Journal of Environmental Management 396 (2025) 128154

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

A decision support tool for rubble stabilization on coral reefs

Shu Kiu Leung [a,*], Tania M. Kenyon [a], Laurie J. Raymundo [b], Helen E. Fox [c], Nathan Cook [d], Kailash Cook [a], Alasdair J. Edwards [e], Eric E. Fisher [f], Arnaud J.T. Brival [g], Freda E. Nicholson [h], Robin W.L. Philippo [i], Andrew C.F. Taylor [j], Scott E. Bryan [k], Brett M. Lewis [k], Kee Alfian Bin Abdul Adzis [l], John P. Edmondson [m], Sean P. Griffin [n], Xiubao Li [o], Xiangbo Liu [o], Hazel A. Oakley [i,p], Tries B. Razak [q], Satrio H. Samudra [q], Marthen Welly [r], Peter J. Mumby [a]

[a] Marine Spatial Ecology Lab, School of the Environment, The University of Queensland, Level 5, Goddard Building, St. Lucia, QLD, 4072, Australia
[b] University of Guam Marine Laboratory, Mangilao, 96923, Guam
[c] Coral Reef Alliance, 48 Market Street, Suite 29802, San Francisco, CA, 94104-5401, USA
[d] KAUST Coral Restoration Initiative, King Abdullah University of Science and Technology, Thuwal, 23955, Saudi Arabia
[e] School of Natural and Environmental Sciences, Newcastle University, Newcastle Upon Tyne, NE1 7RU, United Kingdom
[f] GBR Biology, Cairns, QLD, 4870, Australia
[g] The SEA People, Raja Ampat, Indonesia
[h] Mars Sustainable Solutions, Cairns, QLD, Australia
[i] Tropical Research and Conservation Centre, Sabah, Malaysia
[j] Blue Corner Conservation (Yayasan Blue Corner Konservasi), Bali, Indonesia
[k] School of Earth & Atmospheric Sciences, Queensland University of Technology, Brisbane, Queensland, Australia
[l] MISC Berhad, Kuala Lumpur, Malaysia
[m] Wavelength Reef Cruises, Port Douglas, QLD, Australia
[n] Reef Tech International, Puerto Rico
[o] School of Marine Biology and Fisheries, Hainan University, Haikou, China
[p] Department of Geography, National University of Singapore, Singapore
[q] Department of Marine Science and Technology, Faculty of Fisheries and Marine Science, IPB University, Indonesia
[r] Coral Triangle Center, Bali, Indonesia

ARTICLE INFO

Keywords:
Bayesian belief network
Coral reef management
Reef restoration
Rubble stabilization methods
Decision support tool
Coral rubble

ABSTRACT

Loose, persistently unstable rubble beds are increasingly common on coral reefs due to climate-driven disturbances and human impacts. These rubble beds often act as bottlenecks to reef recovery and typically do not stabilize without intervention. Rubble stabilization is used globally to restore degraded reefs, but there has been limited synthesis of its effectiveness across methods and environments. A growing need exists to translate current knowledge into practical guidance to support management and improve restoration outcomes. Bayesian Belief Networks (BBNs), useful for modeling complex systems with substantial uncertainty, were applied in this study to support decision-making in rubble stabilization. The model integrates expert knowledge and global data on restoration outcomes over time and in various environments. This study compares coral cover benefits of stabilization methods, including Reef Bags, flat meshes and grids, elevated frames, and solid structures, with and without coral outplants. Benefits were defined as the difference in coral cover between restoration and control sites, attributable to outplanting or natural recruitment. All methods led to increased benefits over time, though outcomes varied in magnitude and timing. Methods that included outplants generally produced earlier gains in coral cover, but benefits were density-dependent and longer-term outcomes remain uncertain. Higher coral cover benefits were associated with smaller rubble pieces, steeper slopes, and stronger hydrodynamic forces, provided stabilization structures were well anchored and maintained, which is often challenging in practice. Improved long-term monitoring, consistent terminology, and data sharing will be critical to strengthen model reliability and support decision-making in the global reef community.

* Corresponding author.
E-mail address: shukiu.leung@uq.edu.au (S.K. Leung).

https://doi.org/10.1016/j.jenvman.2025.128154
Received 15 July 2025; Received in revised form 16 November 2025; Accepted 26 November 2025
Available online 3 December 2025

1. Introduction

Globally, coral reefs face growing threats from climate change, with disturbances becoming more frequent and intense (Hoegh-Guldberg, 1999; Hughes et al., 2003, 2018; McWhorter et al., 2022). Disturbances, including extreme weather events, rising sea surface temperatures, and human activities such as ship groundings and blast fishing, cause substantial damage to coral reefs, leading to their degradation and the generation of vast amounts of rubble (Cheal et al., 2017; Hughes et al., 2017; Riegl, 2001). Disturbance-generated rubble fields, mostly composed of loose and unstable rubble pieces, often act as bottlenecks to reef recovery, showing little to no recovery for years to decades (Alcala and Gomez, 1979; Cameron et al., 2016; Chong-Seng et al., 2014; Dollar and Tribble, 1993; Fox et al., 2019; Raymundo et al., 2007; Victor, 2008). These disturbed rubble fields present conditions that are often unfavorable for the survival of coral recruits and live coral fragments, thus limiting the establishment of coral colonies and impeding reef recovery (Kenyon et al., 2023a, 2024; Lewis et al., 2022). For example, when loose rubble is mobilized, coral recruits attached to rubble pieces are subjected to abrasion and smothering due to continual rubble movement, leading to post-settlement mortality (Brown and Dunne, 1988; Clark and Edwards, 1995). As such, areas with persistent, disturbance-generated rubble and limited natural recovery could particularly benefit from rubble stabilization.

Rubble stabilization is an evolving approach aimed at restoring loose, disturbed rubble fields to contribute to overall reef restoration efforts (Ceccarelli et al., 2020). Stabilization methods aim to limit rubble movement, provide alternative surfaces for coral recruitment, or both, ultimately promoting coral growth and reef recovery. Some methods also incorporate coral outplants to increase coral cover and accelerate recovery. Significant progress has been made worldwide in developing and refining rubble stabilization techniques, yet synthesis of project outcomes has been limited (Kenyon et al., 2023a). This can largely be attributed to the scarcity of monitoring and reporting, which is commonly only carried out at local scales.

A comprehensive synthesis is critical for informing decision-making, particularly as increasing rubble generation poses growing challenges for reef management. Synthesizing these efforts presents considerable challenges due to: 1) significant variation in rubble stabilization projects in terms of goals, methods, timeframe, and spatial scale, and 2) limited research on the effectiveness of different rubble stabilization methods across environments. For example, while some stabilization projects have long-term monitoring programs (>5 years), many others are limited to short-term monitoring (usually 1–2 years), primarily due to constraints in funding, resources, and logistical capacity (Leung et al., 2024). In addition, there is currently no standardized approach for monitoring and reporting rubble stabilization success, though recent contributions have been made (Kenyon et al., 2024). Restoration success is typically measured by indicators such as coral cover, recruitment rates, or biodiversity (Bostrom-Einarsson et al., 2020; Goergen and Gilliam, 2018; Howlett et al., 2021; Suggett et al., 2024), but the lack of consistent metrics and monitoring protocols across rubble stabilization projects makes it difficult to compare reported outcomes meaningfully. While several studies have evaluated the effectiveness of rubble stabilization, many focus on single locations or method, with few assessing a broader range of methods across varying ecological and environmental conditions. Moreover, many methods have not been tested within scientifically rigorous frameworks, as they often lack control sites or randomized trials, which are necessary for accurately evaluating the effectiveness of restoration efforts (Goergen et al., 2020; Shaver et al., 2020). As a result, much valuable information regarding restoration outcomes remains unpublished as personal communications of expert opinions or as grey literature.

