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Review

# Ecological quantitative criteria for reef site prioritisation to maximise survivorship and growth of outplanted corals

Adriana Humanes [a,b,*], Katharina E. Fabricius [a], Renata Ferrari [a], Juan Carlos Ortiz [a]

[a] Australian Institute of Marine Sciences, Townsville, 4810, QLD, Australia
[b] School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom

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ABSTRACT

Ocean warming has been identified as an existential threat to coral reefs and their socio-ecological services. Even for the most optimistic climate change scenarios, future climate models consistently predict an increase in the frequency and intensity of marine heatwaves that cause mass coral mortality, indicating an urgent need for management interventions to mitigate their impact on coral reefs. Outplantation of corals to degraded reefs is at the forefront of efforts to restore coral cover and enhance heat tolerance, with large-scale deployments (hectares) planned over the next few years. To do so, the selection of suitable sites at targeted intervention reefs is one of the most critical and neglected considerations for implementation. Ensuring that corals survive and grow where they are deployed is necessary for achieving early and long-term intervention goals. Here we developed a framework using a dynamic set of criteria to evaluate and rank the ecological suitability of sites once a target reef has been selected for restoration. Criteria are centred around heuristics informed by ecological knowledge of the critical conditions that favour survivorship and growth of outplants. Restoration practitioners will benefit from having a quantitative method like the one proposed here to compare and rank potential sites and make informed decisions on where to conduct interventions. This framework is a comprehensive and adaptable approach to identify the ecologically most suitable sites for population persistence and recovery, merging ecological knowledge and expert input.

## 1. Introduction

Coral reefs are the most biodiverse ecosystems in the oceans. Corals, like mangroves, kelps, and seagrasses, are ecosystem engineers. These engineers are increasingly threatened by human activities and climate change (e.g., Tebbett et al., 2023). Marine heatwaves alone caused the loss of 14 % of global coral cover in the past decade (Souter et al., 2021), and even under optimistic climate scenarios, further declines are projected (e.g., Condie et al., 2021). Recent losses foreshadow more severe declines, as heatwaves become more frequent and intense (McWhorter et al., 2021), threatening reef resilience and biodiversity. Even with full implementation of mitigation measures, ocean temperatures will not stabilise immediately (Palazzo Corner et al., 2023) and extensive coral mortality may still occur. This daunting future highlights the urgent need for innovative management strategies to maintain coral reefs ecological state and accelerate coral adaptation rates (e.g., Bay et al., 2023).

Considerable research is presently focused on accelerating coral adaptation to future warming. Unprecedented funding is supporting novel approaches such as assisted evolution, larval seeding, and reef cooling and shading. For example, the Australian Government initiated the 'Reef Restoration and Adaptation Program' (RRAP) in response to the mass bleaching events in the Great Barrier Reef from 2016 to 2017 (Great Barrier Reef Marine Park Authority, Australian Institute of Marine Science, & CSIRO, 2023). RRAP aims to develop innovative solutions to restore and protect coral reefs. 'Mission: Iconic Reefs', led by the US National Oceanographic and Atmospheric Administration and partners, focuses on restoring 28 ha of the Florida Reef Tract by returning coral cover to self-sustaining levels. The G20 nations allocated US$100 million over the next 10 years (starting in 2023) to the 'Coral Research and Development Accelerator Platform', an international organization supporting research and development of solutions to conserve corals globally. These efforts share the common goal of scaling coral outplanting (e.g., larvae seeding, deployment of artificial substrates with

* Corresponding author. School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom.
*E-mail addresses:* adrihumanes@gmail.com (A. Humanes), k.fabricius@aims.gov.au (K.E. Fabricius), R.FerrariLegorreta@aims.gov.au (R. Ferrari), j.ortiz@aims.gov.au (J.C. Ortiz).

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coral juveniles, or coral fragment attachment) and enhancing coral heat tolerance to preserve reef services and functions into the future.

Despite global reef losses, ranging from 200,400 to 1,100,700 ha during bleaching events between 2000 and 2018 (Souter et al., 2021), the largest restoration initiatives have not exceeded 8 ha at a time (Edwards et al., 2024). Proposed outplanting projects, varying from tens to hundreds of hectares, are therefore unprecedented. Achieving these scales will require new decision-making tools and automated site selection. Coral outplanting projects have expanded substantially in recent years (e.g., Ferse et al., 2021), publishing implementation guidelines and manuals (Edwards, 2010; Hein et al., 2020; Shaver et al., 2020). Frameworks for identifying, prioritizing, and selecting reefs have been developed based on semi- or fully quantitative ecological data, projected stress exposure, disturbance history, reef use, and management designations (e.g., Edwards, 2010; Shaver et al., 2020). Predictive habitat suitability maps, remote sensing data, stakeholder knowledge, and site visits are also recommended for identifying restoration sites across large spatial scales of 100 s km$^2$ (Foo and Asner, 2019; Schill et al., 2021). However, once target reefs are chosen, quantitative decision-support tools to evaluate and optimise site selection at finer spatial scales (100 s km$^2$ to a hectare) remain lacking.

Here we propose a systematic approach for selecting suitable coral outplanting sites after intervention reefs have been identified. A set of ecological heuristics based on conditions known to influence growth and survival of sexually propagated corals is used to identify the most appropriate sites and maximise local outplanting benefits. Ecological considerations will need to be complemented by logistic, cultural, social, spiritual and economic criteria, but these are beyond the scope of this study. The ecological criteria presented here determine the compatibility between the source and the deployment sites, and assess biophysical and ecological factors on deployment sites, relative to literature-derived thresholds, to promote outplant establishment and growth to reproductive maturity. By evaluating these criteria at each site, an index summarising their characteristics is estimated, enabling site ranking, comparison, and selection. This framework combines ecological knowledge, and expert input to provide a quantitative method for identifying suitable sites for coral outplanting. We outline how this framework can adapt to specific intervention and stakeholder needs, and demonstrate its use across different intervention types, showcasing adjustments managers can make to evaluate sites within unique ecosystems and project needs. The novelty of this approach lies in translating complex ecological information into a structured, quantitative framework that can easily be applied by users with diverse backgrounds. If this tool helps improve site selection decisions, even modestly, it has the potential to shift restoration outcomes from failure to success, saving time and resources, but most importantly reefs.

## 2. Methods

An initial list of 38 biophysical and ecological criteria were identified from the literature as influencing coral juvenile establishment, survivorship and growth (hereafter referred to as performance), and considered for site selection (Supplement S1). This list was refined to 18 criteria through a systematic process involving: a) expert consultation, b) assessment of empirical evidence, c) evaluation of whether ecologically meaningful scores and thresholds could be established, d) consideration of information required to apply each criterion and logistical challenges, e) assessment of global generality, and f) analyses of mechanistic redundancy, prioritizing more informative criteria.

