based approaches currently exceed these valuations, suggesting their application should be targeted to specialized circumstances.

However, diverse restoration techniques can and should play complementary roles within a comprehensive restoration strategy. While direct reattachment may form the backbone of large-scale efforts, fragment-based approaches could be strategically deployed for rare species propagation or to capitalize on the rapid growth potential of branching corals. Similarly, nursery techniques may be justified for specialized applications such as preserving genetic diversity of threatened species or propagation of corals with desirable traits (e.g., thermal tolerance).

Future research should include extended monitoring to assess long-term trajectories, expansion to additional coral species with different morphologies and life histories, and exploration of technique modifications that might enhance both survival and growth outcomes. As restoration efforts scale up, standardized monitoring frameworks will become increasingly important to evaluate the holistic impact of interventions.

Understanding Local Context Improves Restoration Outcomes

This study highlights the important influence of local environmental conditions on restoration outcomes and underscores the importance of tailoring restoration approaches - and expectations - to the local context. Kahuwai Bay, with its higher coral cover (40-65%), intact reef structure, abundant herbivorous fish, and minimal land-based pollution, consistently outperformed Kealakekua Bay across all restoration techniques. Kealakekua Bay – with its more degraded environment (i.e., 10-30% coral cover, active sedimentation, higher anthropogenic impacts) – generally had lower outplant survival and growth. Despite these challenges, direct reattachment of whole *Porites lobata* colonies emerged as a promising approach across both sites, underscoring the importance of pilot testing to inform strategic restoration intervention.

While direct reattachment of *P. lobata* showed relatively consistent performance across both sites, fragment-based approaches displayed much higher site sensitivity. Species selection was also influenced by local factors, as evidenced by significant crown-of-thorns starfish predation on *P. meandrina* at Kealakekua Bay. Seasonal patterns further underscore the importance of context-specific restoration planning, with all techniques showing accelerated growth during summer months.

Effective coral restoration therefore requires a context-specific approach rather than universal "best practices." Restoration practitioners should understand local environmental conditions, conduct small-scale pilot tests of multiple techniques, and develop strategies that account for site-specific constraints. Setting appropriate expectations based on local context - both for survival rates and recovery timeframes- is essential for accurately evaluating restoration success and effectively communicating outcomes to stakeholders.

Conclusion

This study provides a robust assessment of coral restoration techniques across multiple sites in Hawaiʻi, offering evidence-based guidance for restoration practitioners. Direct reattachment of whole *P. lobata* colonies emerged as the most cost-effective approach for establishing corals across varying reef environments, while fragment-based approaches and alternative species selections may complement this strategy in specific contexts.

The pronounced site-specific variation in outcomes underscores the importance of understanding - and accounting for - local conditions and suggests that restoration efforts should be paired with broader conservation measures that enhance reef health. Systematically evaluating the effectiveness, cost-efficiency, and variability of restoration outcomes across sites strengthens the scientific foundations of coral reef restoration and improves outcomes for both reefs and the communities that depend on them.

References

Bishop, R. C., Chapman, D. J., Kanninen, B. J., Krosnick, J. A., Leeworthy, V. R., & Meade, N. F. (2011). Total economic value for protecting and restoring Hawaiian coral reef ecosystems final report [Technical Memorandum CRCP 16]. National Oceanic and Atmospheric Administration. https://repository.library.noaa.gov/view/noaa/684

Boström-Einarsson, L., Babcock, R. C., Bayraktarov, E., Ceccarelli, D., Cook, N., Ferse, S. C. A., Hancock, B., Harrison, P., Hein, M., Shaver, E., Smith, A., Suggett, D., Stewart-Sinclair, P. J., Vardi, T., & McLeod, I. M. (2020). Coral restoration – A systematic review of current methods, successes, failures and future directions. PLoS ONE, 15(1), Article e0226631. https://doi.org/10.1371/journal.pone.0226631

Conner, M. M., Saunders, W. C., Bouwes, N., & Jordan, C. (2016). Evaluating impacts using a BACI design, ratios, and a Bayesian approach with a focus on restoration. Environmental Monitoring and Assessment, 188, 1-14.