To address these challenges, we provide a structured comparison among the outcomes of various rubble stabilization methods across different environments using a Bayesian Belief Network (BBN) that integrates global survey data and expert opinion. We categorized common rubble stabilization methods into four categories based on their purpose and mechanisms, including 1) direct manipulation of the substrate (e.g., Reef Bags), 2) addition of structures to restrict rubble movement (e.g., flat meshes and grids), 3) addition of structures as an alternative substrate (e.g., elevated frames and solid structures), and 4) propagation of corals and sponges (e.g., coral outplanting and nurseries). Restoration outcomes of these methods were modeled in a BBN, a statistical framework suitable for representing complex systems when there is uncertainty and incomplete knowledge using conditional probabilities (Aguilera et al., 2011; Landuyt et al., 2013; Uusitalo, 2007). Given the nature of the data (inclusion of expert opinion), limited scientific research and monitoring in rubble stabilization methods, the ability of a BBN to infer missing data is especially valuable. Furthermore, BBNs provide transparency by offering access to all model results, and they can be used in reverse to identify the input conditions most likely to achieve desired outcomes (Baldock et al., 2019; Landuyt et al., 2013). Hence, the BBN serves as a valuable tool for summarizing expert opinions and identifying knowledge gaps in the context of rubble stabilization for reef management. By evaluating how rubble stabilization methods perform under different environmental conditions, the BBN helps identify the sites most likely to benefit from stabilization, guiding the selection of appropriate restoration strategies.

Using the BBN, four main research questions were addressed: 1) How much 'benefit', in terms of coral cover (see detailed definition in Section 2.3), is provided by different rubble stabilization methods over time? 2) How do methods with coral outplanting compare to those without in terms of benefits? 3) How are outcomes influenced by the initial outplant density or coral cover? And 4) How effective are rubble stabilization methods across different environments?

2. Methods

2.1. Overall workflow

The BBN was created using Netica version 7.01 (Norsys Software Corporation, 2024), with data cleaning and formatting performed in R version 4.3.1 (R Core Team, 2023) prior to generating the BBN in Netica. Predictions of the BBN were also visualized in R. The workflow followed these key steps: 1) design survey and collect data, 2) determine an appropriate BBN structure, 3) remove data inconsistencies, 4) format and pre-process survey data to ensure compatibility with Netica, 5) generate conditional probability tables (CPTs) using Netica's learning algorithm, 6) evaluate model validity and sensitivity, and finally 7) adjust the BBN manually based on expert opinion.

2.2. Survey design and data collection

The BBN utilized survey data collected during a workshop regarding rubble stabilization, held from 17 to November 21, 2023 (Leung et al., 2024). Experts with demonstrated field experience and technical expertise in planning, implementing, as well as monitoring rubble stabilization projects were invited to participate in an online survey conducted using Qualtrics. The survey was designed to address gaps and uncertainties relating to rubble stabilization methods, by capturing both quantitative data on restoration outcomes and qualitative data determined by expert opinion, to supplement existing knowledge. A total of 24 individuals responded, providing 85 data points from 55 rubble-dominated sites across Australia, Indonesia, Malaysia, China, Puerto Rico, the Philippines, Guam, the Maldives, and Thailand. Experts were asked about site environmental characteristics (e.g., depth, exposure, slope, rubble morphometrics), and restoration outcomes over time, measured in terms of coral-centric metrics (e.g., coral cover, density of recruits, and species composition). Additional data were drawn from Clark and Edwards (1994); Fox et al. (2019); Raymundo et al. (2007) to supplement the survey data. These sources were selected because they provided the necessary information to complete gaps in survey data from the workshop. While some sources (Clark and Edwards, 1994; Raymundo et al., 2007) are relatively dated and reef conditions may have changed, these studies provide the most comprehensive and reliable quantitative estimates for meshes and solid structures to date, which is essential given the limited documentation of rubble stabilization outcomes.

For the BBN, at least one representative method from each of the main categories introduced in section 1 was included (Fig. 1). Other methods, such as rubble removal and barrier fences were included in the survey but excluded from the BBN due to low replication. Methods were grouped based on whether coral outplants were used in combination with the stabilization structure. Coral outplants as a standalone method to stabilize rubble (e.g., by cementing them onto rubble pieces; Rojas et al. (2008)) was not included due to data limitations. Reef Bags (Fig. 1a) refer to a method trialed on the Great Barrier Reef, where loose rubble generated by cyclones was used to fill coconut coir mesh, aiming to provide 3D structural complexity and promote rubble binding without outplanting (Kenyon et al., 2025). The natural materials of the bag eventually biodegrade. Elevated frames (Fig. 1b and c) are hollow structures of various designs that provide an elevated surface above the sea bed and rubble substrate for coral outplants, or recruits that settle on the frames. These structures include A-frames, pyramid-shaped frames, and irregular-shaped metal frames (e.g. framed reef modules; Liu et al. (2024)), PVC frames (Chen et al., 2018), and designs such as Mars Reef Stars (Williams et al., 2019). The original, unprocessed survey data included elevated frames without outplants, but with only two data points from the same environment. Due to low replication, these data points were thus excluded, meaning that all elevated frames represented in the BBN involve the addition of outplants. Flat meshes and grids (Fig. 1d) are structures constructed from metal or plastic, laid flat directly onto loose rubble and pinned in place to limit rubble movement. Survey data for the BBN included both flat meshes with and without outplants. Solid structures (Fig. 1e and f) refer to non-hollow structures that provide an elevated and more extensive surface for coral recruits to settle. These include rocks, concrete blocks, and ceramic structures such as EcoReef modules. As with flat meshes, survey data for solid structures included cases with and without outplants. Elevated frames and solid structures can also indirectly limit rubble movement by reducing water flow around the structures. Some methods are more popular than others, due to their versatility and vast array of designs (Leung et al., 2024). Data from cases where elevated frames were used, for example, make up approximately 30 % of the case file used for CPT learning.

2.3. BBN design and data pre-processing

Raw data collected from the online survey was manually reviewed and pre-processed to minimize inconsistencies and ensure data quality. Data points were excluded if they lacked sufficient detail for inclusion in the BBN model or did not meet the following criteria: 1) values present for key outcome variables (recruitment-driven and outplant-driven coral cover; see Fig. 2); 2) presence of site-specific field information (e.g., laboratory-based experiments); and/or 3) represented by one of the four rubble stabilization method categories described in Section 2.2 (other