Using the 18 criteria, we developed a framework to evaluate and rank site suitability for coral outplanting. Because site suitability depends on intervention goals, the framework starts by identifying one out of three goals for a specific deployment situation: (i) rehabilitation of ecosystem functions and services by outplanting corals (see Gann et al., 2019 for a definition of rehabilitation), (ii) increasing adaptation rates of coral populations by outplanting thermally more tolerant corals (see Bay et al., 2023 on methods to increase thermal tolerance), and (iii) rehabilitation of ecosystem functions and services together with enhancement of population adaptation rates by outplanting thermally more tolerant corals. Similarly, three deployment methods for outplanting sexually propagated corals (weeks to a few months old) were considered: (i) outplanting artificial substrates with settled larvae from target coral species (e.g., Chamberland et al., 2017), (ii) outplanting artificial substrates with settled larvae from unidentified coral species obtained from larval slicks (e.g., Suzuki et al., 2020), and (iii) directly seeding larvae from unidentified coral species onto the reef substrate (e.g., Doropoulos et al., 2019). The framework is based on the performance of sexually propagated corals, but the criteria are also relevant to asexually propagated fragments, although their optimal thresholds may differ. These thresholds can be customised if specific information is available (Supplement S2).

### 2.1. Site evaluation

We developed an open-access, dynamic data tool (see Supplement Excel file) where ecological and biological criteria are listed in rows and the sites to be evaluated are listed in columns. Criteria can be qualitative (*i.e.*, categorical) or quantitative (*i.e.*, numerical). If data for certain criteria cannot be collected, they can be omitted from the evaluation (Table 1). Criterion assessment can use ecological surveys, historical knowledge, habitat maps, remote sensing data, simulated environmental data, and logistical considerations, and are referred here as ‘desktop informed’. Criteria requiring on-site evaluation (within one to two months before deployment) are ‘field informed’. Each criterion is classified as ‘essential’, ‘desirable’ or ‘not applicable’. Essential criteria are factors that are necessary to deem a site suitable, desirable criteria encompass factors that could improve coral outplant performance. Some criteria (*i.e.,* presence of the target species) may be ‘not applicable’ for certain interventions (*i.e.*, larval seeding) and can be excluded from evaluation. As each criterion can differently affect coral performance, the tool enables assigning weights based on relevance to intervention goals. Omitting high-weight criteria only affects site comparisons if the criterion is missing for some sites. In such cases, we recommend either obtaining the missing data given its relevance or omitting the criterion across all sites for consistency.

### 2.2. Site ranking, comparison, and selection

Post-criteria assessment, each criterion response is converted into a score $s_n$ (*i.e.*, 0 to 4), that is used to estimate an average index per site ($I_n$)

$$I_n = \frac{\sum_{i=1}^{N} s_n \times w_N}{N}$$

where $N$ is the number of criteria assessed, $s$ represents the score of the criterion on site $n$, and $w_N$ represents the weight of criterion $N$. Meeting essential criteria elevates a site’s ranking, while failure to meet them categorises the site as unsuitable, leading to a ‘Do not deploy’ decision. Not meeting desirable criteria only lowers the site’s ranking. Criterion types are assigned based on the type of intervention and the outplanting method used (see above). Customisation of criteria (*i.e.*, type of criteria, scores, and threshold values) is possible by selecting the ‘Custom’ option for both intervention and deployment types. Sites with the highest index values are deemed the most suitable for deployment and should be prioritised for intervention.

## 3. Results

### 3.1. Assessment of sites

To assess potential sites, criteria were grouped into three categories

**Table 1**
Site selection framework for evaluating coral outplanting sites based on their biophysical and ecological attributes. A defined number of criteria ($N$) are evaluated at several sites ($n$) using desktop, field information, or both. Criterion assessment results in a response variable ($R$) that can either be categorical (*i.e.*, qualitative description) or numerical (*i.e.*, quantitative description). Criteria type can be either 'essential' or 'desirable'. Essential criteria correspond to factors necessary for deeming a site suitable for intervention, whereas desirable criteria encompass factors that, if fulfilled, could improve coral outplant growth and survival. For some interventions, a criterion may be deemed 'Not applicable' and hence excluded from the site evaluation process. For some criteria, it may not be possible to collect the data owing to logistical constraints. Based on expert knowledge, a weight ($w_N$) can be assigned to each criterion.

| Criterion | Desktop informed (true or false) | Field informed (true or false) | Type of criterion | Criterion weight | Site 1 | Site 2 | Site 3 | … | Site n |
|---|---|---|---|---|---|---|---|---|---|
| 1 | True | True | Essential | $w_1$ | $R1_1$ | $R1_2$ | $R1_3$ | … | $R1_n$ |
| 2 | False | True | Desirable | $w_2$ | $R2_1$ | $R2_2$ | $R2_3$ | … | $R2_n$ |
| 3 | True | False | Essential | $w_3$ | Data cannot be collected | Data cannot be collected | Data cannot be collected | … | Data cannot be collected |
| 4 | False | True | Not applicable | Not applicable | Not applicable | Not applicable | Not applicable | … | Not applicable |
| … | … | … | … | | … | … | … | … | … |
| N | True | False | Essential | $w_N$ | $RN_1$ | $RN_2$ | $RN_3$ | | $RN_n$ |

based on the type of information provided (Fig. 1). The first group evaluates biophysical and ecological similarity between source and deployment sites, as mismatches can reduce outplant performance and viability (Edwards, 2010; Hein et al., 2020; Shaver et al., 2020). The second and third groups describe abiotic and biotic characteristics at the deployment site, which are also crucial for coral performance, as they reflect the site's environmental and ecological conditions. We adjusted the framework (i.e., type of criteria, threshold values) to align with initiatives under development for the Great Barrier Reef and used expert elicitation to optimise scores. However, scores and threshold values can be adapted to specific ecosystems and project needs (Supplement S2).

### 3.1.1. *Compatibility between coral source and deployment site*

When sourcing donor corals, biophysical and ecological similarity between source and destination sites can determine their performance at deployment sites (e.g., Baums et al., 2019). Comprehensive environmental and biological data will help identify distinct reef habitats that support different communities. To avoid outplanting coral species in unsuitable sites, five compatibility criteria were considered within this group (Table 2), as explained below.

