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RESEARCH ARTICLE

Cost-effectiveness of tourism-led coral planting at scale on the northern Great Barrier Reef

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Stakeholder-led coral reef restoration efforts, aimed at locally retaining or rebuilding coral populations, have rapidly grown over the last two decades. However, the cost-effectiveness—and in turn viability—of coral restoration projects remains rarely reported. We therefore evaluated coral planting (often termed "outplanting") cost-effectiveness across the first 3.5 years of the Coral Nurture Program (CNP), a coral restoration approach integrated within tourism operations on Australia's Great Barrier Reef. CNP operator activity reporting forms (63,632 corals planted, 5 tourism operators, and 23 reef sites) were used to opportunistically calculate coral planting costs (PC; US\$ coral^{-1} trip^{-1}) for "routine" planting versus when additional stewardship activities—that regulate planting effectiveness—were undertaken (e.g., nursery maintenance). Mean PC (±standard error) was US\$2.34 ± 0.20 coral^{-1} trip^{-1} (ranging US\$0.78–6.03, 5th–95th percentile), but increased 2- to -6-fold on trips where nursery propagation, site maintenance, or staff training was conducted to support planting efforts. The "realized" cost (PC_R) of establishing coral biomass was subsequently determined by evaluating survivorship of planted corals across space (9 sites, single survey timepoint, n = 4,723 corals up to 3 years old) or over time (2 sites, over 9–12 months, n = 600 corals), resulting in costs increasing from PC to PC_R by 25–71%. We demonstrate how integration of practices into tourism operations creates potential for cost-effective coral planting at "high-value" tourism reef sites, and discuss important steps for improving cost-accounting in stakeholder-led restoration programs that may be similarly positioned to routinely determine their cost-effectiveness.

Key words: coral outplanting, coral survivorship, cost-effectiveness, Great Barrier Reef, restoration costs, site stewardship

Implications for Practice

- Transparent cost-tracking of coral restoration efforts is fundamental to justifying ongoing feasibility and investment.
- Coral planting led by tourism operators on the Great Barrier Reef utilizes existing vessel infrastructure and personnel, enabling lower-cost coral planting (US\$2.34 ± 0.20 coral^{-1} trip^{-1}, mean [±SE]).
- Other essential, but infrequent activities necessary for effective planting modify costs to US\$5.93 ± 0.81 coral^{-1} trip^{-1} when involving nursery propagation and maintenance, or US\$16.14 ± 5.39 when training staff.
- Accounting for outplant survivorship (by site or time) increases costs by 25–71%, and is therefore a necessary consideration where planting cost is used to justify restoration effectiveness.
- Accurate accounting of staff time dedicated to wider restoration activities that govern planting effectiveness is needed to improve cost estimates.

Introduction

Progressive declines in coral reef ecosystem health through climate change and localized impacts are driving modern reef management to implement reactive interventions alongside existing threat mitigation and habitat protection (Hein et al. 2021; Kleypas et al. 2021; McLeod et al. 2022). Global uptake of reef restoration interventions—particularly via in-water asexual coral

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propagation and outplanting ("planting" is used hereafter for brevity) (Boström-Einarsson et al. 2020)—has grown in the past decade as stakeholders attempt to boost coral populations and reef recovery capacity at local scales (e.g., Bayraktarov et al. 2020; Hein et al. 2020; Howlett et al. 2022). Current efforts are rapidly accelerating as in-water nurseries (e.g., Howlett et al. 2021) and coral planting methods (e.g., Suggett et al. 2020; Unsworth et al. 2021) become cheaper and more efficient and as practitioners network to learn collectively (Vardi et al. 2021; Quigley et al. 2022). Furthermore, recent declarations of decadal priorities in restoration and ocean science have catalyzed new financing mechanisms geared toward advancing the scale, equity, and sustainability of reef restoration efforts (Hein & Staub 2021; Suggett et al. 2023).

Several programs have shown promise in facilitating targeted and scalable recovery of locally impacted reef areas (e.g., Montoya-Maya et al. 2016; Hein et al. 2020; Peterson et al. 2023) while simultaneously building the site stewardship capacity of reef-dependent communities; for example, stakeholders including citizen scientists and recreational divers in Florida (Hesley et al. 2017); local fishermen, diver centers, and hoteliers in Latin America (Bayraktarov et al. 2020); and tourism operators on the Great Barrier Reef (GBR) (this study; see also Howlett et al. 2022). However, few restoration programs have reported costs needed to justify on-going investment and/or develop operational strategies to improve cost-efficiencies in practice (Bayraktarov et al. 2019; Quigley et al. 2022). As such, delivery of informed and sustained investment into restoration practices remains challenged by uncertainty regarding the cost and feasibility of different approaches (Bayraktarov et al. 2019; Hein & Staub 2021; Suggett et al. 2023). Costs involved in coral restoration efforts are highly context-specific, spanning multiple activities that directly or indirectly carry monetary value. As such, where coral restoration costs have been reported, approaches have typically not been comprehensive, standardized, or transparent (Edwards et al. 2010; Iacona et al. 2018; Bayraktarov et al. 2019). Important contextual details underpinning costs are often absent; such as, labor costs reported in local monetary values rather than comparable units of time (Edwards et al. 2010), currency conversion rates (Bayraktarov et al. 2019), disclosing where volunteer labor or in-kind contributions have been employed (Edwards et al. 2010), or factoring in project life-cycle costs from planning through to monitoring (Spurgeon & Lindahl 2000; Bayraktarov et al. 2019). Collectively such inconsistences in cost reporting can limit the ability of restoration practitioners and reef managers to evaluate ongoing cost-effectiveness, identify context-specific suitability, or develop realistic budgets for future implementation (Bayraktarov et al. 2015). Such lack of transparent reporting—and how it relates to activity goals—may further undermine efforts to provide trust and confidence to future investment opportunity (Suggett et al. 2023).

A novel asexual coral propagation and planting approach on Australia's GBR, stewarded by reef tourism operators (Coral Nurture Program [CNP]; Howlett et al. 2022), has shown promise in resolving several logistical and cost-efficiency constraints on rehabilitating coral populations (Suggett et al. 2020; Howlett et al. 2021, 2022, 2023). The CNP was initiated in 2018 in response to the 2016–2017 mass bleaching events on the GBR. Activity was conceived to build capacity for reef tourism operator staff to assist the recovery of hard coral cover at reef sites regularly accessed during tourism trips. This integrated approach enabled lower operational costs through harnessing existing resources on the reef (i.e., the vessel infrastructure, trained personnel, equipment, and in-depth site knowledge of reef tourism operators) for restoration purposes. In parallel, the development of a novel coral attachment device (Coralclip®) has shown improved planting safety, speed, and costs compared to previous methods (Suggett et al. 2020). However, these previously reported planting cost estimates for Coralclip® (US$0.6–3.0/coral) were based on only approximately 4,500 outplants at a single reef and therefore unlikely captured the variability of coral planting costs, given the range of reef site ecologies and tourism operations across the CNP (described in Howlett et al. 2022).

Here we evaluate the broader cost of tourism-led coral planting operations using Coralclip® by examining >3 years of CNP activity that resulted in 63,632 corals planted by five diverse tourism operations across 23 sites on seven reefs of the northern GBR (from 271 "planting trips"). We used CNP daily activity reporting forms to determine the range in planting costs under "routine" outplanting as well as other operational contexts, and in turn discuss the factors that influence these costs. To better resolve planting cost-effectiveness during this period, we further evaluated the survivorship of planted coral material (termed "outplants"). Specifically, by adjusting planting costs with subsequent outplant survivorship (Edwards et al. 2010), we determine the "realized" cost of establishing new coral biomass on the GBR through tourism industry-driven site stewardship. In doing so, we provide the first cost assessment of targeted coral planting efforts at scale in Australia.