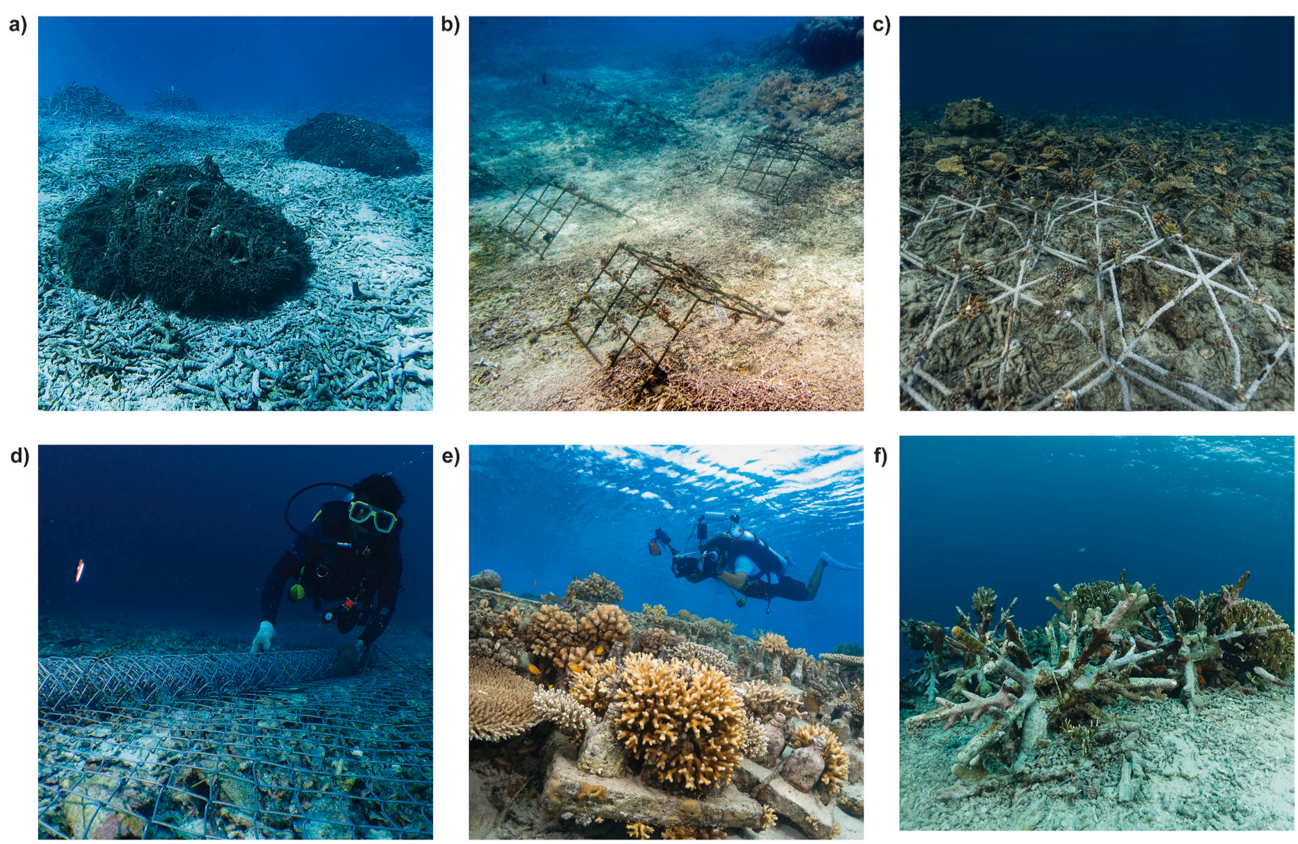


Fig. 1. Various stabilization methods of which restoration outcomes are included in the survey data: (a) Reef Bags installed at Bait Reef, Great Barrier Reef (direct manipulation of the substrate); (b) A-frames installed in the Nusa Islands, Indonesia (addition of structures as an alternative substrate); (c) Mars Reef Stars installed in Pulau Bontosua, Indonesia, arranged as an interconnected web following Mars Sustainable Solutions' recommendations (addition of structures as an alternative substrate); (d) Galvanized fencing mesh installed in Raja Ampat, Indonesia (addition of structures to restrict rubble movement); (e) Concrete blocks with embedded glass bottles installed in Pom Pom Island, Malaysia (addition of structures as an alternative substrate); and (f) EcoReef modules installed in Manado Tua, Indonesia (addition of structures as an alternative substrate). Photo credits: a) Conor Jones, BMT Australia, b) Andrew Taylor, Blue Corner Conservation, c) Mars Sustainable Solutions, d) Arnaud Brival, The Sea People, e) Robin Philippo, TRACC Borneo, f) Idris, The Indonesian Coral Reef Foundation.

methods that were too poorly replicated were excluded). In addition to excluding data that failed to meet these criteria, data regarding outcomes of interventions 10- and 20-year post-installation were also excluded. This was due to low replication, as most projects had only 1–2 years of data, with a few extending to 5 years. As a result, the final processed dataset contains 71 data points from 46 rubble-dominated sites.

The structure of the BBN was defined based on expert input from the workshop, focused on how environmental variables influence rubble stabilization, and in turn, the effectiveness of different interventions post-installation, for up to five years. Key variables were selected based on expert discussions, as they were identified as the most influential in determining intervention effectiveness. These variables include the main cause of rubble, rubble size, slope, wave exposure, current strength, water depth, and geomorphic zone. While additional variables, such as underlying substrate type and deposited sediment load on the substrate, were considered in the survey, the model focused on only the key variables to balance model complexity with data limitations. Stabilization methods varied in terms of whether corals were outplanted onto them or not, and thus whether outcomes were linked solely to natural recruitment, or also to the survival and growth of coral outplants. The response variables of the BBN disaggregated 'recruitment-driven' and 'outplant-driven' coral cover at the intervention site (%), coral cover on adjacent control rubble (%), and the 'benefits' of intervention in terms of coral cover (%) (Fig. 2). While the survey collected other restoration outcomes using metrics such as coral species composition, coral abundance, and the density of different life stages, we used coral cover as the response metric in the BBN because it had the most comprehensive data available. Although spillover effects are possible with restoration efforts, such as the contribution of coral larvae and fish biomass to nearby or downstream reefs (Cruz et al., 2014; Frys et al., 2020; Hernández-Delgado et al., 2018; Raymundo et al., 2007), the survey only considered data at the restoration site and did not include surrounding areas.

The term, 'benefits', reflect the additional coral cover that the intervention helped to establish, beyond what would have occurred without intervention. Benefits were calculated as the difference between recruitment-driven or outplant-driven coral cover at the restoration site and coral cover on control rubble (the counterfactual, indicating what would occur if rubble stabilization were not implemented at a site). *'Positive'* benefits indicate that the intervention resulted in higher coral cover than if the site had been left without intervention. *'Near-zero'* benefits suggest that the intervention had little impact on coral cover (regardless of whether the rubble had been successfully stabilized by the structure/method or not), as coral cover in this case was similar between stabilized and control rubble. *'Negative'* benefits imply that the intervention was unsuccessful or even detrimental, leading to lower coral cover than if the rubble had been left to stabilize on its own. Note that positive benefits do not necessarily mean that coral cover at the intervention site increased over time; rather, they could indicate that while coral cover remained constant or even declined slightly, the reduction was less severe than on the control rubble. Similarly, negative benefits do not necessarily imply that the intervention site experienced a decrease in coral cover; it could be that any gains were outpaced by larger increases in the control rubble, rendering the restoration efforts counterproductive.

To simplify the BBN structure, each environmental variable was categorized into two states to reduce entries required for completing the CPTs (Table 1). Survey responses were reclassified based on data distribution to correct inconsistencies. For example, there were some cases where experts qualitatively reported 'low' wave exposure (i.e., sheltered environment), but provided a quantitative measure of wave height that

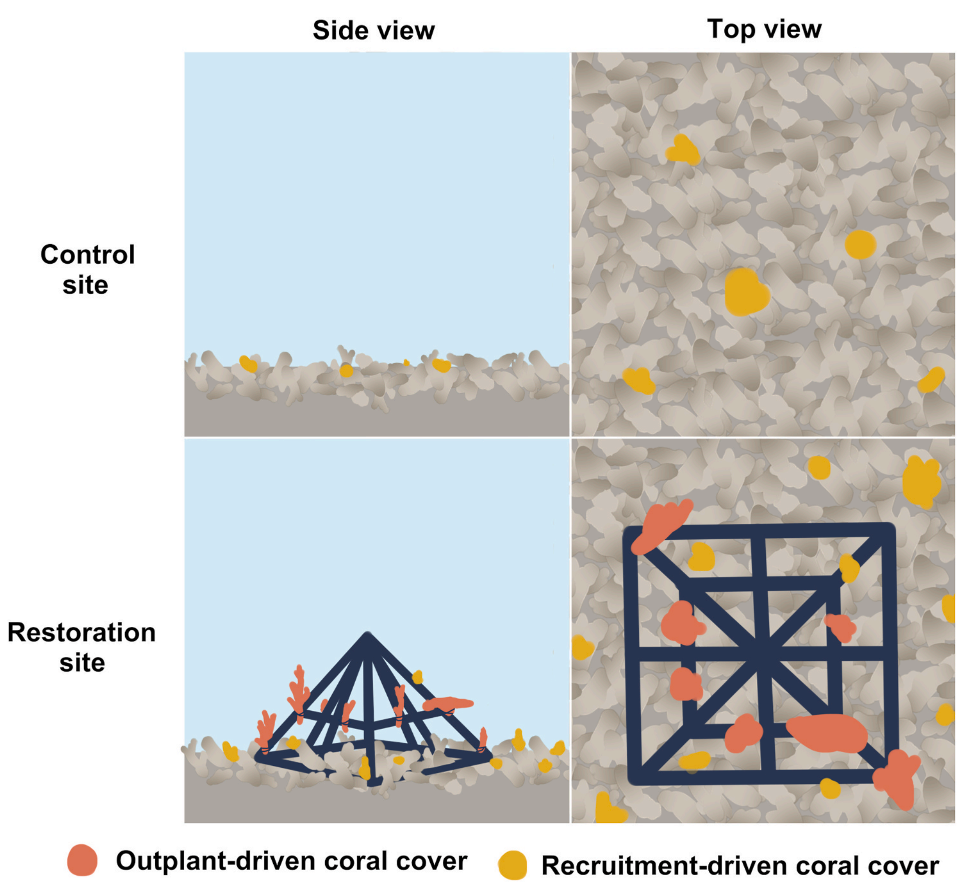


Fig. 2. Conceptual diagram showing side and top views of hypothetical control and restoration sites. Coral cover attributed to outplanting is shown in red, while recruitment-driven coral cover either on stabilization structures or surrounding rubble, is shown in orange.

was higher than what most respondents associated with a 'low' exposure environment. Instead of using the raw qualitative responses, which might be influenced by high subjectivity, we reclassified exposure levels using the quantitative distribution of wave height data. A latent variable, 'Hydrodynamic force', was also introduced to simplify the BBN structure. A latent variable refers to a variable that is not directly observed or measured in the dataset but still influences other variables in the network. Hydrodynamic force was categorized as 'strong' or 'weak' based on different combinations of wave exposure, current strength, and water depth. While hydrodynamic force was not directly measured in the survey, it represents an underlying factor suspected to influence stabilization effectiveness (Kenyon et al., 2023a; Viehman et al., 2018), based on expert knowledge and patterns of these environmental combinations.