1. ***Is the target species or morphotaxon naturally present at the deployment site, or is there evidence that it can thrive at the deployment site?***

To evaluate if environmental conditions at the deployment site favour the performance of the targeted taxon, this criterion examines species presence using desktop and field information. It is not considered for larval seeding, as coral species identification within larval slicks is currently unfeasible, though future molecular techniques could allow

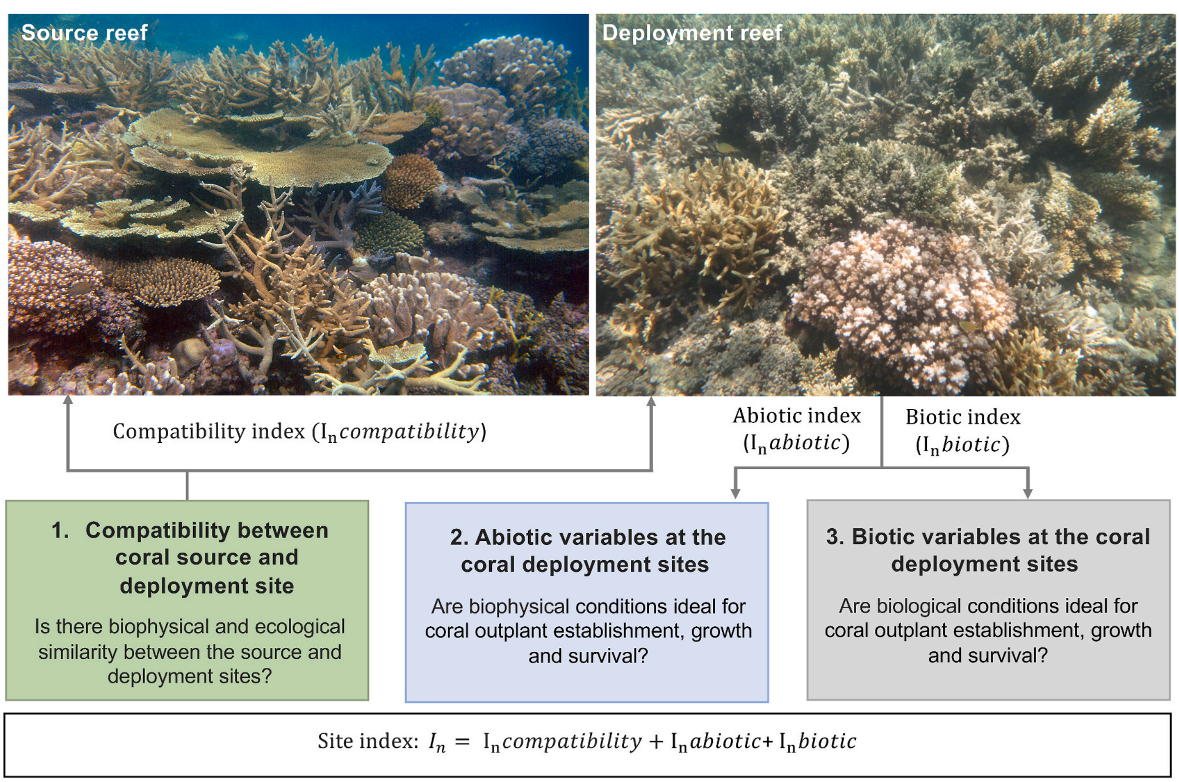


**Fig. 1.** The three groups of criteria to assess, rank and compare potential coral outplanting sites. The first group of criteria evaluates the similarity between the source and the deployment sites to assess compatibility. The second and third group evaluate the abiotic and biotic variables at the deployment site respectively. An average index for each criteria group per site is calculated ($I_n$*compatibility*; $I_n$*abiotic*, $I_n$*biotic*, see methods for calculation of the site index). These group indexes are added to estimate and average index per site ($I_n$).

**Table 2**
Criteria examined to assess compatibility in biophysical and ecological characteristics between source and the deployment sites, showing whether assessments can be accomplished via desktop or field derived data. Criteria response options and their conversion into a score are listed. Criteria types are assigned to each criterion based on the type of intervention and the outplanting method used (see sheet 'Type of criteria' in the Supplement Excel file). When the responses include two scores, the first corresponds to the score if the criterion is considered essential while the second relates to a criterion considered desirable.

| Criteria | Desktop informed | Field informed | Response options | Score |
|---|---|---|---|---|
| 1. Is the target species or morphotaxon naturally present at the deployment site? Or is there evidence that it can thrive at the deployment site? | True | True | Species is present at the site | 4 |
| | | | Species used to be present and abundant in the site, but even after mitigating or controlling the stress factor that decimated its population, the species is still absent | 3 |
| | | | Species is not present at the site, but empirical evidence indicates that it can thrive at the site under current conditions | 2 |
| | | | Morphotaxon is present at the site | 1 |
| | | | None of the above | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |
| 2. What is the difference between the average collection depth and the depth range were corals will be deployed? | True | True | ≤±3 m | 4 |
| | | | ±4 m | 3 |
| | | | ±5 m | 2 |
| | | | ±6m | 1 |
| | | | >±6 m | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |
| 3. Is the annual mean turbidity at the deployment site within the turbidity range (±5 mg/l) to the source site? | True | True | Yes | 4 |
| | | | No | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |
| 4. What is the difference in the yearly Minimum Monthly Mean (ΔMinMM °C) when sourcing corals from a hotter site, or the yearly Maximum Monthly Mean (Δ MaxMM °C) when sourcing corals from a colder site, between the source and deployment sites? | True | True | Δ°C MinMM< 2 °C when sourcing from a hotter site or Δ°C MaxMM < 1.5 °C when sourcing from a colder site | 4 |
| | | | Δ°C MinMM > 2 °C when sourcing from a hotter site or Δ°C MaxMM >1.5 °C when sourcing from a colder site | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |
| 5. Does the geomorphological reef zone at the deployment site correspond to the zone where the donor colonies resided (i.e., back reef, crest, inner flat, outer flat, patch, exposed slope, sheltered slope, lagoon)? | True | True | Yes | 4 |
| | | | No | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |

this (e.g., Byrne et al., 2023). If the species is present at the site, select "Species is present at the site" (score 4). If the species inhabited the site previously, but is now absent due to disturbances (e.g., blast fishing), select "Species used to occur in the site, but even after mitigating or controlling the stress factor that decimated its population, the species is absent" (3). If the species is absent but the intervention aims to establish a new population, transplant trials are recommended to assess site suitability before large-scale outplanting. If trials suggest suitability, select "Species is not present at the site, but there is empirical evidence that it can thrive at the site under current conditions" (2). If the species is absent, but morphologically similar corals (e.g., *Acropora* tabulate) or genera exist at the site, select "Morphotaxon is present at the site" (see (Althaus et al., 2015) for a definition of morphotaxa) (1). If none apply, select "None of the above", which will result in a "Do not deploy" outcome if the criterion is essential or the lowest score (0) if considered desirable.

2. ***What is the difference between the average collection depth and the depth range where corals will be deployed?***

Depth affects abiotic conditions, including light, temperature, and wave stress (Hoogenboom and Connolly, 2009), influencing coral performance. Coral assemblages have consistent depth zonation, with species occupying discreet depths across regions (Done, 1982; Hughes et al., 2012) and showing local adaptation (e.g., Bongaerts et al., 2011). Species depth ranges are available from museum records and literature (e.g., Laverick et al., 2018), making this a desktop-informed criterion. However, depth range alone is an unreliable indicator as many species are abundant only within a narrow depth range (Roberts et al., 2019), therefore, on-site verification at both source and deployment sites is recommended. Deployment closer to the optimal species depth will improve outplant success. If source and deployment depths align, this criterion scores highest. If depths differ by more than ±6 m, a "Do not deploy" recommendation will apply if the criterion is essential, or the lowest score (0) assigned if it is considered desirable.