Methods

CNP Operational Context, Activity, and Data Capture

Our cost analysis focuses on CNP coral planting activities at sites on the northern GBR approximately 30–50 km offshore from Cairns to Cape Tribulation, between August 2018 and December 2021 (Fig. 1; see also Howlett et al. 2022, 2023). Coral planting and propagation activity was initiated by one tourism operator at Opal Reef in August 2018 (under permit G18/40023.1). After an initial validation phase, activity was scaled to include four additional "high standard" operators (with a certified commitment to ecological sustainability; GBRMPA 2023) with commercial moorings at Mackay, Hastings, Upolu, and Moore Reef from January 2019 to February 2020 (under permits G19/42553.1 and G20/43740.1) (Howlett et al. 2022). Owing to their value to reef tourism, such sites are considered to be of disproportionately high economic value

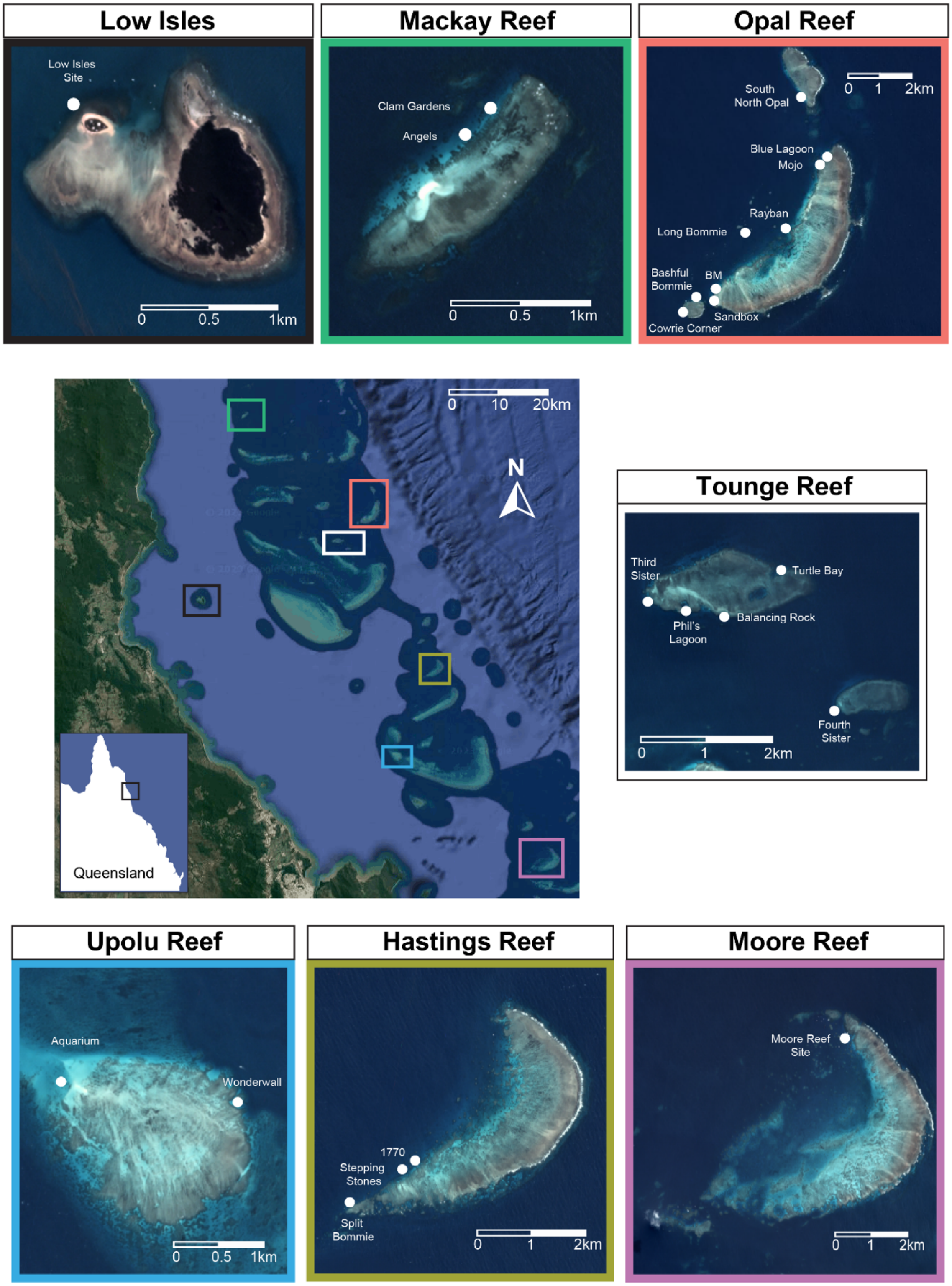

Figure 1. Map showing the locations of all 23 Coral Nurture Program (out)planting sites on seven reefs within the Cairns-Port Douglas region of the Northern Great Barrier Reef, Australia: Opal Reef (16°13′S, 145°53.5′E, red square)—"Blue Lagoon," "Mojo," "RayBan," "Beautiful Mooring (BM)," "Bashful Bommie," "Long Bommie," "Cowrie Corner," "Sandbox," "South–North Opal"; Tongue Reef (16°16′51.2″S, 145°49′11.7″E, white square)—"Turtle Bay," "Phil's Lagoon, "Third Sister," "Fourth Sister," "Balancing Rock"; Hastings Reef (16°31.3′S, 146°0.45′E, yellow square)—"1770," "Stepping Stones," Split Bommie"; Mackay Reef (16°2.8′S, 145°38.8′E, green square)—"Angels," "Clam Gardens"; Low Isles (16°23.2′S, 145°33.8′E, black square—"Low Isles Site"; Upolu Reef (16°40.6′S, 145°56.3′E, blue square)—"Wonderwall," "Aquarium"; Moore Reef (16°52.5′S, 146°14.0′E, purple square)—"Moore Reef Site Pontoon" (see also Howlett et al. 2022). Satellite image via GoogleEarth and allencoralatlas.org.