Response variables (coral cover and benefits) were discretized based on the distribution of their values (Fig. S3). Narrower bins were used where observations tend to cluster were near zero to capture finer distinction. Broader bins were used for higher values where observations are sparser. The lower and upper bounds of these categories were set by the minimum and maximum values observed in the dataset. For example, recruitment-driven coral cover on structures was categorized as 0–1, 1–5, 5–10, 10–20, and 20–50 %. This discretization was also designed with management considerations in mind, aiming to capture subtle, early changes in coral cover following intervention, which may otherwise be overlooked with broader categories.

The condensed survey dataset was then formatted into a compatible 'case file' (.cas) for use with the learning algorithms in Netica using R version 4.3.1, as well as packages 'tidyverse' (Wickham et al., 2019) and 'MASS' (Venables and Ripley, 2002). A case file is a structured dataset that stores all observations recorded during the survey. Each observation (row) in the case file data frame includes a response (recruitment-driven and outplant-driven coral cover, coral cover on rubble, and benefits) based on a combination of input variables (method, time point, and environmental conditions), at a certain timepoint.

Table 1
Reclassification process of environmental variable categories in the BBN.

Variable	Categories	Recategorisation process
Wave exposure	Sheltered, Exposed	Reclassified as sheltered (<0.8 m significant wave height - H_S) and exposed (≥0.8 m H_S) based on reported wave height distribution (Fig. S1). All reef flats and lagoons were also classified as sheltered.
Zone	Reef flat/lagoon, Reef slope	Deep reef flats (>6 m) were reclassified as lagoons. An outlier 'lagoon' with unusually high wave heights (2 m) was reclassified as an exposed reef slope. For 'Other' or 'NA' responses, reclassifications were confirmed with experts after assessing site location using coordinates.
Slope	Flat to moderate, Steep to extreme	Five survey categories (flat, gentle, moderate, steep, extreme) were condensed into two: Flat to gentle (<20°) and Moderate to extreme (≥20°).
Main cause of rubble	Blast fishing, Other	Survey responses to the question of how rubble was generated were open-ended (text entry) and later condensed into two categories. Blast fishing generally results in much smaller rubble than that created from other types of disturbances (Fox and Caldwell, 2006; Fox et al., 2003). 'Other' disturbances include tourism (e.g., trampling, human contact with corals), wave action, coastal development, earthquakes, fishing nets, boat anchors, reef clearing, coral mining, ship groundings, and storms (cyclones, hurricanes, typhoons).
Water depth	Shallow, Deep	Sites with depths of 0–5 m (inclusive) were classified as shallow, while those between >5 and 20 m were classified as deep.
Rubble size	Small, Large	Reclassified as Small (≤10 cm) and Large (>10 cm).
Current strength	Weak, Moderate to strong	Reclassified as weak (<0.5 m/s) and moderate to strong (≥0.5 m/s) based on reported current speed distribution (Fig. S2).

2.4. Construction of CPTs by learning

The BBN was trained using 192 observations extracted from survey responses and Netica's built-in expectation maximization (EM) algorithm for parameter learning. The EM algorithm comprises two steps: (1) Expectation step, where missing data for certain input variable combinations are estimated through Bayesian inference, and (2) Maximization step, where the BBN parameters are updated based on the estimated data, iteratively improving the log likelihood (i.e., how well the model explains the observed data) until the model is considered 'best fit' given the observations (Norsys Software Corporation, n.d.). For example, some survey responses lack precise classification of rubble size, and were marked as uncertain in the BBN case file. In the expectation step (E-step), the model estimates the probability that each site with missing rubble size information falls into either the 'small' or 'large' category, based on the current state of the BBN and the relationships between rubble size and other variables. In the maximization step (M-step), once the missing data (rubble size) has been estimated, the model updates the conditional probability tables (CPTs) using both the observed data and the newly inferred values to maximize the log likelihood. The EM algorithm is also compatible with latent variables (Norsys Software Corporation, n.d.), making it suitable for this study, where hydrodynamic forces were modeled as a latent variable. The CPT for hydrodynamic forces was computed using Bayesian inference and correlations among its connected nodes, including wave exposure, current strength, and water depth.

2.5. Model evaluation and manual adjustments

Sensitivity analysis was conducted using Netica's built-in function, 'Sensitivity to Findings', which assesses how changes to input nodes affect recruitment-driven and outplant-driven benefits (i.e., mean difference between coral cover on stabilization structures and coral cover on control rubble). To evaluate model performance and prevent overfitting, a three-fold cross-validation approach was applied (Aguilera et al., 2011). The dataset was randomly divided into three subsets, with each subset containing 64 observations, used alternately for training and testing. Specifically, the model was trained on two subsets (128 observations in total) and tested on the remaining one, ensuring that every case was used for both training and validation. For the final product intended for end users, the model was trained using all 192 observations. The 'Test Net Using Cases' function in Netica was used to compute accuracy rates and generate confusion matrices, with results averaged across all three runs to provide an overall performance measure.

Following model evaluation, manual adjustments to the CPTs were necessary to address missing entries that persisted after training. Missing probability values were inferred based on the most similar environmental conditions with available data. For example, if CPT data were unavailable for Reef Bags at a site with small rubble, a flat to gentle slope and strong hydrodynamic forces, probabilities were adapted from the closest comparable environment. For this particular case, values were applied from a trial of Reef Bags in a site with similar slope and hydrodynamic energy, but on large rubble.

To ensure consistency in these adjustments, several key assumptions were made. For Reef Bags, the probability distribution of recruitment-driven coral cover on smaller rubble was adjusted by a one-year offset on flat to gentle slopes. It was assumed that, upon disintegration of Reef Bags after one year (Kenyon et al., 2025), coral cover on smaller rubble would stall initially due to increased mobility of small rubble compared to larger rubble. Over time, as the rubble binds and stabilizes, coral cover on Reef Bags filled with small rubble is expected to converge with that of Reef Bags filled with larger rubble, though at a slower rate. On moderate to extreme slopes, coral cover was assumed to drop to 0–1 % after one year due to slumping of the bags. For flat meshes and grids, coral cover was assumed to be independent of rubble size on flat to gentle slopes, as practitioners would match mesh size to rubble size so that stability was achieved in either case. On moderate to extreme slopes, lower coral cover was expected due to increased instability and the risk of burial of the mesh by rubble higher up on the slope, especially in the case of small, more mobile rubble. For elevated frames and solid structures, coral cover was assumed to be similar across different categories of rubble size and slope, because corals on elevated surfaces are less impacted by rubble movement or burial at the level of the substrate. Further information pertaining to missing input combinations is provided in section 3.2 BBN Limitations (Table 2).