3. ***Is the annual mean turbidity at the deployment site within the turbidity range (±5 mg/l) of the source site?***

Turbidity affects light penetration into the water column, a key parameter determining community composition (Done, 1982). Consequently, coral performance is optimised when turbidity regimes are similar across source and deployment sites. High sediment loads, both suspended and deposited, reduce coral autotrophy (Anthony and Connolly, 2004), growth (e.g., Humanes et al., 2017), reproductive output (Jones et al., 2015), and increase tissue necrosis (Weber et al., 2012). Sudden turbidity increases can physiologically stress corals, leading to bleaching (e.g., Bessell-Browne et al., 2017) or increased disease susceptibility (Pollock et al., 2014). Likewise, high-turbidity specialists such as *Turbinaria reniformis* may not thrive in clear waters due to reduced nutrients and photoinhibition (Jones et al., 2020). This criterion can be desktop-informed using satellite-derived benthic irradiance (e.g., Canto et al., 2021), or biophysical models (i.e., e-reefs, https://www.ereefs.org.au/). Alternatively, turbidity can be characterised through water sampling or loggers (Schaffelke et al., 2012). If turbidity levels are similar among source and deployment sites, select "Yes" (score 4), if turbidity levels are not similar, the option "No" should be selected. In such cases, a "Do not deploy" recommendation may be made if the criterion is essential, or the lowest score (0) assigned if it is considered desirable.

4. ***What is the difference in the yearly Minimum Monthly Mean (ΔMinMM °C) when sourcing corals from a hotter site, or the yearly Maximum Monthly Mean (Δ MaxMM °C) when sourcing corals from a colder site, between the source and deployment sites?***

Temperature affects many biological processes, especially in ectothermic, sessile organisms like corals that cannot regulate body temperature by relocating. An organism's thermal biology is characterized by its thermal tolerance (survival to extreme temperatures) and thermal performance (how growth, fecundity, survival vary with temperature) (e.g., Angilletta, 2009). While thermal performance differs between species, its curve shape is consistent within species (Alvarez-Noriega et al., 2023), indicating limited capacity for rapid adaptation to changing thermal regimes. Hence, aligning thermal regimes between source and deploying sites will enhance outplant performance. Corals from hotter sites can underperform in colder sites, while those from cooler sites risk heat stress in warmer environments. Based on results across five species (Alvarez-Noriega et al., 2023), we recommend ≤2 °C difference in yearly Minimum Monthly Mean (MinMM) between sites to avoid reduced performance, yielding the highest score (4). For sourcing corals from cooler areas (e.g., for genetic rescue), ≤1.5 °C difference in yearly Maximum Monthly Mean (MaxMM) between sites is advised. Differences beyond these thresholds warrant a "Do not deploy" outcome if the criterion is essential or the lowest score (0) if considered desirable. This criterion can be desktop-informed using satellite-derived temperature data (e.g., NASA's Multi-scale Ultra-high Resolution sea surface temperature Version 4.1–1 km resolution) or multi-year on-site temperature loggers (Humanes et al., 2022).

5. ***Does the geomorphological reef zone at the deployment site correspond to the zone where the donor colonies resided?***

Geomorphological reef zones (Kennedy et al., 2021) are characterized by specific environmental (e.g., water flow, light exposure, depth, sedimentation) and biological (e.g., competition, predation) conditions. Consequently, coral communities within a reef zone tend to have similar species composition and abundance. Transplanting corals within the same geomorphological zone increases the likelihood of similar conditions, reducing transplantation stress and bolstering coral performance. This criterion can be desktop-informed including data from museum records, monitoring, habitat distribution maps (e.g., Atlas, 2022), and be corroborated with on-site visits. If zones at both source and deployment sites are the same (e.g., back reef, reef crest, inner flat, outer flat, patch,

**Table 3**
Criteria examined to assess abiotic variables at deployment sites. Criteria response options and their conversion into a score are listed. Criteria types are assigned to each criterion based on the type of intervention and the outplanting method used. When the responses include two scores, the first corresponds to the score if the criterion is considered essential while the second relates to a criterion considered desirable.

| Criteria | Desktop informed | Field informed | Response options | Score |
|---|---|---|---|---|
| 6. What is the slope averaged along the deployment site? | True | True | ≤10º | 2 |
| | | | >10º and ≤20º | 4 |
| | | | >20º and ≤30º | 3 |
| | | | >30º and ≤40º | 1 |
| | | | >40º | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |
| 7. How is the rugosity at the deployment site? | True | True | Very low | 1 |
| | | | Low | 2 |
| | | | Medium | 4 |
| | | | High | 3 |
| | | | Very high | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |
| 8. What is the average wave exposure at the deployment site? | True | False | Very low | 1 |
| | | | Low | 3 |
| | | | Medium | 4 |
| | | | High | 2 |
| | | | Very high | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |
| 9. How thick is the layer of deposited sediments on the reef substratum at the deployment site? | False | True | There are no sediments deposited | 4 |
| | | | Thin layer easy to resuspend | 3 |
| | | | Moderate layer that offers resistance to be resuspended | 1 |
| | | | Thick layer deep layer that is not possible to resuspend | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |
| 10. What is the thermal status of the deployment site? | True | True | Refugia | 4 |
| | | | Neutral | 2 |
| | | | Hot spot | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |
| 11. What is the carrying capacity (i.e., maximum available space for corals to inhabit) at the deployment site? | True | False | > 85 and ≤ 100% | 4 |
| | | | > 70 and ≤ 85% | 3 |
| | | | > 55 and ≤ 70% | 2 |
| | | | > 40 and ≤ 55% | 1 |
| | | | ≤ 40% | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |

exposed slope, sheltered slope, lagoon) or very similar, the “Yes” option should be selected, awarding the highest score (4). Conversely, if zones are not similar, select “No”. In such cases, a “Do not deploy” recommendation may apply if the criterion is essential, or the lowest score (0) assigned if considered desirable.

#### 3.1.2. Abiotic variables at the coral deployment sites

Abiotic variables at the deployment site influence conditions for outplanted coral performance (Randall et al., 2022). Habitat maps (e.g., Lyons et al., 2020), remote sensing or model data (e.g., Foo and Asner, 2019; Schill et al., 2021), and field observations (Carlson et al., 2024) can be incorporated in statistical models to predict coral cover or species distributions. Six abiotic criteria were considered for assessment within this group (Table 3) and are described below.

6. ***What is the slope averaged along the deployment site?***

The angle of the substrate slope can determine transplanted coral performance. Steeper slopes experience more shading, reducing coral performance due to light limitations, and stronger water currents. In contrast, gentle slopes offer calmer conditions and greater light exposure that could promote sedimentation and heat stress conditions. Phototrophic octocorals richness declines on slopes >40°, while heterotrophic organisms increase with slope and flow (Fabricius and De’Ath, 2008). Therefore, this 40-degree threshold is used here. Substrate slopes ≤10° score 2, >10°-≤20° score 4, >20°-≤30° score 3, and >30°-≤40° score 1. Slopes >40° should be avoided and a “Do not deploy” recommendation may apply if the criterion is essential, or the lowest score (0) is assigned if desirable. This criterion can be measured in 5° increments using a plumb bob and protractor, or desktop-informed using acoustic sonar systems, high-resolution satellite imagery, camera-mounted autonomous surface or aerial vehicles (e.g., Roelfsema et al., 2020).