Division of Aquatic Resources. (2021). Coral restoration review guidelines. State of Hawaiʻi Department of Land and Natural Resources' Division of Aquatic Resources. https://dlnr.hawaii.gov/coralreefs/files/2021/07/Coral-Restoration-Review-Guidelines.pdf

Forsman, Z. H., Page, C. A., Toonen, R. J., & Vaughan, D. (2015). Growing coral larger and faster: Micro-colony-fusion as a strategy for accelerating coral cover. PeerJ, 3, Article e1313. https://doi.org/10.7717/peerj.1313

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

Grafeld, S., Oleson, K. L. L., Teneva, L., & Kittinger, J. N. (2017). Follow that fish: Uncovering the hidden blue economy in coral reef fisheries. *PLoS One*, 12(8), e0182104. https://doi.org/10.1371/journal.pone.0182104

Greene, W. O., Marshall, S., Li, J., & Dahlgren, C. P. (in review). ReefShape: A system for the efficient collection and automated processing of time-series underwater photogrammetry data for benthic habitat monitoring. *Journal of Visualized Experiments*.

Hernández-Delgado, E. A., Suleimán-Ramos, S. E., Mercado-Molina, A. E., & Fonseca, A. C. (2018). Testing the feasibility of coral nurseries in an upwelling area in the North Pacific of Costa Rica. PeerJ, 6, Article e5561. https://doi.org/10.7717/peerj.5561

Hughes, T. P., Baird, A. H., Morrison, T. H., & Torda, G. (2023). Principles for coral reef restoration in the Anthropocene. One Earth, 4(8). https://doi.org/10.1016/j.oneear.2023.04.008

Knapp, I. S. S., Forsman, Z. H., Greene, A., Johnston, E. C., Bardin, C. E., Chan, N., Wolke, C., Gulko, D., & Toonen, R. J. (2022). Coral micro-fragmentation assays for optimizing active reef restoration efforts. PeerJ, 10, Article e13653. https://doi.org/10.7717/peerj.13653

Page, C. A., Muller, E. M., & Vaughan, D. E. (2018). Microfragmenting for the successful restoration of slow growing massive corals. Ecological Engineering, 123, 86-94.

Raymundo, L. J., & Maypa, A. P. (2004). Getting bigger faster: Mediation of size-specific mortality via fusion in juvenile coral transplants. Ecological Applications, 14, 281-295. https://doi.org/10.1890/02-5373

Reguero, B. G., Cole, A., Lowe, E., Shope, J. B., Gibbs, A. E., Nickel, B. A., McCall, R. T., van Dongeren, A. R., Beck, M. W., & Storlazzi, C. D. (2019). Rigorously valuing the role of

U.S. coral reefs in coastal hazard risk reduction. *U.S. Geological Survey*. https://doi.org/10.3133/ofr20191027

Rodgers, K. S., Bahr, K. D., Jokiel, P. L., & Richards Donà, A. (2017). Patterns of bleaching and mortality following widespread warming events in 2014 and 2015 at the Hanauma Bay Nature Preserve, Hawai'i. PeerJ, 5, e3355. https://doi.org/10.7717/peerj.3355

Spalding, M., Burke, L., Wood, S. A., Ashpole, J., Hutchison, J., & zu Ermgassen, P. (2017). Mapping the global value and distribution of coral reef tourism. *Marine Policy*, 82, 104-113. https://doi.org/10.1016/j.marpol.2017.05.014

Winston, M., Oliver, T., Couch, C., Donovan, M. K., Asner, G. P., Conklin, E., Fuller, K., Grady, B. W., Huntington, B., Kageyama, K., Kindinger, T. L., Kozar, K., Kramer, L., Martinez, T., McCutcheon, A., McKenna, S., Rodgers, K., Shayler, C. K., Vargas-Angel, B., & Zgliczynski, B. (2022). Coral taxonomy and local stressors drive bleaching prevalence across the Hawaiian Archipelago in 2019. PLOS ONE, 17(9), e0269068. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0269068