Lastly, the resulting BBN was visualized using R version 4.3.1 and packages 'ggplot2' (Wickham, 2016), 'ggpubr' (Kassambara, 2023), and 'cowplot' (Wilke, 2024) to show the effectiveness of different stabilization methods, represented by marginal posterior probability distribution and expected average coral cover. The expected value was calculated as the weighted average of possible outcomes, adjusted by their probability of occurrence (Norsys Software Corporation, n.d.). The recruitment-driven and outplant-driven coral cover were compared over time across eight combinations of input variables including rubble size, slope, and hydrodynamic forces. Each of the three variables has two possible states—rubble size (small or large), slope (low or high), and hydrodynamic forces (weak or strong), thus creating eight unique combinations of scenarios. The three variables were investigated individually to assess their contribution to intervention effectiveness.

3. Results

3.1. Overview of the BBN

The BBN illustrates the benefits, i.e., the difference in coral cover due to intervention compared to natural recovery in rubble, of installing rubble stabilization structures in different environments (Fig. 3). The BBN incorporated nine input variables, including six method categories, four time points, seven environmental variables (each with two categories), and five continuous output variables.

3.2. Model evaluation

A 3-fold cross-validation of the model indicated that the accuracy of the learned model prior to manual editing using expert knowledge was 74 ± 7 % (mean ± SD) for the output node *Benefits (recruitment-driven coral cover %)* and 69 ± 12 % (mean ± SD) for *Benefits (outplant-driven coral cover %)*. The confusion matrices for recruitment-driven and outplant-driven benefits show that most predictions align with actual data, with the highest values mostly found along the diagonal line (Table S1, Table S2). For recruitment-driven benefits, the BBN tends to perform more accurately in middle ranges but struggles with extreme values, overestimating benefits in lower coral cover categories and underestimating in higher coral cover categories. Whereas for outplant-driven benefits, the model performed least accurately in the middle ranges, likely due to insufficient data in those ranges.

The sensitivity analysis revealed that the most influential input variables on the benefits of restoration were *Time since installation* for *Benefits (recruitment-driven coral cover %)* and *Rubble stabilization method* for *Benefits (outplant-driven coral cover %)*, which accounted for 11.8 % and 14.2 % variance reduction, respectively (Table S3, Table S4). Among all the environmental variables analyzed, both benefit variables showed the highest sensitivity to rubble size, with variance reductions of

Table 2
Major caveats and data limitations for using the BBN by methods and environments.

Method	Number of unique environments where the method is applied	Major caveats and advice	
		Recruitment-driven coral cover/benefits	Outplant-driven coral cover/benefits
Reef Bags (NOP)	3	The BBN has data for varied environmental combinations including flat to gentle slopes and large rubble. Predictions are more reliable for these conditions over time periods of one to three years. Data for five-year projections carries higher uncertainty.	Not applicable
Elevated frames (OP)	15	The BBN has data for all combinations involving flat to gentle slopes. Predictions are more reliable for these conditions over all time points. Some data is available for combinations with moderate to extreme slopes, mostly under strong hydrodynamic forces. There is limited data for moderate to extreme slopes with weak forces.	The BBN has data primarily for flat to gentle slopes, or with strong hydrodynamic forces at lower outplant-driven coral cover (0–35 %) at the time of installation. Predictions are most reliable for these conditions over all time points.
Flat meshes or grids (NOP)	3	The BBN has data for various combinations of slope, hydrodynamic forces, and rubble sizes over one-, three-, and five-year periods. There are some gaps for the two-year time period, particularly for moderate to extreme slopes, strong hydrodynamic forces and small rubble size.	Not applicable
Flat meshes or grids (OP)	8	The BBN has data mainly for large rubble across varied slopes and hydrodynamic forces. The model can provide reliable predictions only up to the three-year mark.	The BBN can only provide estimates for up to three years when outplant-driven coral cover at installation is 0–35 % and up to one year when cover is 35–100 %, due to a lack of data. Predictions are most reliable for combinations with large rubble or weak hydrodynamic forces.
Solid structures (NOP)	6	The BBN can reasonably predict outcomes, particularly at the two-year and five-year time points. While there is also data for one- and three-year post-installation, there are significant gaps for combinations with moderate to extreme slopes, or flat to gentle slopes with strong hydrodynamic forces.	Not applicable
Solid structures (OP)	10	The BBN has data for all combinations involving flat to gentle slopes, except for one scenario: flat to gentle slopes with weak hydrodynamic forces and large rubble at five years. Data involving moderate to extreme slopes and small rubble on these slopes are generally limited.	The BBN can only provide estimates for up to three years when outplant-driven coral cover at installation is 35–100 % due to the lack of data. Predictions are more reliable for environments with flat to gentle slopes.

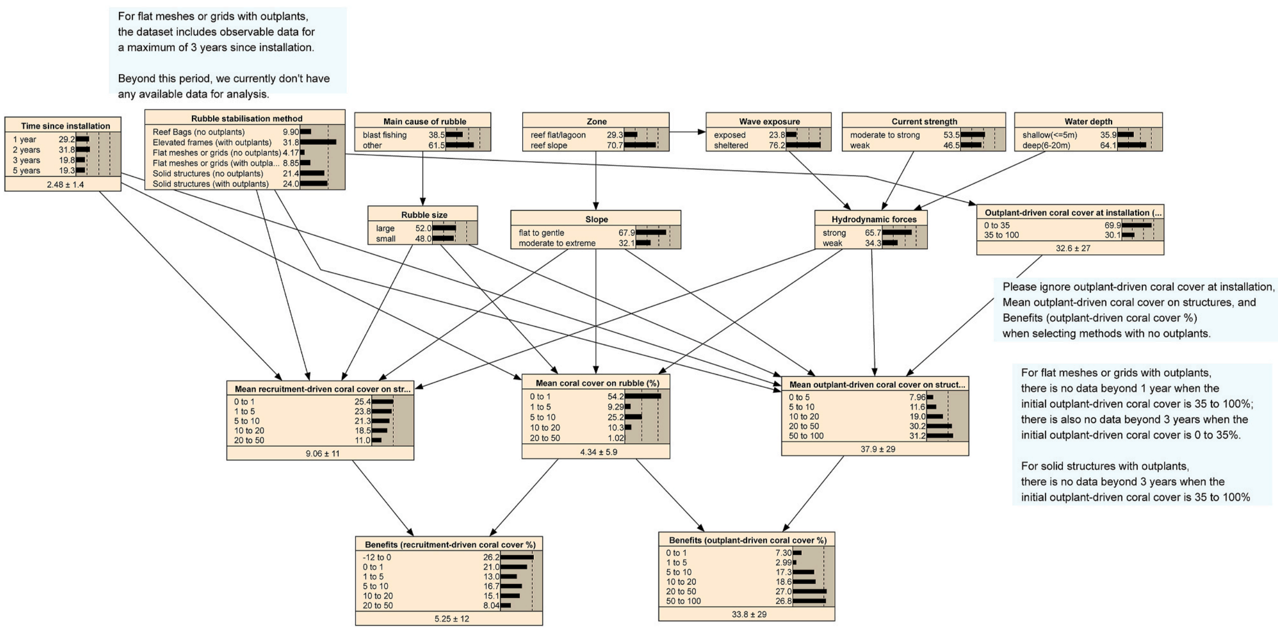


Fig. 3. The Netica user interface showing the structure of the BBN and the states of its different variables. The BBN calculates prior probabilities of variable states based on case files (survey records) using the EM algorithm in Netica, meaning that the likelihood of a node being in a certain state reflects the data distribution across different methods and environment.

2.6 % for recruitment-driven benefits and 1.55 % for outplant-driven benefits.