7. ***How is the rugosity at the deployment site?***

Rugosity, the ratio of the substrate surface area to its planar area, measures habitat structural complexity (Pygas et al., 2020) and links to biodiversity (e.g., Ferrari et al., 2017) and ecological dynamics (Graham and Nash, 2013). High rugosity includes crevices where organisms can attach reducing displacement from waves (e.g., Chamberland et al., 2017), increases larval settlement space, and boosts corals survival, but also leads to increased competition among benthic organisms. On degraded reefs with low coral cover, intermediate rugosity supports recovery by offering settlement substrates and reduced competition. Rugosity can be estimated using the chain-and-tape or qualitative methods (Polunin and Roberts, 1993; Wilson et al., 2006). Visual observations can categorise site rugosity as: no vertical relief (very low), low and sparse relief (low), low but widespread relief (medium), moderately complex (high), very complex with numerous fissures and caves (very high) (Polunin and Roberts, 1993). Medium rugosity scores highest (4), followed by high (3), low (2) and very low (1). Very high rugosity warrants a “Do not deploy” recommendation if the criterion is essential, or the lowest score (0) if it is desirable. Remote sensing, visual (e.g., Ferrari et al., 2016) or acoustic surveys can also assess rugosity, but their results should be calibrated against Polunin and Roberts (1993) grading system to align the scoring proposed here.

8. ***What is the average wave exposure at the deployment site?***

Spatial gradients in wave energy sites influence benthic (e.g., Lange et al., 2021) and fish (e.g., Karkarey et al., 2020) community composition and their population dynamics (Lange et al., 2021). Wave exposure affects water movement, temperature stratification (e.g., West and Salm, 2003), sediment flux (e.g., Wolanski et al., 2005), nutrient availability (Hearn et al., 2001), oxygen concentration (e.g., Finelli et al., 2005), and at higher levels acts as a mechanical stressor (e.g., Denny, 1994). Coral susceptibility to wave damage depends on morphology and size, with top-heavy morphologies facing higher dislodgement risk when large (e.g., Madin et al., 2014). High wave energy in shallow waters often lowers coral cover, favouring morphologies like encrusting or massive corals (e.g., Gove et al., 2015; however see Lange et al., 2021). High wave action can also reduce bleaching mortality (e.g., Raymundo et al., 2017) but poses logistical challenges for deployment. As with other criteria, matching wave conditions between source and deployment sites improves outplant success. Wave exposure can be assessed using physical models (Denny and Gaylord, 2010), cartographic indices (Harborne et al., 2006), or data on the geomorphology, fetch and wind climate (e.g., Callaghan et al., 2015). Wave exposure can be graded from very low to very high, with medium exposure scoring the highest (4), followed by low (3), high (2) and very low (1). Very high exposure will lead to a “Do not deploy” recommendation if the criterion is essential, or the lowest score (0) if it is considered desirable. If outplanting non *Acropora* spp. corals such as massive *Porites* spp., scores can be customised (see Supplementary material S2) assigning low and very low exposures scores of 3 and 4, as these species thrive in low-wave habitats.

9. ***How thick is the layer of deposited sediments on the reef substratum at the deployment site?***

Deposited sediments reduce coral performance. The thickness of deposited sediments can serve as a proxy of sedimentation rates and can be assessed through a single visual evaluation. To capture spatial variability, we recommend conducting assessments at a minimum of ten randomly distributed areas across the site and average the results to obtain a representative value for the criterion. Deposition can be evaluated using a 4-point scale (Fabricius and De’ath, 2001): no sediment deposition (score 4), a thin layer that easily resuspends by fanning (3), a moderate layer offering some resistance to be resuspended by fanning (1), and a thick deep layer that cannot be resuspended by fanning, which results in a “Do not deploy” recommendation if the criterion is essential, or the lowest score (0) if considered desirable.

10. ***What is the thermal status of the deployment site?***

Site selection should target areas with low climate change vulnerability to enhance outplant performance under future conditions (Shaver et al., 2020). Evaluating temperature history offers insights into thermal dynamics at a site. Across seascapes, some reefs experience higher-than-average heat stress (hotspots), while others are subjected to less intense heat stress (thermal refugia). These patterns have been reported to occur across large (>1000 km; e.g., Cheung et al., 2021) and small spatial scales (<150 km; Lachs et al., 2024). Coral thermal tolerance depends on environmental (e.g., Sahin et al., 2023) and biological factors (e.g., Humanes et al., 2024), but cumulative temperature stress during the warm season triggers mass coral bleaching and mortality (Skirving et al., 2019). Therefore, deployment sites should be avoided in hotspot areas unless the goal is to increase population thermal tolerance by using enhanced coral, in which case scoring can be customised to value higher hotspot locations (Supplement S2). Site thermal status can be assessed using satellite data or *in-situ* temperature loggers at outplanting depths. Refugia sites score the highest (4), neutral sites score 2, and hotspot sites will receive a “Do not deploy” recommendation if the criterion is essential, or the lowest score (0) if it is considered desirable.

11. ***What is the carrying capacity (i.e., maximum available space for corals to inhabit) at the deployment site?***

Geomorphic and habitat maps can estimate hardbottom area supporting living corals and algae together with free consolidated substrate, representing the potential suitable available space for corals to inhabit (Atlas, 2022; Cresswell et al., 2024; Roelfsema et al., 2021). While it does not reflect available consolidated substrate at the time of deployment, it helps to rule out sites with low coral growth potential. This criterion can be desktop informed using satellite data to produce high-resolution maps and complements criterion 12. We suggest assigning the highest score (4) to sites where available space >75 %. Sites >60 % but ≤75 % receive a score of 3; those with >45 % but ≤60 % a score of 2, and those with >30 % but ≤45 % a score of 1. Sites with <30 % available substrate should be avoided, as these might be dominated by sand or unconsolidated substrate. In such cases, a "Do not deploy" recommendation applies if the criterion is essential, or the lowest score (0) will be assigned if it is considered desirable.

### 3.1.3. Biotic factors at the deployment site

Biotic factors at the intervention site, especially competition for space with other benthic organisms and corallivores, will affect the performance of outplanted corals (Omori, 2019; Randall et al., 2020, 2022). While monitoring data and habitat maps can provide insights into biotic factors, post-survey disturbances may have altered the state of the biotic community. Consequently, site visits for rapid ecological assessments (Smith et al., 2020) are recommended within a month or two before outplanting. Seven criteria were considered within this group (Table 4) and are described below.