Supplementary Materials

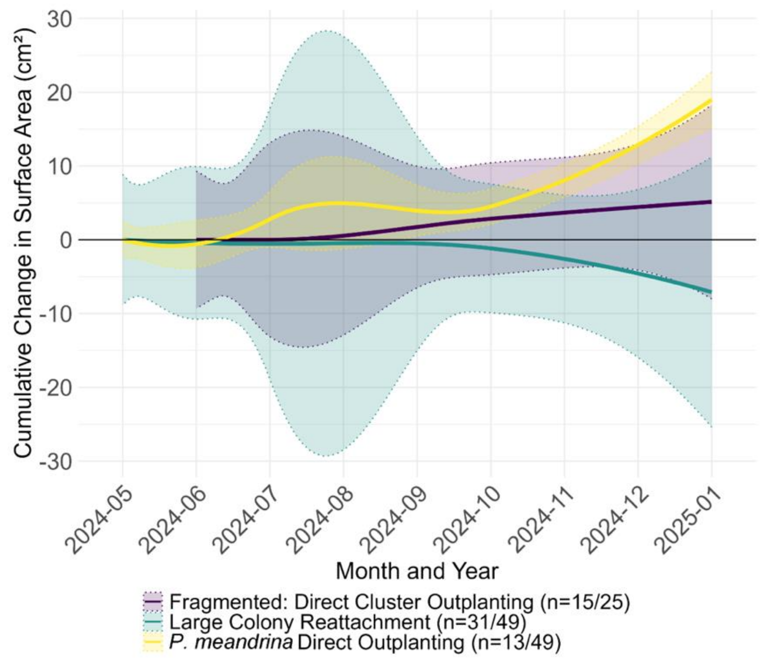

Figure S1. Average cumulative change in surface area (cm²) and standard error over month and year for three restoration techniques: fragmented direct cluster out-plantings, large colony reattachment, and *P. meandrina* direct out-planting in Kealakekua Bay.

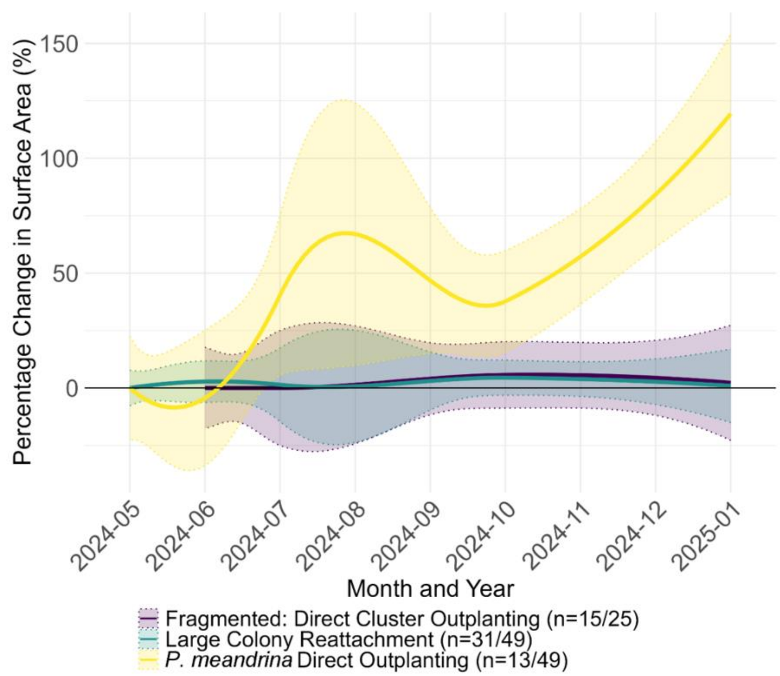

Figure S2. Average cumulative change in surface area percent change from starting size with standard error over month and year for three restoration techniques: fragmented direct cluster out-plantings, large colony reattachment, and *P. meandrina* direct out-planting in Kealakekua Bay.