3.3. Model predictions

3.3.1. Rubble stabilization effectiveness across methods

Regardless of stabilization method, the probability of gaining greater benefits increased over time (Fig. 4a). Notably, flat meshes and grids with no outplants (hereafter NOP) consistently performed best over time, exhibiting the highest probability of achieving 20–50 % recruitment-driven benefits, surpassing methods that provide vertical relief such as solid structures. These methods also achieved greater benefits faster, with a 35 % chance of having a 20–50 % benefit after two years, and an 85 % chance after five years. Reef Bags and solid structures

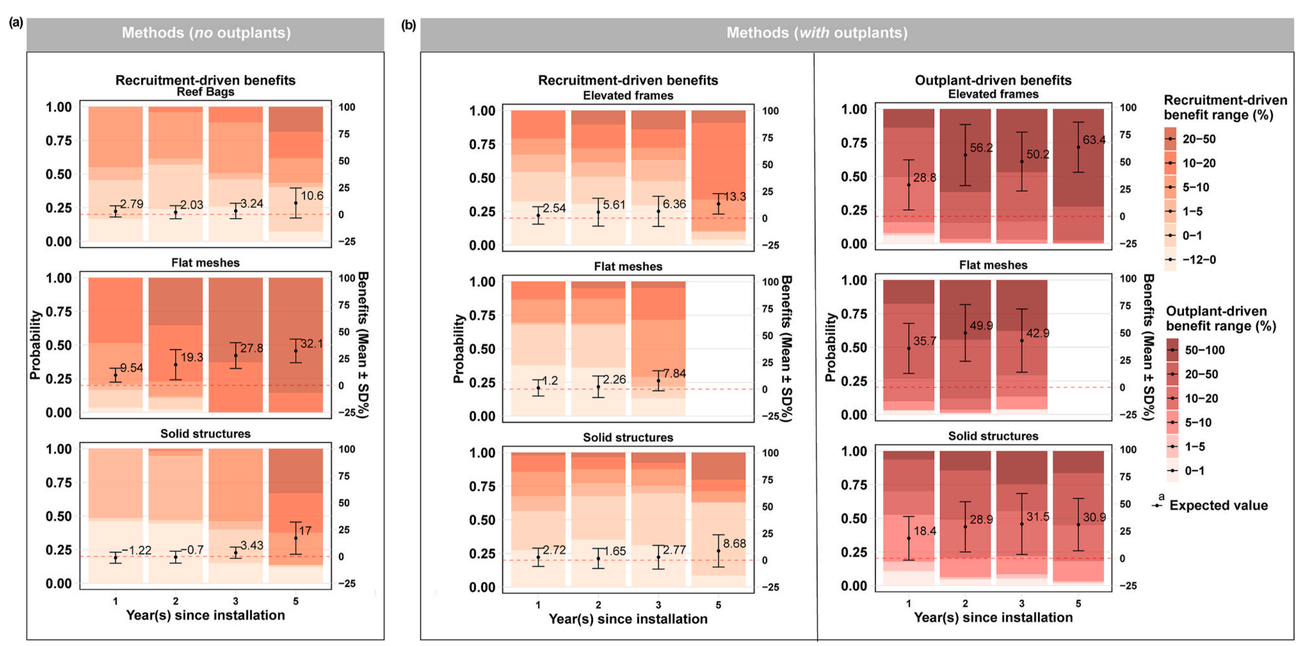


Fig. 4. Marginal posterior probability distribution and expected values of recruitment-driven and outplant-driven benefits (%), for rubble stabilization methods installed (a) without coral outplants and (b) with corals outplanted onto structures over time. The terms 'recruitment-driven benefit' and 'outplant-driven benefit' refer to benefits in terms of coral cover attributed to natural recruitment and coral outplants on the structures, respectively. The x-axis represents time (years) since the installation of stabilization methods. The primary y-axis (left) indicates the probability that benefits will fall within specified ranges (Recruitment-driven benefits shown in orange gradient, and outplant-driven benefits shown in red gradient). The secondary y-axis (right) shows the expected average recruitment-driven or outplant-driven benefit (%). The horizontal red dotted line indicates 0 % benefits. Error bars represent the standard deviation of the expected value. There is no data for flat meshes and grids with outplants at five years since installation.

(NOP) were unlikely to exhibit 20–50 % benefits in recruitment-driven coral cover until after three years. However, installing solid structures was more likely to result in higher coral cover at intervention sites after five years, compared to Reef Bags.

For methods with outplants, the benefits attributable to outplants were greater than those attributable to natural recruitment (Fig. 4b). Elevated frames with outplants (hereafter OP) had the highest chance (72.3 %) of achieving 50–100 % outplant-driven benefits within 5 years. However, the relative contribution of recruitment-driven and outplant-driven coral cover shifted over time, as reflected in the changing ratio of recruitment-driven to outplant-driven benefits. For example, between two and five years after installation, solid structures (OP) showed growing recruitment-driven benefits, likely reflecting increased recruitment, while outplant-driven benefits remained relatively stable.

For the same methods with and without outplants (OP and NOP), OP always provided additional outplant-driven benefits on top of recruitment-driven benefits (Fig. 4), though the extent of this varied among methods. When comparing the total benefits (recruitment-driven *plus* outplant-driven) from OP with the recruitment-driven benefits of NOP, the difference was greater for solid structures than for flat meshes from 2 years post-installation onwards. By year 3, the mean recruitment-driven benefit of solid structures (NOP) was 3.4 %, while the addition of outplants meant that mean total benefit of solid structures (OP) reached 34.3 %, resulting in a difference of 30.8 %. In contrast, the difference for flat meshes and grids at year 3 was smaller at 22.9 %.

3.3.2. *Influence of initial outplant-driven coral cover on rubble stabilization effectiveness*

Although outplants provide an immediate boost in coral cover, the effect size was influenced by the initial number of outplants at the time of installation (Fig. 5, Fig. S4). Outplant-driven benefits increased up to two years post-installation, regardless of initial outplant-driven coral cover. Where initial outplant-driven coral cover was lower (0–35 %), benefits continued to increase up to the five-year mark (54.6 %). However, where initial cover was high (35–100 %) benefits steadily declined after the two-year peak (58.9 %), and at five years (30.0 %) dropped below the one-year benefit level (39.6 %).

3.3.3. *Rubble stabilization effectiveness across environments*

Averaged across methods, the model predicted the greatest recruitment-driven benefits within the shortest time frame for environments characterized by small rubble (Table 1), moderate to extreme slopes, and strong hydrodynamic forces (Fig. 6a). Conversely, in environments with large rubble, flat to gentle slopes, and weak forces, increases in recruitment-driven benefits occurred during the first three years, but then declined, leading to recruitment-driven benefits of only 6.2 % at year 5. On the other hand, in environments with small rubble, higher outplant-driven benefits - derived from stabilization methods - only occurred under strong rather than weak hydrodynamic forces, regardless of slope. For most environments, the outplant-driven benefits declined or plateaued by year 3, except for environments with large rubble, moderate to extreme slopes, and weak forces, which increased steadily to 52 % at year 5 (Fig. 6b).

Looking more closely at individual stabilization methods, the relationship between environmental conditions and benefits becomes more complex and varies across methods. Most methods generated greater recruitment-driven and outplant-driven benefits in small rubble. However, Reef Bags (NOP) and flat meshes and grids (OP) showed the opposite trend, with both benefits being smaller in small rubble (Fig. S5). Slope angle appeared to be a weaker driver than rubble size. For solid structures (with or without outplants), recruitment-driven and outplant-driven benefits differed little between slope categories, whereas for elevated frames, outplant-driven benefits were similar across slope (Fig. S6). For Reef Bags, recruitment-driven benefits on moderate to extreme slopes remained near zero and even became negative after two years. Finally, when considering hydrodynamic forces, all methods with outplants had greater outplant-driven benefits in sites with strong compared to weaker forces, across all time points (Fig. S7). Recruitment-driven benefits were also generally higher in sites with stronger forces (except for solid structures (OP) and flat meshes and grids (OP)).