12. ***What is the average percentage of consolidated substrate (not sand, rubble, or macrobenthos including live corals) availability per 10 × 10* m at the deployment site?**

Consolidated substrate provides a sturdy surface for coral growth, reducing dislodgement risk from water movement. Sites dominated by sand, rubble or unconsolidated substrate, where corals are unlikely to attach, should be avoided. Consolidated substrates are often dominated by crustose coralline algae which contribute to limestone formation and reef cementation, thus, this criterion is considered biotic. Sites where consolidated available substrate covers >75 % of the area receive the highest score (4), >60 % to ≤75 % coverage (3), >45 % to ≤60 % (2), and those with >30 % to ≤45 % (1). Sites with <30 % available consolidated substrate should be avoided for outplanting. In such cases, a "Do not deploy" recommendation applies if the criterion is essential or the lowest score (0) is assigned if it is considered desirable.

13. ***What is the average height of turf algae mats at the deployment site?***

Turf algae are ubiquitous on reef substrata, facilitating coral recruitment. However, avoiding thick filamentous turf algae mats during coral outplanting is essential, as they contribute to early-stage coral mortality through overgrowth (Arnold et al., 2010). Thick mats compete with corals for space and nutrients, and can worsen sedimentation impacts due to sediment trapping. To assess turf algae mats, we suggest measuring their height *in-situ* using callipers or 0.1 cm precision ruler every 10 m along a 100 m transect. Mats <1.0 cm in height will receive the highest score (4), while mats >1.0 cm should be avoided for coral outplanting. In such cases, a "Do not deploy" recommendation will be made if the criterion is essential or the lowest score (0) is assigned if it is considered desirable.

**Table 4**
Criteria examined to assess biotic variables at deployment sites. Criteria response options and their conversion into a score are listed. Criterion types are assigned to each criterion based on the type of intervention and the outplanting method used. When the responses include two scores, the first corresponds to the score if the criterion is considered essential while the second relates to a criterion considered desirable.

| Criteria | Desktop informed | Field informed | Response options | Score |
|---|---|---|---|---|
| 12. What is the average percentage of free consolidated substrate (not sand, rubble or live benthic organism) availability per 10x10 m at the deployment site? | False | True | > 75 and ≤ 100% | 4 |
| | | | > 60 and ≤ 75% | 3 |
| | | | > 45 and ≤ 60% | 2 |
| | | | > 30 and ≤ 45% | 1 |
| | | | ≤ 30% | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |
| 13. What is the average height of turf algae mats at the deployment site? | False | True | Less than 10 mm | 4 |
| | | | 10 mm or more | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |
| 14. What is the average percentage of macroalgal cover per 10x10 meter at the deployment site? | False | True | = 0% | 4 |
| | | | > 0% and ≤ 10% | 3 |
| | | | > 10% and ≤ 20% | 2 |
| | | | > 20% ≤ 30% | 1 |
| | | | > 30% | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |
| 15. What is the average percentage of coral cover per 10x10 meter at the deployment site? | False | True | ≤ 5% | 1 |
| | | | > 5% and ≤ 15% | 4 |
| | | | > 15% and ≤ 20% | 3 |
| | | | > 20% and ≤ 30% | 2 |
| | | | > 30% | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |
| 16. What is the average density of coral juveniles per square meter at the deployment site? | False | True | ≤ 3 | 4 |
| | | | > 3 and ≤ 7 | 3 |
| | | | > 7 and ≤ 9 | 2 |
| | | | > 9 and ≤ 11 | 1 |
| | | | > 11 | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |
| 17. What is the density of Crown of Thorns Seastar (CoTS) per hectare at the deployment site? | False | True | > 0 and ≤ 0.05 | 4 |
| | | | > 0.05 and ≤ 0.10 | 3 |
| | | | > 0.10 and ≤ 0.15 | 2 |
| | | | > 0.15 and ≤ 0.22 | 1 |
| | | | > 2 | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |
| 18. What is the density of *Drupella* spp snails per hectare at the deployment site? | False | True | ≤ 50 | 4 |
| | | | > 50 and ≤ 100 | 3 |
| | | | > 100 and ≤150 | 2 |
| | | | > 150 and ≤200 | 1 |
| | | | > 200 | Do not deploy, 0 |
| | | | Data cannot be collected | Not considered |

14. ***What is the average percentage of macroalgal cover per 10 × 10 m at the deployment site?***

Several physical and biological factors shape reef algal communities, including herbivory, eutrophication, hydrodynamics and sedimentation (e.g., Fabricius et al., 2023). Among these, herbivory is a primary determinant of benthic succession (reviewed by Burkepile and Hay, 2006), with strong negative relationships between herbivore biomass and macroalgae cover (e.g., Williams and Polunin, 2001). Macroalgae compete with corals for space, often dominating substrates after disturbances and limiting coral larval settlement (Birrell et al., 2008), survival, and growth (Ferrari et al., 2012). They can also reduce coral gamete production (e.g., Cetz-Navarro et al., 2015), larval metamorphosis (Baird and Morse, 2004), recruitment (Webster et al., 2015), growth, and juvenile survival (e.g., Rasher and Hay, 2010). Transplanted corals near macroalgae show reduced growth, while those in cleared areas perform comparably to corals in coral-dominated zones (Clements et al., 2018). Macroalgae cover can be estimated from images (Lechene et al., 2019) or visually *in situ* using manta tow surveys where a snorkel diver is towed behind a boat at a constant speed, assessing benthic organisms cover during 2-min tows. Sites without macroalgae score highest (4), followed by those with ≤10 % cover (3), >10 % to ≤20 % (2), and >20 % to ≤30 % (1). Sites with >30 % macroalgal cover should be avoided, and in such cases, a “Do not deploy” recommendation will be made if the criterion is essential, or the lowest score (0) will be assigned if it is considered desirable. In areas exceeding the 30 % threshold, repeated manual removal could expand suitable outplanting sites (e.g., Ceccarelli et al., 2018).

15. ***What is the average percentage of hard coral cover per 10 × 10 m at the deployment site?***

Outplanting interventions target reefs with reduced coral cover. However, small-scale heterogeneity within metres can result in patches with high coral cover that should be avoided to ensure space for outplants to grow. Average coral cover can be estimated using manta tow surveys where a snorkel diver is towed behind a boat at a constant speed, assessing coral cover during 2-min tows. Cover is recorded on a categorical scale: 0 = 0 %, 1 = >0–10 %, 2 = 10.1–30 %, 3 = 30.1–50 %, 4 = 50.1–75 %, 5 = 75.1–100 %. Scores are then averaged to estimate site-level coral cover. Sites with coral cover ≤5 % receive the lowest score (1) as these might reflect poor environmental conditions for coral growth. Sites with >5 %-≤15 % coverage score 4, >15 %-≤20 % coverage score 3, >20 %-≤30 % coverage score of 2. Sites with >30 % coral cover should be avoided, as they may have enough corals to promote local recruitment and recovery, and the existing corals there are likely to overgrown newly deployed corals rapidly. In such cases, a “Do not deploy” recommendation will be made if the criterion is essential or the lowest score (0) will be assigned if it is considered desirable.