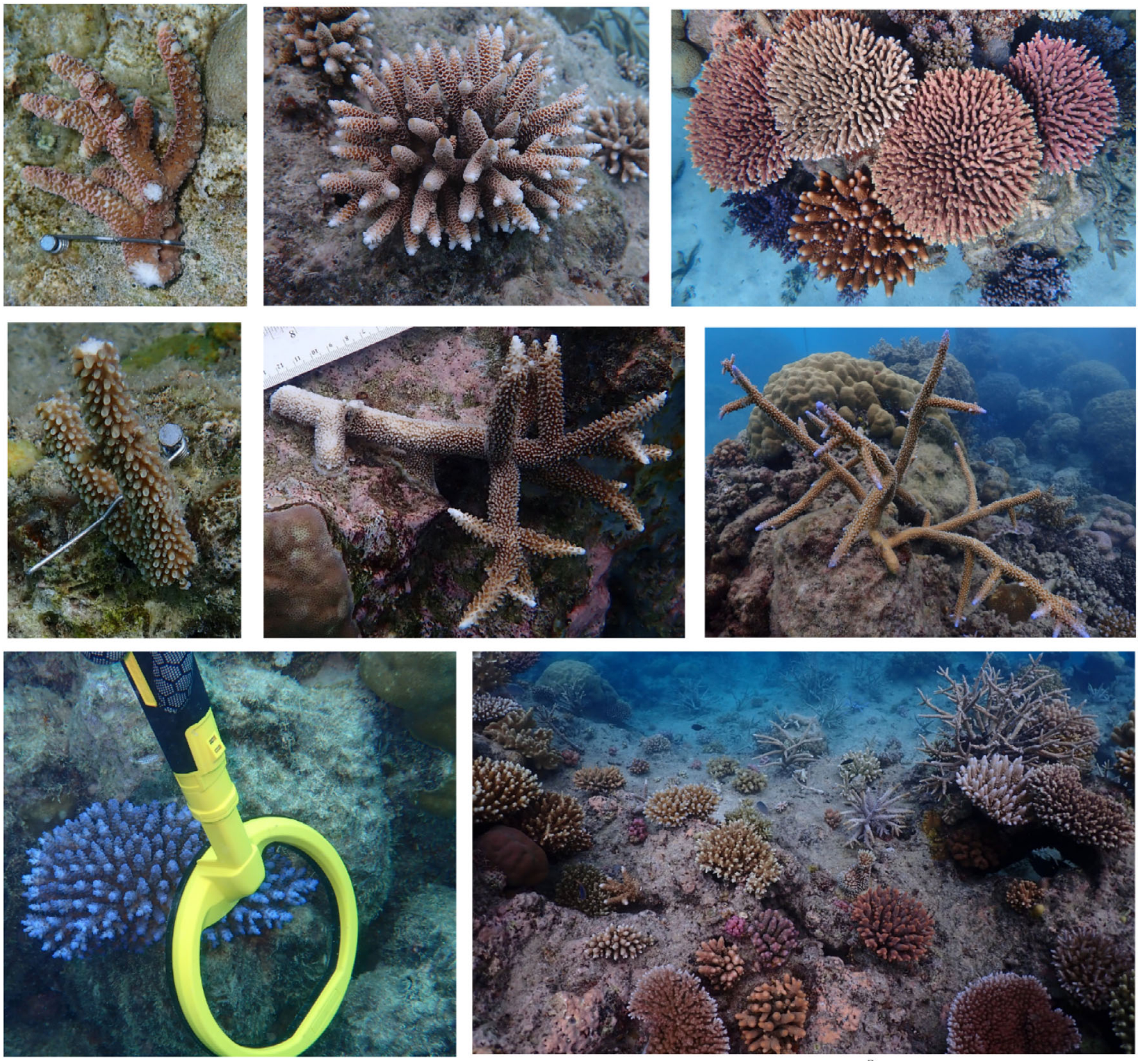

Figure 2. Example images of coral fragments of varying ages planted with Coralclip®, consisting of a stainless steel spring-loaded clip secured into consolidated substrate with a masonry nail. Top row of images show *Acropora millepora* as a new outplant (left), approximately 12 months post-planting where the Coralclip® is no longer visible (middle) and colonies planted in June 2019 that spawned from November 2021. Middle row of images show *Acropora intermedia* as a new outplant (left), 12 months post-planting and fused to the substrate (middle), and colony >12 months old (right). (Note: images are not of the same colony.) Coralclip® is often still visible for established outplants of arborescent branching species, and thus in roving survivorship surveys, these corals would be counted by a visual surveyor (see Supplement S1.2). The bottom row shows the metal detector (Video S1) used in roving survivorship surveys on an established *Acropora* sp. outplant (left) and a reefscape with a mix of planted colonies and wild colonies demonstrating the difficulty in distinguishing between the two (right) (Photos by J. Edmondson and R. Scott).

(Spalding et al. 2017; Howlett et al. 2022; Suggett et al. 2023). By the end of December 2021, operator staff had planted corals at 23 distinct "high-value" tourism sites spanning seven diverse reefs on the GBR (Fig. 1). Activity remains ongoing at the time of publication. All coral planting used the metal attachment device, Coralclip® (Fig. 2; Suggett et al. 2020), for predominantly branching *Acropora* and *Pocillopora* species sourced largely as naturally detached fragments (corals of opportunity [CoO]; Howlett et al. 2022), and supplemented by corals propagated on mid-water nursery platforms (Fig. S1; Howlett et al. 2021), or occasionally from wild donor colonies within permit requirements.

Intensity and frequency of coral planting, propagation, and site maintenance activities (herein referred to as "CNP activity") was dependent on operational factors (such as site access opportunities, trained personnel availability, tourism guest numbers, funding availability, operator preference) as well as local site conditions (e.g., availability of bare substrate or coral material for planting, nursery maintenance needs, etc.) (Howlett et al. 2022). To maximize cost-effectiveness, CNP activity was originally conceived for integration into routine activity where additional paid staff (e.g., a dive-buddy pair) joined existing tourism day trips. In practice, this "routine" approach was periodically complimented by more intensive activity with vessel use "dedicated" to coral planting (i.e., non-tourism trip). Both "routine" and "dedicated" days could also include other stewardship activities such as maintenance of nursery structures and outplant areas, reef health surveys, or corallivore control (e.g., Crown of Thorns starfish [*Acanthaster planci*] or *Drupella* sp.) at site.

Many of the costs associated with coral propagation and planting (e.g., diving equipment and vessel use) were largely absorbed by operators where resources were already in use for tourism operations. However, costs for CNP staff, nursery materials, planting equipment, and occasional "dedicated" vessel charters were compensated through funding sources; specifically; (1) the Australian Federal and Queensland Governments (2018–2019); (2) during the COVID-19 pandemic in 2021 via the Great Barrier Marine Park Authority's "Tourism Industry Activation and Reef Protection Initiative" (GBRMPA, 2022; see Howlett et al. 2022); and (3) from 2021 onwards by the Australian Government Reef Trust in partnership with the Great Barrier Reef Foundation, and private funding from Diageo Australia. No funding was available in 2020, and CNP activity was fully absorbed at the tourism operators' own cost. Regardless of funding source (e.g., externally funded or "in-kind" tourism staff time), all coral planting trips during the study period were considered for inclusion in our cost analysis. We did not include the capital costs of nursery frames in this current exercise (approximately US$60 per frame, holding as many as 150 corals—depending on size—at any one time; see Suggett et al. 2020) since: (1) CoO accounted for approximately 90% of coral outplants during this period (Howlett et al. 2022); (2) propagated colonies are regularly pruned to collect fragments rather than planting entire colonies; and (3) operators routinely plant a mix of nursery-propagated and CoO on any given trip. As such, it was not possible to apply an accurate propagation cost per outplant.

To meet permitting requirements, all CNP activity was recorded using a standardized CNP reporting form with which operators documented planting and propagation activity for each reef trip including the sites visited, the number of personnel conducting activity, and the quantity, taxonomy (identified to species if possible, otherwise genus and morphology), and origin of coral outplants (CoO, nursery-propagated material, or wild donor colonies). Operators also recorded details on nursery maintenance (noting installation of frames, addition of coral material, and occasional removal of biofouling organisms) and other site maintenance activities (e.g., corallivore removal, outplant and site monitoring). Given our aim was to quantify costs for coral planting, trips where reporting forms did not differentiate personnel time allocation to planting and non-planting activity were excluded from this analysis. As such, of the 63,632 corals planted across 271 trips during this period, only 67% (43,054 corals over 154 trips) were used for our costing dataset.

We next filtered our costing dataset to resolve coral outplanting costs under four different operational contexts: (1) routine planting days—planting-only activity during tourism day trips (30,031 outplants over 110 trips); (2) propagation and maintenance days—mixed activity days where nursery maintenance and propagation, site maintenance, and monitoring were reported in addition to planting (3,298 outplants over 30 trips); (3) training days—dedicated to training tourism personnel in planting with Coralclip®, coral identification, and propagation techniques (848 corals outplants over 6 trips); and finally, (4) dedicated planting days—non-tourism days where either vessel use was covered by external funding for the purpose of high-throughput planting, or were representative of trips dedicated to conducting stewardship activity at sites less desirable for tourism visitation (i.e., for rehabilitating degraded or storm-damaged sites [8,877 outplants over 8 trips]).

Quantifying the Costs of Coral Planting Under Different Operational Contexts

Planting costs (PC) were calculated per coral for each reef "trip" where planting was conducted (US$ coral^{-1} trip^{-1}); specifically, PC is expressed as the sum of labor, materials, and vessel costs relative to the number of corals planted (Eq. 1):

$$\text{PC} = \frac{\left(\left((\$S \cdot \text{FTE}) + \$D\right)^{*} n_{(D)}\right) + \left(\$c \cdot n_{(F)}\right) + \$V + \$P}{n_{(F)}} \quad (1)$$

where $S is the daily wage per staff member, FTE is a full-time equivalent weighting (quantifying staff time contribution to CNP activity), $D is diving costs per diver, and $n_{(D)}$ is the number of divers conducting planting (Table 1). Also, $c is the cost per Coralclip® attachment device, $n_{(F)}$ is number of coral outplants, $V is the vessel cost for accessing sites, and $P is the capital cost for planting equipment. Each factor in Equation 1 is treated as fixed (kept constant over time across all trips, e.g., $S, $c, $P) or variable (change on any given trip, e.g., $D, FTE, n_D, n_F, $V), and subject to several assumptions (Table 1): To determine staff time contribution to CNP activity within routine activity ("routine planting days" and "propagation and maintenance days") we applied an FTE weighting. FTE was calculated based on the number of sites reported for CNP activity in trip logs, expressed as a proportion of the total number of sites visited per day trip (Table 1).