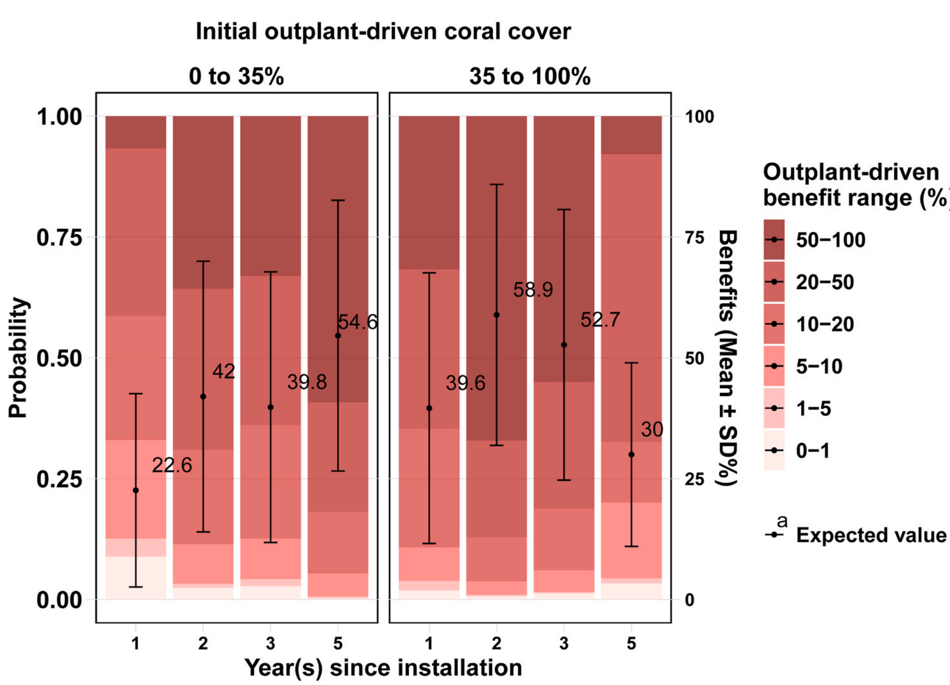
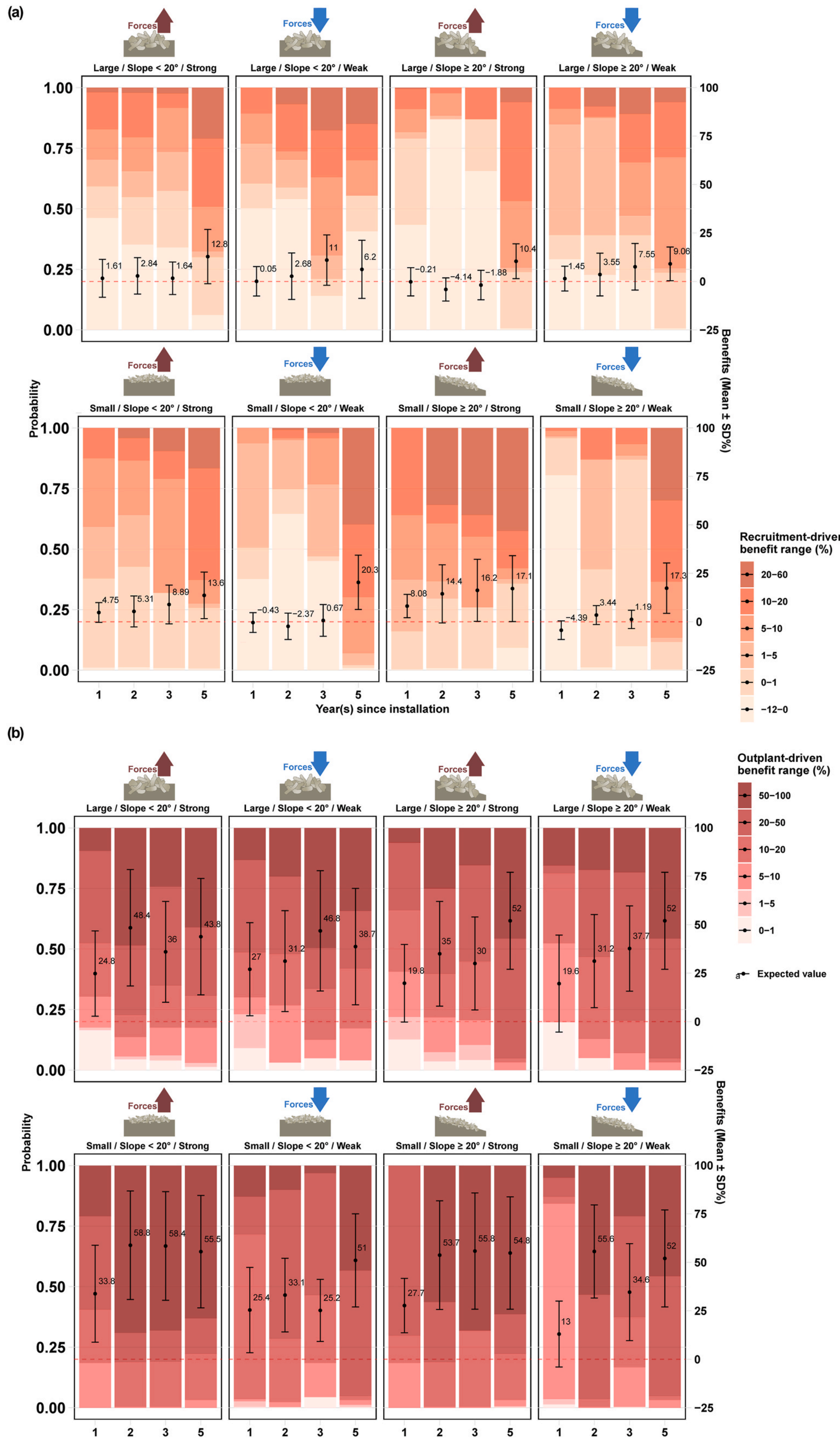


Fig. 5. Marginal posterior probability distribution and expected values of outplant-driven benefits (%) over time for two categories of initial outplant-driven coral cover: 0–35 % and 35–100 %, averaged across all methods with outplants (except flat meshes and grids with outplants at the five-year time point due to a lack of data). The x-axis represents time (years) since the installation of stabilization methods. The primary y-axis (left) indicates the probability of benefits falling within specified ranges (red gradient), while the secondary y-axis (right) shows the expected average benefit (%).



(caption on next page)

Fig. 6. *Marginal posterior probability distribution and expected (a) recruitment-driven (b) outplant-driven benefits (%) across eight environments over time, averaged across stabilization methods. Small/Large indicates small (*<10 cm*) or large (*>10 cm*) rubble size; Slope (*<20°*)/(*≥20°*) indicate flat to gentle or moderate to extreme slope angles; and Weak/Strong indicate weak or strong hydrodynamic forces. The x-axis represents time (years) since the installation of stabilization methods. The primary y-axis (left) indicates the probability of benefits falling within specified ranges (Recruitment-driven benefits shown in orange gradient, and outplant-driven benefits shown in red gradient), while the secondary y-axis (right) shows the expected* average *benefit (%). The horizontal red dotted line indicates 0 % benefits. Error bars represent the standard deviation of the expected value.*

4. Discussion

The model predicts that rubble stabilization commonly leads to an increase in benefits over time, in terms of coral cover, emphasizing the role of active restoration in addressing the growing prevalence of rubble on coral reefs (Kenyon et al., 2023a, 2023b). Although published literature on stabilization method effectiveness is limited, this finding has been highlighted in several previous studies assessing methods including flat meshes (Raymundo et al., 2007), rock piles (Fox et al., 2019) and Mars Reef Stars (Vida et al., 2024). Without intervention, loose, unstable rubble beds can persist for years or even decades with limited recovery (Brown and Dunne, 1988; Cameron et al., 2016; Chong-Seng et al., 2014; Dollar and Tribble, 1993; Fox et al., 2003; Raymundo et al., 2007; Victor, 2008). In many cases, rubble stabilization interventions enhance coral cover and have important implications for reef management and conservation (Ceccarelli et al., 2020). Yet, outcomes are variable in terms of methods and environments, and long-term gains are not always realized despite substantial investment.