16. ***What is the average density of coral juveniles per square meter at the deployment site?***

Coral larval supply, settlement, and recruitment are key processes in reef recovery, though high mortality during early stages limit their contribution to coral cover recovery after a disturbance. Once early-stage bottlenecks are overcome, survivorship improves, supporting natural recovery (e.g., Ortiz et al., 2021). Consequently, interventions that effectively increase juvenile densities are less effective at sites with high juvenile coral densities that have already overcome these bottlenecks and are more likely to naturally recover. To maximise intervention impact, sites with high densities of juvenile corals of any genera should be avoided. Juvenile density (<5 cm in diameter) can be assessed through visual surveys along a known reef area (Jonker et al., 2020). Sites with juvenile densities >0-≤3 corals per $m^2$ receive the highest score (4), >3-≤7 colonies per $m^2$ receive a score of 3, and >7-≤9 colonies per $m^2$ receive a score of 2. Additionally, sites with >9-≤11 corals $m^2$ would receive a score of 1. Sites with >11 juveniles per $m^2$ suggest ongoing natural recovery (Morais et al., 2023), and their rapid growth may compromise the competitive ability of deployed corals. In such cases, a “Do not deploy” recommendation will be made if the criterion is essential or the lowest score (0) will be assigned if it is considered desirable.

17. ***What is the density of Crown of Thorns Seastar (CoTS) per hectare at the deployment site?***

Corallivores influence on coral cover loss through predation, disease transmission (e.g., Williams and Miller, 2005), reduced recruitment (e.g., Lenihan et al., 2011) and preventing recovery following bleaching (e.g., Bruckner et al., 2017). *Acanthaster* spp., (Crown of Thorns Seastar (CoTS) are among the most destructive invertebrates in Indo-Pacific reefs (Glynn and Enochs, 2010), consuming up to 250 $cm^2$ of coral daily (e.g.Chesher, 1969; Glynn, 1973). Although typically found at low densities (<0.001 individuals per 100 $m^{-2}$)(Pratchett et al., 2017), outbreaks can lead to severe coral cover loss (e.g., Pratchett M et al., 2014). To survey CoTS we recommend using the manta tows (Miller et al., 2018), where an observer counts CoTS during 2-min tows (~200 $m^2$). Outbreak status is defined on number of CoTS per tow: no CoTS (0 CoTS), no outbreak (0–0.1 CoTS), potential outbreak (0.1–0.22 CoTS), incipient outbreak (0.22–1 CoTS) and active outbreak (more than 1 CoTS). Sites with CoTS densities <0.22 per hectare receive the highest score (4), whereas ≥0.22 CoTS per hectare should be avoided due to elevated outbreak risk. In such cases, a “Do not deploy” recommendation will be made if the criterion is essential or the lowest score (0) will be assigned if it is considered desirable.

18. ***What is the density of Drupella*** **spp.** ***snails per hectare at the deployment site?***

*Drupella* spp. snails scrape coral tissue with their radula, leaving distinctive white scars. While they prefer fast-growing branching corals like *Acropora* and *Pocillopora* (e.g., Al-Horani et al., 2011; Schoepf et al., 2010), they also feed on slower-growing corals like *Porites* (Hamman, 2018). Outbreaks of *Drupella* spp. snail have been linked to widespread coral mortality and cover decline across Indo-Pacific reefs (e.g., Turner, 1994). In the Caribbean *Coralliophila abbreviata*, *C. caribaea*, and *C. galea* similarly contribute to coral loss (e.g., Baums et al., 2003). To estimate snail densities, we suggest five 50 × 2m transects. An outbreak is defined at 6.4 *Drupella* spp. per $m^2$ (Cumming, 2009). Due to their cryptic nature, surveys can be time-consuming, but warning signals include snails on small colonies (<10 cm), infestation of >6 % of corals, or aggregation on stressed or diseased corals (Cumming, 2009). Sites with densities >0-≤50 snails per hectare receive the highest score (4), >50-≤100 (3), >100-≤150 (2), >150-≤200 (1). Sites with ≥200 snails per hectare should be avoided, as this suggests elevated risk of a *Drupella* spp. outbreak, and in such cases, a “Do not deploy” recommendation will be made if the criterion is essential or the lowest score (0) will be assigned if it is considered desirable.

### *3.2. Evaluation and ranking of sites*

In addition to the average index per site ($I_n$), an average index for each criteria group was calculated, resulting in three additional indexes: compatibility between the source and deployment site ($I_n$*compatibility*), and the abiotic ($I_n$abiotic) and biotic ($I_n$biotic) conditions at the deployment site. Here, we present results from evaluating the proposed criteria across 10 hypothetical Great Barrier Reef sites, which are also applicable to other central and western Pacific reefs. Reef rehabilitation via outplanting artificial substrates with settled larvae from target coral species was the intervention assessed (Table 5). Although some sites (i.e., Sites 1, 2 and 7, or 4, 5 and 6) accrued similar average indexes ($I_n$),

**Table 5**
Coral outplanting sites evaluation and ranking for an intervention aimed at rehabilitating a reef by outplanting corals of known species. The assessment is based on the corals' source and deployment site compatibility (criteria 1 to 5), which is summarised by an average compatibility index ($I_n$*compatibility*), the abiotic conditions at the deployment site (criteria 6 to 11), which is summarised by an average abiotic index ($I_n$*abiotic*), and the biotic conditions at the deployment site (criteria 13 to 19), which is summarised by an average biotic index ($I_n$*biotic*). A total average index ($I_n$) summarises each site properties. Sites with the highest index values are considered as most suitable for coral deployment.

| Criteria | Site 1 | Site 2 | Site 3 | Site 4 | Site 5 | Site 6 | Site 7 | Site 8 | Site 9 | Site 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $I_n compatibility$ | 4.00 | 3.60 | 3.00 | 3.40 | 3.60 | 4.20 | 4.20 | 3.60 | 3.00 | Do not deploy |
| $I_n abiotic$ | 2.33 | 2.50 | 1.83 | 1.67 | 1.50 | 1.33 | 2.33 | 1.50 | Do not deploy | Do not deploy |
| $I_n biotic$ | 3.25 | 3.00 | 2.29 | 3.00 | 2.67 | 2.56 | 2.56 | Do not deploy | Do not deploy | Do not deploy |
| $I_n$ | 3.37 | 3.00 | 2.44 | 2.70 | 2.55 | 2.60 | 2.90 | Do not deploy | Do not deploy | Do not deploy |

their suitability for outplanting differed based on compatibility, abiotic or biotic indexes (i.e., Site 7 had a notably lower biotic index than for Sites 1 and 2). If at least one essential criterion was unmet, the site received a "Do not deploy" decision (i.e., Sites 8, 9 and 10). Site 1 resulted as the most suitable for coral outplanting, followed by Sites 7, 2, 4, 6, 5, and 3 in descending order. Sites 8, 9, and 10 were deemed unsuitable for coral outplanting.