Whereas, for "training days" and "dedicated planting days," staff time for the entire day was dedicated to CNP activity and hence FTE was assumed as 1.0. Vessel costs ($V) were assigned a value of $0 where CNP activity was integrated within routine tourism trips; however, for "dedicated planting days," we assigned an "at-cost" vessel charter value, applied universally across CNP operations where applicable (approximately US $2,700; Table 1). Finally, diving gear costs ($D) were typically absorbed by operators as cost-efficiencies (i.e., $0) since gear was already being utilized for diving operations or vessel/mooring maintenance; however, for this cost analysis we assigned a variable $D value based on the number of sites reported (Tables 1 & S1). For each trip, PC was calculated from fixed values in 2018 Australian dollars (AU$) and was subsequently converted to US dollars (US$) using the corresponding mean monthly exchange rate, which ranged US$1 = AU$1.29–1.61 over the study period (OECD.stat 2023; Table 1). Costs were not adjusted for inflation throughout as the Australian Consumer Price Index (CPI) change from the August 2018 baseline

Table 1. Description of the value and rationale for the variables involved in calculating coral planting cost (PC; US\$ coral^{-1} trip^{-1}) values for Coral Nurture Program (CNP) propagation, planting, and maintenance activity (Eq. 1). All values are per trip. Costs are presented in Australian dollars (2018 AU\$), with the cost range in US\$ equivalent shown in brackets (range depicts variable mean monthly exchange rate during the study period that was applied to final PC values). Variable factors are those that change with any given trip, whereas fixed factors and costs are kept constant across all trips over time.

Factor	*Value AU\$ (US\$ Range)*	*Description*	*Rationale*	*Factor Treatment*
Staff wages (\$*S*)	\$312.50 (US\$193.75–242.48)	Compensated labor costs per tourism staff member (8-hour workday), which includes return travel time to reef sites, and between 60 and 180 minutes of total dive time.	Fixed value over 2018–2021 determined through prior consultation with operators and funders. For "dedicated planting days" and "training days," costs were calculated with in-kind research student and staff labor accounted for (i.e., AU \$312.50/day).	Fixed
Diving gear costs (\$*D*)	\$5.26–13.26 (US \$3.29–10.29)	Per diver assuming one dive for conducting CNP activity per site with a dive equipment cost of AU\$1.26 per day and AU\$4.00 per SCUBA tank refill (one tank per site) (Table S1).	Dive equipment cost based upon the daily cost of a full set of diving gear (AU\$1,500) with a lifespan of 5 years and four annual services costing \$200.00. Operators have access to air compressors for filling tanks for diving operations, and hence tank costs are lower than commercial refills from dive shops (approximately AU\$15 per tank).	Variable
$n(\mathcal{D})$	No. of divers	Number of staff conducting CNP activity on any given day/trip.	This number occasionally includes in-kind research staff or student (i.e., volunteers) whose time was costed in staff wages (\$*S*).	Variable
Full-time equivalent (FTE)	0.33, 0.67, 1.0 (three sites); 0.5, 1.0 (two sites); 0.5 (one site)	FTE calculated as the number of sites reported for CNP activity expressed as a proportion of the maximum number of sites visited per trip for each respective operation, and assuming one dive was conducted per site: maximum three sites (FTE = 0.33 for one site, 0.67 for two sites, or 1.0 for three sites), maximum two sites (FTE = 0.5 for one site or 1.0 for two sites). For tourism operations which routinely visit only one site in a trip, we assumed CNP activity was conducted for one out of two possible dives (FTE = 0.5).	For "routine planting days" and "propagation and maintenance days," FTE weights staff time contribution to CNP activity based on the number of sites where activity is conducted. For "training days" and "dedicated planting days," staff time for the entire day is dedicated to CNP activity and hence FTE was assumed as 1.0.	Variable
Cost per Coralclip® (\$*c*)	\$0.28 (US\$0.17–0.22)	Unit cost per Coralclip® planting device (one used per each coral planted).	Inclusive of materials cost, and labor costs for assembly.	Fixed
$n(F)$	No. coral planted	Number of reported coral fragments planted per trip.	Operator practice is to count a set Coralclip® number (e.g., 100) before entering the water, and counting the remaining number upon finishing the dive.	Variable
Vessel costs (\$*V*)	\$0.00 or \$3,750 (US \$2,330.17 – 2,909.71)	Cost of a full-day (approximately 8 hour) return trip to outer reef sites (approximately 30–50 km offshore). Operator vessels are >24 m dual-hull catamarans requiring minimum three crew to operate.	Vessel operations costs were absorbed where CNP activity was conducted within routine tourism trips—i.e., \$0 for "routine planting days," "propagation and maintenance days" and "training days."	Variable

Table 1. Continued

Factor	Value AU$ (US$ Range)	Description	Rationale	Factor Treatment
		The true running costs for large tourism vessels on the GBR can be upward of AU$7,000 per day (including overheads); however, “dedicated planting days” were chartered at cost-price (consistent across all CNP operations).	An “at cost” vessel charter value of AU$3,750 was applied to “dedicated planting days,” covering operational expenses (fuel, skipper, and wages for necessary crew).	
Planting equipment capital cost ($\$P$)	$3.58 (US$2.22–2.78)	Planting equipment includes a hammer (AU $9.00), scrubbing brush (AU$5.00), wire mesh or plastic basket for holding fragments and Coralclip® units (AU$25.00), and a chisel or wire cutters for fragmenting corals (AU$20.00).	Value calculated based on biennial replacement (equipment lifespan of 2 years) of four sets of equipment (AU$118.00/year), assuming 33 trips for CNP activity are conducted per year (average number of trips across operators in 2021) (Table S1).	Fixed

remained below 5% until the final month of our study in December 2021 (ABS 2021).

To examine the relationship between planting output (PO) and cost (PC; Eq. 1), we further calculated PO as the number of corals planted per diver per site (corals diver^{-1} site^{-1}) for each trip (Eq. 2):

$$\mathrm{PO} = \frac{n_{(F)}/n_{(D)}}{n(\mathrm{sites})} \quad (2)$$

Quantifying Survivorship of Planted Corals

Attachment and survival of coral fragments planted with Coralclip® have been evaluated at various CNP sites on an *ad hoc* basis since 2019, using either (1) a rapid roving survey technique to capture Coralclip® effectiveness of diffusely planted corals across a large area and sample size (as per Suggett et al. 2020), or (2) marked fate-tracked plots to evaluate species and site-specific survivorship (Howlett et al. 2022; Strudwick et al. 2023). These prior fate-tracking assessments yielded coral outplant survivorship ranging 31.8–95.8% after 6–12 months (Table S2). A similar dual survivorship assessment was employed for our current study to enable more robust intercomparability across locations and to determine survivorship values to employ in “realized planting cost” calculations (described below). First, broadscale survivorship of coral outplants of varying ages (up to 3 years post-establishment) was quantified across five reefs via visual roving-surveys, which utilized a metal detector to locate “established” outplants (that had overgrown the Coralclip®) (Fig. 2; see also Video S1). Second, fate-tracked outplant plots were established at two sites (“1770”: Hastings Reef and “Angels”: Mackay Reef) and outplant survivorship was visually assessed 3–4 times over 9–12 months. These new fate-tracking assessments yielded mean outplant survivorship of 68–88% across reefs (roving surveys, $n = 5$ reefs), and 59% after 9 months or 70% after 12 months at Mackay Reef or Hastings Reef, respectively (fate-tracked plots). Full methods and findings of these experiments are presented in Supplement S1, and are not discussed further here.

Realized Cost of Coral Planting

PCs for each trip (Eq. 1) were finally adjusted to account for the mean survivorship of outplants across reefs, and so derive a “realized planting cost” (cost per surviving coral planted) ($\mathrm{PC_R}$ = \$ coral^{-1} trip^{-1}). Specifically, the number of coral fragments planted for each trip ($n(F)$ in the denominator of Eq. 1) was multiplied by the mean survivorship proportion (%) observed for the corresponding reef ($\mathrm{mS_{(Reef)}}$) through roving surveys (Eq. 3):

$$\mathrm{PC_R} = \frac{\left(\left((\$S \cdot \mathrm{FTE}) + \$D\right) \cdot n_{(D)}\right) + \left(\$c \cdot n_{(F)}\right) + \$V + \$P}{n_{(F)} \cdot \mathrm{mS_{(Reef)}}} \quad (3)$$

To further consider the time-dependent nature of coral outplant survival (e.g., Edwards et al. 2010; Morand et al. 2022), Equation 3 was also used to calculate $\mathrm{PC_R}$ using the mean

Table 2. Summary statistics for planting cost (PC; US$ per coral planted per trip), planting output (PO; number of corals planted per diver per trip), and realized planting cost (PC_R; cost per estimated surviving outplant per trip) values for trips as part of the Coral Nurture Program (CNP) between August 2018 and December 2021. PC_R accounts for the mean survivorship of coral outplants derived from roving surveys at respective reefs (Supplement S1.2). Trips are classified under four different operational contexts: routine planting day—planting-only within tourism trip; propagation and maintenance day—mixed activity within tourism trip; training day—training on tourism trips; dedicated planting day—nontourism trip where vessel use is dedicated to CNP activity (and is hence costed). Lower and upper range values represent the 5th and 95th percentiles.

		PC (US\$ coral^{-1} trip^{-1})			*PO (corals diver^{-1} site^{-1})*			*PC_R (US\$ coral^{-1} trip^{-1})*		
Operational Context (n Trips)	*No. of Outplants*	*Mean (±SE)*	*Lower Range*	*Upper Range*	*Mean (±SE)*	*Lower Range*	*Upper Range*	*Mean (±SE)*	*Lower Range*	*Upper Range*
Routine planting day (110)	30,031	2.34 (0.20)	0.78	6.03	67.04 (3.44)	17.95	132.40	2.99 (0.24)	0.96	7.64
Propagation and maintenance day (30)	3,298	5.93 (0.81)	1.95	13.77	32.64 (4.35)	8.73	72.50	7.42 (0.92)	2.59	15.61
Training day (6)	848	16.14 (5.39)	3.53	34.63	16.30 (3.20)	7.12	24.97	20.99 (6.26)	4.60	40.83
Dedicated planting day (8)	8,877	4.61 (0.57)	2.92	6.59	88.07 (14.85)	42.78	138.16	6.15 (0.79)	3.61	8.86

survivorship of corals planted in fate-tracked plots at site “Angels” (Mackay Reef) and “1770” (Hastings Reef) at respective survey timepoints between September 2021 and October 2022 (see Supplement S2 for the costing dataset used to calculate PO, PC, and PC_R for all trip contexts described above).

Data Analysis

Statistical analysis and data visualization were conducted using R statistical software (version 4.0.0; R Core Team 2021). All variables were visualized and tested for normality and equal variance prior to undertaking statistical analysis. *P*-values <0.05 were considered significant for analyses of all data considered

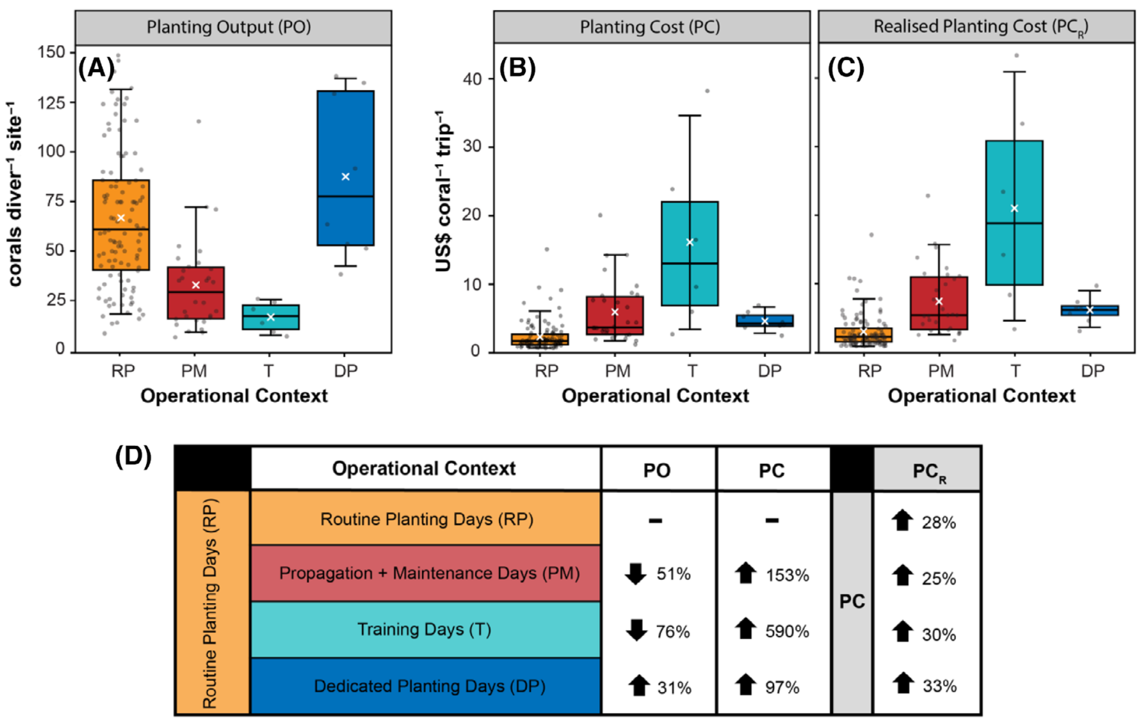

Figure 3. (A) Planting output (PO; number of corals planted per diver, per site); (B) planting cost (PC; US$ per coral planted per trip); and (C) realized planting cost (PC_R; US$ per surviving coral planted per trip) values (Table 2) for planting trips as part of the Coral Nurture Program (CNP) under four different operational contexts. (D) Summary matrix depicting % change in mean PC and PO for operational contexts compared to PC and PO values for “routine planting days” (–), and % change from mean PC to PC_R values for all operational contexts: (1) routine planting day ($n = 110$)—coral planting-only within tourism trip; (2) propagation and maintenance day ($n = 30$)—mixed activity within tourism trip; (3) training day ($n = 6$)—training on tourism trips; (4) dedicated planting day ($n = 8$)—non-tourism trip dedicated to CNP activity where vessel charter costs are included. Boxplots A–C show the median (center line) and interquartile range (colored box), with whiskers representing the 5th and 95th percentiles. White crosses overlain on boxplots show mean values. Gray dots represent data individual points.

here. PO, PC, and PC_R values were pooled across reefs, and summary statistics were computed for each under the four different CNP operational contexts. For "routine planting days," PO and PC values were further grouped by reef, $Log_{10} + 1$ transformed to stabilize group variances and analyzed for distributional differences using the nonparametric Kruskal–Wallis rank sum test and Dunn post hoc test, applying a Bonferroni *p*-value adjustment for multiple comparisons. Time-dependent PC_R values from fate-tracked plots were visually compared using bar graphs.

Results

Coral Planting Activity Costs

Mean (±standard error) PC across CNP tourism operations was lowest for "routine planting days" at US\$2.34 ± 0.20 $coral^{-1}$ $trip^{-1}$, ranging from \$0.78 to \$6.03 (5th–95th percentile) (Table 2). However, single PC values as low and high as \$0.69 and \$15.09 $coral^{-1}$ $trip^{-1}$ were recorded (Fig. 3B). Mean (±SE) PO was 67.04 ± 3.44 corals $diver^{-1}$ $site^{-1}$, but varied widely (Table 2; Fig. 3A). Of note, on "routine planting days," both PC and PO differed across reefs, with mean PC values lowest for Opal Reef (US\$1.58 ± 0.11 $coral^{-1}$ $trip^{-1}$) and highest for Moore Reef (US\$7.37 ± 1.19 $coral^{-1}$ $trip^{-1}$) and PO values lowest for Moore Reef (20.39 ± 2.92 corals $diver^{-1}$ $site^{-1}$) and highest for Mackay Reef (85.70 ± 8.48 corals $diver^{-1}$ $site^{-1}$) (Table S3; Fig. S2). Given the conflation of different tourism operations and environmental variables inherent to each reef, we were unable to resolve these site-based differences. However, in extracting data to determine PC (and PO) from CNP routine operations logs, we identified diverse logistical and environmental factors that appear to impact the workflow of CNP activities—and hence influence costs. These factors are summarized in Table 3 and include site access, underlying site condition and ecology, coral material source, nursery maintenance needs, and planting experience level. Such factors were variable or conserved (i.e., applicable to all) across CNP tourism operations and sites (Table 3), and presumably interact in any number of combinations to contribute to the dynamic range of PC (PO) reported here. We return to this point in the discussion.