## 4. Discussion

The success of coral outplanting depends on ecological suitability at the deployment site and will fail if sites are unsuitable for coral performance. Biological interactions within reef communities and their interplay with environmental conditions require knowledge of biophysical and ecological site dynamics. Here we present a framework using heuristic criteria informed by ecological knowledge of factors promoting coral performance. By combining environmental and biological information, practitioners can better align species preferences and maximise outplanting outcomes.

A crucial consideration in selecting outplanting sites is understanding species' niche limits (*i.e.*, depth range, temperature, turbidity, etc.), as coral performance depends on adaptive potential. Generalist species (e.g., *Pocillopora damicornis*) exhibit plasticity enabling survival across environments, whereas specialists (*i.e.*, *Acropora hyacinthus*) require more constrained conditions. Prioritizing sites where target species thrive will improve the effectiveness and sustainability of outplanting initiatives. Coral performance also hinges on the efficacy of the deployment method. If the method fails to secure coral attachment to the reef substrate and promote growth to reproductive maturity, success will be compromised. Numerous methods and artificial substrates exist for outplanting sexually propagated corals, often tailored to site-specific conditions (e.g., Randall et al., 2022), each with strengths and limitations. However, empirical evidence on the performance of sexually propagated corals using these methods remains scarce, limiting predictive performance criteria. Our framework includes key factors known to affect early coral life stages, and can be refined as knowledge emerges.

### *4.1. Implications and recommendations for practice*

Planning large-scale coral outplanting initiatives must incorporate site-specific ecological data to improve the chances of preserving populations under future warming. To maximise outcomes, site selection should consider abiotic and biotic compatibility between source and deployment sites. A systematic evaluation, guided by ecological heuristics, can support informed decision-making and enhance spatial prioritisation for coral outplanting. However, assessing all potential sites on a reef may be logistically challenging, particularly in complex systems like the Great Barrier Reef, which may contain 350 and 750 potential sites (Cresswell et al., 2024). While some criteria can be evaluated using existing knowledge (desktop informed), others require on-site assessments, which may be unfeasible at scale. As a solution, site evaluation and ranking could occur in stages. First, logistical and stakeholder considerations would eliminate non-targetable sites based on factors like site distance and size, stakeholder values, etc. Second, desktop-informed criteria would rank the remaining sites. Finally, if the number of sites remaining is larger than the number of sites that can be visited for logistical reasons, on-site assessments would prioritise top-ranking sites. Following restoration and rehabilitation guidelines (Edwards, 2010; Hein et al., 2020; Shaver et al., 2020), outplanting should be avoided during disturbances (*i.e.*, storms, marine heat waves, disease outbreaks), which stress corals and jeopardize survival, unless the initiative explicitly targets such events.

Population thermal tolerance enhancement is the goal of two of the three intervention types considered here. A key challenge of artificially enhancing population tolerance is the scale of implementation. The most commonly proposed mechanism to upscale intervention impact is taking advantage of the reproductive strategies of corals and considering the spread of thermal tolerance from deployed corals to sites receiving the offspring of these corals when they become reproductive. As a consequence, connectivity between sites and demographic interactions between enhanced corals and the native corals in the receiving populations are essential to evaluate the effects of heat tolerance enhancement, though this is not included in the proposed framework. Network analysis (Hock et al., 2017) or ecosystem models including connectivity (Cresswell et al., 2024) can help assess larval dispersal benefits, but might not align with site rankings that maximise outplant performance. This creates a trade-off between maximising local impact and spill-over benefits to neighbouring sites. If enhancement effects are expected to be low, focus should be on outplant performance; if enhancement is expected to be high, site selection can prioritise enhancement spread. In this case, the framework should first be used to filter out unsuitable sites, then rank remaining sites by spill-over potential.

The framework was adjusted to align with initiatives under development for the Great Barrier Reef, though adapting it to other reef systems will require local knowledge for intervention goals and criteria. In regions with very low coral cover (e.g., the Caribbean), identifying suitable source and deployment sites is challenging, and management actions may require additional actions, including gamete cryopreservation, macroalgae removal, rebuilding herbivore populations, controlling corallivores, and managing disease. These factors can complicate site selection, as source corals may need to come from multiple reefs, and deployment sites may score as unsuitable. In these cases, the framework can help identify factors to manage in order to improve outplanting success. Additionally, different outplanting methods may be needed, requiring framework customisation. This framework, grounded on coral ecology, aims to support management programs in improving site selection. It also offers practitioners a quantitative tool to guide stakeholder discussions, rank potential sites, and identify abiotic and biotic factors to manage that could enhance site suitability for coral outplanting. Updates incorporating new research will improve its effectiveness over time.

### 4.2. Limitations of the framework

With ongoing coral reef decline, best-practice strategies are essential to optimise restoration success. While grounded in current science, a key limitation of this framework is the lack of empirical validation using data from restoration initiatives. However, long-term coral outplanting monitoring data remain scarce, and published studies often lack detail on coral sourcing and intervention sites, hindering validation. Rigorous validation would require assessing outplanting outcomes across a wide range of sites with varying suitability scores to reproductive maturity, requiring years of data collection. Nevertheless, high outplanting costs (e.g., Bayraktarov et al., 2019) and rapid intervention development underscore the need for ecological guidance in site selection.

Even with appropriate deployment methods and site selection, outplanted corals lacking adaptive potential to withstand future stressors (e.g., intensified marine heat waves) may not survive under projected mid-to-late century climate conditions. Likewise, if coral density is too low for fertilization due to Allee effects (Mumby et al., 2024), long-term intervention benefits will be limited. However, due to limited understanding of outplant survivorship to reproductive stages, coral density was excluded as a criterion. The framework also ignores sites spatial distribution, risking clustered site selection vulnerable to local disturbances. Incorporating a spatial ranking to prioritise widely separated sites could be performed after identifying the highest scoring sites. Furthermore, criteria can vary in weight, as scoring and thresholds can be better informed for some criteria than others. Assigning higher weights to better-understood criteria can reduce this bias. Moreover, prioritizing sites fulfilling most criteria will improve selection as more knowledge will be used to evaluate their suitability.

## 5. Conclusions

The presented framework overcomes challenges in site selection, emphasizing the evaluation of factors influencing coral performance. Given the global scale in coral outplanting, future research must focus on characterizing performance and growth to reproductive stages of sexually propagated corals under current and future stressors. Once available, this information will refine criteria and thresholds proposed in this framework, enabling more effective quantitative site assessments. As empirical evidence on outplanting methods accumulates, the framework stands ready for refinement and validation, enhancing predictions of outplant performance outcomes. Ongoing dedication to experimental approaches will expand the framework's applicability and advance coral outplanting success globally.

## CRediT authorship contribution statement

**Adriana Humanes:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Katharina E. Fabricius:** Conceptualization, Methodology, Writing – review & editing. **Renata Ferrari:** Conceptualization, Methodology, Writing – review & editing. **Juan Carlos Ortiz:** Conceptualization, Methodology, Formal analysis, Writing – review & editing.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126585.

## Data availability

No data was used for the research described in the article.

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