As expected, on "propagation and maintenance days" where staff time was dedicated to activities other than coral planting, mean PO was approximately 50% lower than that of "routine planting days" (Fig. 3A & 3D), and hence mean PC was 50% higher at US\$5.93 ± 0.81 $coral^{-1}$ $trip^{-1}$ (Table 2, Fig. 3B). Similarly, mean PO for "training days" was 75% lower on "routine planting days" (Fig. 3D), and hence PC was approximately 6-fold greater at US\$16.14 ± 5.39 $coral^{-1}$ $trip^{-1}$ (Table 2, Fig. 3B & 3D). Mean PO on "dedicated planting days" was 31% higher than on "routine planting days," presumably from more intensive focus on coral planting; however, inclusion of vessel costs (which accounted for 60% of total "dedicated" trip costs, on average) resulted in a near doubling of mean PC to US\$ 4.61 ± 0.57 $coral^{-1}$ $trip^{-1}$ (Table 2, Fig. 3A & 3B).

Realized Cost of Coral Planting

Mean outplant survivorship was assessed via roving surveys at sites on Opal, Mackay, Hastings, Upolu, and Moore Reefs and ranged between 68 and 88% (see Supplement S1.2). Accounting for outplant survivorship resulted in realized planting costs (PC_R; US\$ $coral^{-1}$ $trip^{-1}$) that were higher by 25–33% compared to the original PC across all operational contexts (Table 2; Fig. 3D). For example, on "routine planting days," mean PC_R was higher by \$0.60 compared to PC to US\$2.99 ± 0.24 $coral^{-1}$ $trip^{-1}$ (Table 2). When trips were separated by

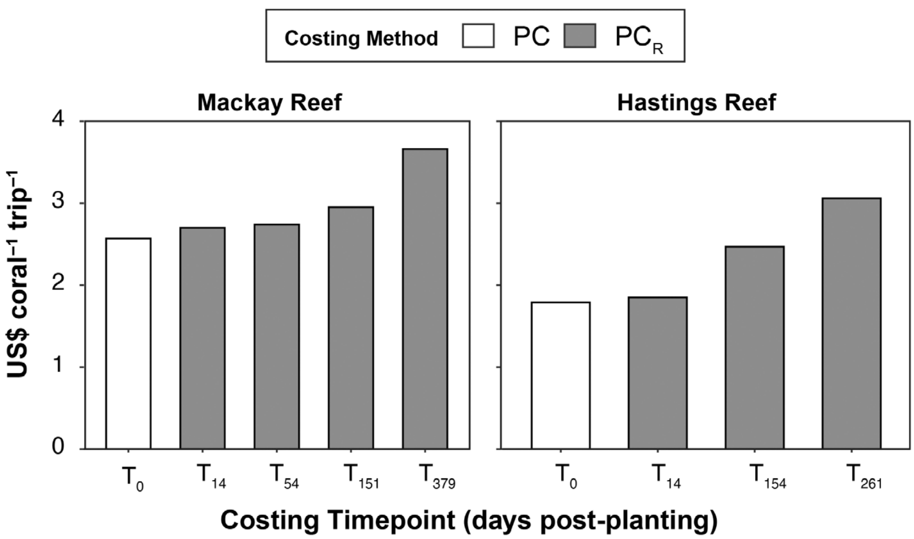

Figure 4. Cost (US\$) over time for coral fragments ($n = 300$) planted in controlled plots in September 2021 at Site "1770" at Hastings Reef and "Angels" at Mackay Reef (Fig. 1). White bars represent planting cost (PC) for each respective deployment (US\$ $coral^{-1}$ $trip^{-1}$; Eq. 1), where 100% of corals are alive at planting (T0). Gray bars show the realized planting cost (PC_R; US\$ $coral^{-1}$ $trip^{-1}$; Eq. 3) of surviving corals in these plots at respective survey timepoints across 9–12 months at each site (Supplement S1.1).

Table 3. Operational and environmental factors that regulate the workflow of Coral Nurture Program (CNP) coral propagation and planting activities and how these factors influence planting output (PO), planting cost (PC), and the realized planting cost (PC_R). Such factors are variable (different) or conserved (applicable to all) across the tourism operations and sites of the CNP and hence influence PC, PO, and PC_R to differing extents. Activities were often not time or cost-tracked but interactions between factors contribute to the restoration cost-effectiveness life cycle involved in boosting live coral cover. We therefore identify the core attributes required to resolve PC and PC_R variability for CNP operations more accurately. CoO = corals of opportunity.

Activity	*Factor Influencing PC, PO, and PC_R*	*Factor Variable or Conserved Across CNP Operators and/or Sites?*	*Considerations for PC (and/or PO, PC_R)*	*Cost Attributes*
Site access	• Distance to reef site from port	Variable	• Island-based or fringing reef operations potentially require smaller vessels and enable greater time at site while removing (reducing) fuels costs.	• Fuel cost
	• Underlying site condition	Variable	• Near-shore sites may experience reduced water flow and/or greater nutrient and sediment loads, which can increase potential for fouling (results in greater nursery cleaning [greater labor cost]; poorer outplant survivorship).	• Time spent at site/ dive time
			• Reef sites with lower live coral cover are targeted for assisted site recovery but are less desirable for tourism visitation, and so may necessitate more costly "dedicated planting days"—however, efforts at degraded sites may deliver greater ecological benefit.	• Vessel charter cost • Site- and time-specific coral survivorship • Ecosystem-scale metrics e.g., coral cover, population structure, restored area
Accessing coral outplant material	• Source of coral material for planting	Variable	• Sites where CoO are readily available—often in areas with high existing cover of naturally fragmenting species may require less time for material collection.	• Proportion of dive time spent propagating, harvesting, preparing, and transporting (in situ) material vs. planting
	• Distance between source and outplant site	Conserved	• CoO in more degraded areas may require more time pruning to ensure outplant quality. • Pruning fragments from nursery-propagated colonies can reduce coral material collection time. • Material pruned from colonies propagated in nurseries requires transport to outplant site (and ensure nurseries are well maintained). Transport needs—swimming or boat—increase over time as planting footprint increases.	• Vessel and fuel cost if ex situ transportation required • Dive labor and equipment costs
Nursery propagation and maintenance	• Nursery cleaning (coral health)	Variable	• Absence of beneficial fish communities that facilitate removal of biofouling algae and invertebrates on nursery structures will require greater time nursery cleaning.	• Proportion of dive time spent (1) sourcing stock material for nurseries, and (2) cleaning and maintaining (including stock inventories and tracking) nurseries vs. planting
	• Time spent sourcing donor material for stocking nurseries	Variable	• Presence of corallivores may transmit disease and necessitate additional protective structures or continual stocking. • Maximizing genetic, taxonomic, and functional diversity (cultivation of rare/ecologically	• Dive labor and equipment costs

Table 3. Continued

Activity	Factor Influencing PC, PO, and PC_R	Factor Variable or Conserved Across CNP Operators and/or Sites?	Considerations for PC (and/or PO, PC_R)	Cost Attributes
			important species) requires time identifying and tracking.	
Planting	• Availability of consolidated, bare substrate for planting	Variable	• Decreases over time, and hence more time is required to find suitable substrate as planting footprint expands.	• Dive labor and equipment costs
	• Planting experience level (secure attachment and speed).	Variable	• PO likely to increase over time with experience. • Volunteers reduce costs but require more training time and may result in slower (and less effective) planting if sporadic, requiring more maintenance. • Planting experience level impacted by tourism staff turnover.	• Proportion of dive time (labor) spent auditing outplants (monitoring) vs. planting
Monitoring, site maintenance	• Control of corallivores e.g., Crown-of-Thorns starfish (COTs), *Drupella* spp. etc.	Conserved	• Necessitates time away from planting; however, critical for improving outplant survival and overall site health.	• Proportion of dive time (labor) spent on "other" gardening and site maintenance activities vs. planting
	• Other coral "gardening" (overturning coral, wedging fragments, maintaining or replacing outplants, etc.)	Variable	• Corals "re-planted" via wedging, overturning, or maintaining existing outplants (e.g., removing failed or refilling empty Coralclip®) are often part of the workflow but are not reported.	• Time (labor) and materials spent on post-planting record keeping, research, and data analysis
	• Monitoring outplant areas, research trials, data capture.	Variable	• Record-keeping, reporting, and monitoring can divert time away from planting however are critical to knowledge generation that leads to adaptive practice, and potential cost savings (e.g., PC_R).	

reef, mean PC_R ranged from US\$1.95 ± 1.06 to US\$8.35 ± 4.06 coral^{-1} trip^{-1}, increasing PC values by 13–48%, on average, across reefs (Fig. S3) via differences in reef-specific mean outplant survivorship (Supplement S1.2). Mean PC_R on "routine planting days" remained the lowest of all operational contexts (Table 2; Fig. 3C).

Fate-tracked outplant plots were established at sites "1770" at Hastings Reef and "Angels" at Mackay Reef to determine outplant survivorship over time, and hence evaluate time-dependent PC_R (see Supplement S1.1). Here PCs were US\$2.57 and \$1.79 coral^{-1} trip^{-1} at Hastings and Mackey Reef, respectively. Planting at Hastings Reef occurred over 2 days, necessitating greater staff time, and hence resulting in a higher PC. Accounting for declining outplant survivorship at Hastings Reef (to 70.2% ± 2.7 by 379 days post-planting; Supplement S1.1) resulted in PC_R increasing by 42% from the initial PC at T0 to US\$3.66 coral^{-1} trip^{-1} after 12 months (Fig. 4). Declines in outplant survivorship were similarly documented at plots at Mackay Reef (to 58.5% ± 8.2 after 261 days; Supplement S1.1). Hence, PC_R increased by 71% from the initial PC (at T0) to US\$3.06 coral^{-1} trip^{-1} after 9 months (Fig. 4). As such, accounting for the time-dependent nature of survivorship is clearly critical to more accurately resolving PC_R.

Discussion

Asexual-based coral propagation and planting approaches have increasingly grown in technical and biological feasibility for reef restoration (Rinkevich 2019; Boström-Einarsson et al. 2020). However, the costs of interventions and the factors underpinning these costs have been sparsely documented alongside outcomes, thereby limiting evaluation of their viability as cost-effective reef management aids for ongoing and future implementation (Bayraktarov et al. 2019). Here we discuss factors influencing costs of coral planting activity under the CNP tourism-led targeted site restoration approach on Australia's GBR, and identify several core steps needed to better establish a life-cycle costing framework for informing investment, management, and practitioner decisions in sustaining or initiating reef restoration activity.

Planting Cost Considerations Under a Tourism-Stewardship Model

CNP was originally conceived as a site stewardship and restoration model integrated into existing tourism day trips (Howlett et al. 2022). As expected, PCs were therefore lowest on "routine planting days" where CNP activity was focused on planting corals, resulting in a higher PO. Here, PC was less than US $3.00 coral^{-1} trip^{-1} for 79% of trips (representing 28,466 corals). This suggests that previous PC estimates for tourism-integrated planting activity at Opal Reef (US$0.60–3.00 coral^{-1}; Suggett et al. 2020) were generally representative of the "routine" PCs that we observed here for more diverse CNP reef systems and tourism operations. We note that costs reported for Opal Reef by Suggett et al. (2020) ($n = 4{,}580$; August 2018–May 2019) represent <20% of the outplants we considered here for Opal Reef ($n = 22{,}445$, August 2018–December 2021). Suggett et al. (2020) was specifically measuring Coralclip® planting speed, and hence precisely calculated staff time as US$/coral deployed per minute. Furthermore, they did not explicitly account for diving or planting equipment costs as we have here (though these accounted for <6% of trip costs across operational contexts), and together these factors presumably contributed to their lower reported cost range. In our current study, across the different operational contexts, CNP staff wages accounted for approximately 85% on average of overall trip costs, with the exception of "dedicated planting days" where vessel charter costs outweighed the expense of staff wages (which in this instance, were <33% of trip costs on average). As such, PC values across CNP trips were predominantly moderated by staff labor costs and PO. This reaffirms the need for effective operational models (e.g., absorption of expensive vessel running costs) and cost-effective, user-friendly attachment methods for scaling coral propagation and planting efforts (Suggett et al. 2020; Vardi et al. 2021).

The wide variation in PO across CNP trips, reefs and/or tourism operations is likely the result of a conflation of operational and environmental variables that can both impact different stages in the coral restoration workflow. Environmental variables include underlying coral cover and composition (ranging 3–52% across CNP sites; Howlett et al. 2022; Roper et al. 2022) and the presence of herbivorous fish communities that remove biofouling algae from nursery frames (see also Frias-Torres et al. 2015). Operational and logistical factors include distance to reef from port, tourism operation size, the number of nurseries installed at sites, staff turnover rate, other site stewardship requirements (e.g., reef surveys, COTs removal), and the tailored adoption of restoration activity to operations (e.g., less frequent and intensive planting vs. regular, less intensive approaches as described in Howlett et al. 2022, 2023). Such factors are largely variable across CNP operations, and together influence "in-water time" as well as staff time allocation to planting where it may otherwise be dedicated to nursery cleaning requirements, suitable site selection, and time collecting coral material.

Reports of coral restoration costs via propagation and planting to date are few but range from US$10,000 to $1.5 million/ha (Bayraktarov et al. 2019, 2020). Other programs have specifically reported costs that vary by an order of magnitude lower than (e.g., US$0.15–0.36/coral, the Philippines; dela Cruz et al. 2014), higher than (e.g., US$33.40/coral, Seychelles; Montoya-Maya et al. 2016, in Bayraktarov et al. 2019) or similar to (US$5.30/coral planted, the Philippines; Villanueva et al. 2012) the mean PC determined here for CNP "routine planting days" (US$2.34 coral^{-1} trip^{-1}). However, direct cost comparison between studies remains challenging and in some cases not appropriate where costs are governed by location-specific restoration contexts, and logistical and socioeconomic factors. For example, labor costs and vessel charter costs on the GBR, Australia (high-income country, approximately 30–50 km to outer reef sites), are several orders of magnitude greater than those reported for fringing-reef coral restoration projects in lower middle-income countries in the Western Pacific region (e.g., labor costs of US$13–28/day in the Philippines; dela Cruz et al. 2014; Baria-Rodriguez et al. 2019; Harrison et al. 2021; compared to >US$200/day in our current study). The PC values reported here are therefore reflective of Australian socioeconomic and ecological conditions (specifically the tourism operational context of the northern GBR), and thus will inevitably differ when applied to restoration projects in other reef regions.

Importantly, cost differences also reflect use of alternate restoration methods (which again may be location or project specific), the degree of volunteer involvement, scales, time frames, and cost-accounting methodology across projects (Bayraktarov et al. 2019). For example, Villanueva et al. (2012) employed sexual propagation and planting, and hence accounted for the costs of parent coral collection, hatchery work, 6 months of *ex situ* nursery rearing and monitoring in addition to coral planting. As such, despite lower labor costs in the Philippines, reported per-coral costs were higher than "routine" PC values reported here. Similarly, costs reported for a 3.5-year restoration project in the Seychelles were inclusive of nursery propagation, monitoring, as well as program overheads and research (Montoya-Maya et al. 2016, in Bayraktarov et al. 2019). Therefore, although costs for coral planting often represent a significant expense (approximately 30–50% of project costs; Edwards et al. 2010; Toh et al. 2017; Humanes et al. 2021), they are rarely the only costs involved in reef restoration. As such, higher cost estimates may also result from differences in cost-accounting across the "whole life" or life cycle of interventions spanning project initiation through longer-term monitoring (Spurgeon & Lindahl 2000; Bayraktarov et al. 2019; Hein & Staub 2021). Hence, we also considered PC estimates to account for other modes of operation essential to site stewardship under CNP activity.

"Propagation and maintenance days" and "training days" were less frequent than "routine planting days," and unsurprisingly mean PC was 2 to 6 times higher (US$5.93 and US$16.14 coral^{-1} trip^{-1} compared to $2.34 coral^{-1} trip^{-1}). While cost factors across these operational contexts remained the same (e.g., wages and equipment costs), higher costs were predominantly the result of fewer corals planted relative to staff wages (lower PO). Such an outcome is consistent with other coral propagation projects employing intermediate nursery propagation phases, owing to added capital costs for nursery materials and labor requirements for cleaning and maintenance (e.g., Shafir & Rinkevich 2010; Montano et al. 2022). However, while nursery propagation and maintenance move focus from coral planting, coral nurseries provide readily available (Bostrom-Einarsson et al. 2020; Howlett et al. 2022, 2023) and selected-for coral stock (Baums et al. 2019; Shaver et al. 2022), thereby reducing time required for coral material collection on planting days. Nurseries importantly serve as visually appealing demonstration sites for educating visitors on reef stewardship activity (Howlett et al. 2022) and hence are necessary for overall project life-cycle investment for the CNP operational approach.

"Training days" were conducted most infrequently and were the costliest operational context owing to the additional cost of a CNP researcher conducting training, and high staff costs (FTE weighting of 1) relative to low PO. However, despite the greater expense inherent to "training days," capacity-building reef industry-stakeholders is foundational to the CNP "learn by doing" approach (sensu Quigley et al. 2022; also, Howlett et al. 2022), which in turn is the critical step to improving planting efficiency (Suggett et al. 2020), and hence PO that regulates PC. In other reef restoration programs, costs of capacity-building reef stakeholders through training are unclear, yet undoubtedly deliver immense benefit for reef-dependent communities via enhanced employment opportunities, income diversification, and community education (e.g., projects in the Caribbean and Eastern Tropical Pacific, Israel, and the Seychelles; Bayraktarov et al. 2020; Vaughan 2021). Indeed, for several tourism operators in the CNP, such capacity provided industry resilience during tourism downturns in 2020–2021 where tourism operators received funding for site stewardship activities, including restoration, thereby assisting staff retention (Howlett et al. 2022; Suggett et al. 2023). Furthermore, the near doubling of mean PC on "dedicated days" via the additional cost of vessel charters demonstrates how cost-effective planting on the GBR—as with other restoration programs globally (e.g., dela Cruz et al. 2014; Toh et al. 2017; Bayraktarov et al. 2020)—hinges upon stakeholder involvement. Capacity-building and stewardship are key success indicators of coral restoration (Hein et al. 2017), and integral to the longer-term sustainability of local restoration efforts (Hein et al. 2020; Quigley et al. 2022), and hence costs of training would appear logical to consider in life-cycle costings.

Resolving discrete time- and cost-tracking of the individual stages involved in the full life-cycle of reef site restoration (e.g., as per Edwards et al. 2010; see also Humanes et al. 2021) was not possible here, but clearly remain an important means to guide improved operational cost-effectiveness in future. It is important to reiterate that the data captured through CNP reporting logs—and used to examine costs here—were largely opportunistic of the requirement to report coral planting and nursery propagation activities for permitting. Such opportunistic cost-tracking often precluded differentiation of staff time to nonplanting activity for several trips, necessitating exclusion from this cost-analysis. Stakeholder-led restoration projects are often not initially set up to capture critical cost attributes, or incentivized to report them in scientific literature (Bayraktarov et al. 2015, 2020), as depth of data recording and reporting presents a time–cost trade-off to planting effort and funding is often governed—or indeed program success measured—by simple activity metrics such as the number of corals planted (Hein et al. 2021; Suggett et al. 2023). In the case of CNP operations, time–cost trade-offs between data reporting and activity are governed by tourism schedules (Howlett et al. 2022). Thus, resolving greater accuracy of PC estimates, and indeed the full life-cycle costs of the processes underpinning successful restoration, requires more rigorous documentation of staff time—the greatest cost under the CNP approach—across planting and non-planting activities. Regardless, in resolving the higher PCs for "propagation and maintenance days" and "training days," our data can guide the increased financing required when initiating projects when such essential activities may predominate over actual coral planting.

"Realized" Costs of Planted Corals

While coral propagule survivorship is broadly acknowledged as an insufficient metric to describe overall project feasibility and socioecological effectiveness (Bayraktarov et al. 2015; Hein et al. 2017; Boström-Einarsson et al. 2020), it provides a useful means to benchmark and compare restoration costs in terms of new biomass retained on the reef (Edwards et al. 2010). PC_R were achieved by adjusting PC by outplant survivorship quantified through (1) roving surveys of outplants of varying ages across the five CNP reefs and (2) newly established fate-tracked plot at two sites monitored over 9–12 months. When average outplant survivorship across reefs was accounted for in cost calculations, mean PC_R increased by 25–33% compared to PC across all operational contexts. Such an outcome is consistent with other studies, with realized costs increasing by several orders of magnitude (e.g., 13-fold; Baria-Rodriguez et al. 2019), where variable survivorship of coral propagules is accounted for. Fate-tracking outplants in experimental plots resulted in time-dependent survivorship, and a resultant increase in PC_R of 42–71% after 9–12 months post-planting. As such, realized costs are inevitably time-bound to when "effectiveness" is evaluated (Edwards et al. 2010; Baria-Rodriguez et al. 2019). For example, in a larval enhancement project, Harrison et al. (2021) documented an approximately 40% increase in realized costs over time owing to mortality, from US$13.73/coral at 10 months to US$17.79/coral at 34 months. Such costings are further confounded in circumstances where propagules reach reproductive maturity and result in self-generation of further biomass to the reef (e.g., Harrison et al. 2021) or indeed mass mortality events that may occur after PCs are reported (e.g., Fadli et al. 2012). Longer-term fate-tracking is therefore clearly warranted but inevitably entails higher monitoring costs, thus highlighting the need to resolve cost–benefit trade-offs that enable practitioners to optimize restoration approaches. For example, Humanes et al. (2021) and Baria-Rodriguez et al. (2019) determined that extending coral nursery rearing periods for sexual recruits resulted in enhanced survivorship over the long term, thereby negating any additional costs associated with longer husbandry periods. In the context of the CNP, although typically more expensive, "training days" and "dedicated days" are not only critical to evaluating efforts, trialing new techniques, training staff, and improving practice, but also concentrating efforts at more degraded sites where coral population recovery is most needed (Roper et al. 2022; Howlett et al. 2023).

Ultimately, the realized costs of restoration efforts are dynamic over space and time, and are highly dependent upon stochastic disturbances on reefs (Boström-Einarsson et al. 2020), and importantly how "effectiveness" is defined and measured, and for how long. For example, employing ecological changes (e.g., live coral volume—Morand et al. 2022; or population structure—Roper et al. 2022), ecosystem service values (Abrina & Bennett 2021) or socioeconomic benefits (Hein et al. 2017) in cost evaluations rather than outplant survivorship, would likely deliver vastly different, and arguably more informative (Suggett et al. 2023) assessments of cost-effectiveness. Furthermore, as climate-driven disturbances increasingly drive coral mortality, measures of ecological and social resilience will become essential to justify return-on-investment in iterative cost–benefit analyses (Shaver et al. 2022).

As global necessity and investment for coral restoration grows, it is increasingly time-sensitive to resolve a framework for transparent cost accounting and evaluation that can feasibly be adopted across stakeholder-led restoration programs. Implementing such a framework will require sufficient and realistic program budgeting and funding horizons to implement, measure and report on activity (e.g., >3 years; Hein & Staub 2021; Suggett et al. 2023). Our approach identifies how opportunistic activity reporting can be exploited to examine costs, and in turn identify factors (e.g., staff time quantification, longer monitoring periods) needed to more robustly leverage this valuable data source to further improve resource allocation within restoration practice. We have presented the first reports for costs associated with tourism-led restoration of "high-value" GBR sites, and the inherently variable nature of cost-effectiveness across highly diverse operations and environments.

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Supporting Information

The following information may be found in the online version of this article:

Figure S1. Low-cost coral nurseries used across Coral Nurture Program sites.
Table S1. Calculations employed to calculate \$*P* and \$*D* values in planting cost and realized cost.
Table S2. Summary of coral outplant survivorship data collected across Coral Nurture Program sites.
Supplement S1. Quantifying survivorship of planted corals.
Supplement S2. Supplementary dataset used to calculate PC, PO, and PC_R for Coral Nurture Program coral planting trips.
Figure S2. Distribution of planting cost (PC) and planting output (PO) values from 110 Coral Nurture Program "Routine Planting Days" across 5 reefs.
Table S3. Reef-based differences in PC and PO of coral planting activity on Coral Nurture Program "Routine Planting Days."
Figure S3. Comparison of planting cost (PC) and realized cost (PC_R) values of 30,031 corals.
Video S1. Video file demonstrating successful detection of coral colonies planted with Coralclip® using the metal detector.

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