Considering different methods, flat meshes and grids were shown to outperform solid structures (e.g., rocks, concrete blocks, EcoReef modules) in terms of both recruitment-driven and outplant-driven benefits. Stabilized coral rubble provides a suitable substrate for coral recruits to settle when environmental conditions are favorable (Babcock and Mundy, 1996; Edmunds et al., 2004; Yadav et al., 2015), and flat meshes contribute to substrate stability by physically pinning rubble (Raymundo et al., 2007). This can mitigate post-settlement mortality (Chong-Seng et al., 2014; Victor, 2008), resulting in coral cover benefits with limited vertical relief. In contrast, solid structures provide vertical relief and restore rugosity to a flattened rubble bed, creating elevated surfaces for coral recruits above the level of the substrate (Ceccarelli et al., 2020; Edwards and Gomez, 2007). The elevation helps to prevent corals from being abraded or buried by rubble movement at the substrate level (Fox et al., 2005). While both methods can be successful under the right conditions, we anticipated greater benefits for solid structures compared to flat meshes or grids. One possible explanation for this is that some of the solid structures (OP) are cement-based, and may require a conditioning period for the development of an appropriate biofilm before becoming suitable for recruitment (Clark and Edwards, 1999), delaying positive benefits. Furthermore, the pinning action of meshes/grids may enhance the degree of rubble stability while still facilitating access to light and flow (depending on mesh hole size, e.g., (Kenyon et al., 2025)). Solid structures completely cover the rubble beneath them, and while rubble between structures is likely to be more stable owing to reduced hydrodynamic energy, it may not be as stable as under a mesh. The enhanced benefits of flat meshes in the BBN might also be attributable to sampling bias in the dataset. Many solid structures were deployed in the Caribbean, where slow-growing corals such as *Orbicella* spp. and *Porites* spp. are common (Gladfelter et al., 1978), and recovery rates are generally slower than those in the Indo-Pacific (Roff and Mumby, 2012). In contrast, most flat mesh sites were in SE Asia, where conditions and coral species differ. For example, one of the mesh sites was located in the Calagcalag Marine Protected Area, central Philippines, where coral recruitment is high and unstable rubble is the primary barrier to recovery (Raymundo et al., 2007). High recruitment likely contributed to the rapid increase in coral cover at such sites. Furthermore, structurally complex rocks were also added to the mesh in this project. It should be acknowledged that the survey data were collected in different years, with some projects more recent (e.g., MARS Reef Stars) than others. Two studies were carried out more than ten years ago: Raymundo et al. (2007), and Clark and Edwards (1994). Unfortunately, geographic location, temporal differences, and coral composition could not be accounted for in the model due to data paucity, limiting our ability to ascertain the efficacy of different types of methods.

Regardless of stabilization method, the BBN showed that methods used in combination with outplants are likely to deliver more immediate benefits, intuitively providing a quick boost in coral cover. Coral outplanting, when combined with rubble stabilization, is particularly useful in accelerating reef recovery where recruitment is limited by low larval supply (Boström-Einarsson et al., 2018; Clark and Edwards, 1995; Edwards, 2010; Edwards and Gomez, 2007). The magnitude of the effect of outplanting differed, however, among methods, evidenced when comparing methods that had both OP and NOP variants. In the case of flat meshes and grids, the benefits were already relatively high without outplants (NOP), so the added value of outplanting (OP) was smaller. In contrast, outplanting made a bigger difference for solid structures, and relying solely on natural recruitment (in NOP) resulted in only minor benefits within the surveyed period. This could be due to the elevation and subsequent enhanced survival of corals outplanted onto solid structures like rocks (Leung et al., 2024). Furthermore, attaching outplants to flat meshes can be less practical than on solid structures. Outplants on meshes often require zip ties, which can be less effective in terms of breakage than adhesives like cement, which are commonly used on solid structures (Raymundo, *pers. comm.*). However, due to a lack of data beyond three years for flat meshes and grids with outplants, it is difficult to determine if outplants are more effective in the long term for either method. It is important for future studies to compare flat and elevated methods within the same environmental conditions to assess their efficacy.

While the initial boost in coral cover was predominantly driven by outplants for OP methods, the balance between natural recruitment and outplant-driven benefits shifts over time. Thus, natural recruitment may eventually play a greater role in reef recovery than outplant growth. Methods without outplants showed higher recruitment-driven benefits compared to those of the same methods with outplants. For example, three years after installation, flat meshes and grids (NOP) most often had 20–50 % more coral cover than nearby control sites, compared to only 5–10 % more coral cover for the same method *with* outplants (OP). In other words, at sites installed with flat meshes or grids (OP), natural recruitment still occurred but at much lower levels than NOP variants, so benefits were driven mostly by outplants. One possible explanation is that experts are more likely to opt for outplanting in recruitment-limited sites, to offset expected low natural recruitment. Outplanting at sites with sufficient larval supply may not be cost-effective due to the substantial expenses and labor required for installation and maintenance (Edwards and Gomez, 2007). Furthermore, it can become challenging to distinguish the cover of outplants versus naturally recruited corals if outplants are not tagged (Nicholson, pers. comm.), thus natural recruitment could be underestimated. Finally, high densities of outplants may also reduce available space for recruits to settle, potentially limiting the contribution of natural recruitment to overall coral cover. For example, natural coral recruitment was minimal at the Mars Reef Star site at Moore Reef on the Great Barrier Reef over a monitoring period of two years, possibly due to the extensive cover of outplants occupying much of the available substrate (Fisher, pers. comm.).

The BBN supported the supposition that initial outplant cover does affect longer-term benefits. Notably, while higher initial outplant-driven coral cover (35–100 %) led to greater *immediate* benefits, declines in these benefits occurred over time. This could be attributed to density-dependent effects on coral growth, competition and predation (Ladd et al., 2016). At higher densities, coral outplants often compete for space and resources (Goergen and Gilliam, 2018; Rinkevich, 2014), and corallivores may find it easier to feed on corals due to the increased availability of prey (Moerland et al., 2016; Morton and Blackmore, 2009; Roff et al., 2011). Reports of corallivorous *Drupella spp.* predation on coral outplants by survey respondents align with these patterns (Edmondson, pers. comm.; Voorhuis, pers. comm.). That said, these patterns are not universal. For example, two years of monitoring at Moore Reef, Great Barrier Reef, found no difference in juvenile crown-of-thorns starfish density between Mars Reef Stars restoration sites and nearby rubble sites during the first two years of monitoring (Fisher, pers. comm.), suggesting other site-specific factors may mediate predator responses. Another factor contributing to the reduced benefits could be that coral mortality is more apparent when coral cover is initially high, and disease spreads more easily at high density (Yakob and Mumby, 2011). The decline in benefits with high initial outplant-driven coral cover predicted by the BBN should not, however, be used as evidence to outplant fewer corals, considering the limited temporal understanding. The long-term (e.g., decadal) trajectory of coral cover was not fully captured in the Bayesian network and thus remains uncertain.

Environmental factors, including rubble size, slope angle, and flow velocity significantly influence rubble mobilization and binding capacity (Kenyon et al., 2023a), thus affecting the effectiveness of stabilization interventions. Furthermore, due to differences in design and materials, stabilization methods vary in performance, and in their fragility in certain environments (Leung et al., 2024). The BBN found that stabilization methods are most likely to achieve the greatest benefits in environments characterized by smaller rubble, steeper slopes, and stronger hydrodynamic forces. Small rubble pieces are more susceptible to movement and transport (Edwards and Clark, 1994; Kenyon et al., 2023b, 2024), leading to substrate instability that can hinder coral recruitment, growth, and survival (Brown and Dunne, 1988; Fox et al., 2003; Kenyon et al., 2020). As a result, the counterfactual coral cover on small rubble is likely to remain low over time, meaning any increase in coral cover on the structure will result in a substantial benefit. Conversely, the benefits of stabilization methods installed on larger rubble would be comparatively lower owing to the inherently greater stability of larger rubble pieces (Gischler and Ginsburg, 1996; Kenyon et al., 2024). In fact, stabilization may be unnecessary in some cases for rubble beds comprising large pieces, because they are more likely to interlock, bind and provide a stable environment for coral survival and growth (Kenyon et al., 2024; Leung et al., 2024).

Curiously, while most methods yielded higher benefits on small rubble, Reef Bags (NOP) and flat meshes and grids (OP) performed better in sites with *larger* rubble. For Reef Bags, after biodegradation of the coir netting ~1 year after installation, the rubble pile is *no longer* contained by the netting and is more prone to slumping. Thus, if Reef Bags are filled with small rubble, the pile may become flatter at this stage as pieces shift and are transported away. As a result, restoration sites where Reef Bags have been filled with small rubble would be expected to have lower coral cover and lower benefits compared to if they are filled with larger rubble, which would remain better interlocked and stable after bag disintegration. However, since Reef Bags have not been tested on smaller rubble, these results are based solely on assumptions. As such, this is a key example that demonstrates how missing information is handled in the BBN and how qualitative and quantitative data are integrated within the network. For flat meshes and grids (OP), small, loose rubble bordering and moving onto the structures might cause more damage to growing coral outplants, leading to lower benefits for small rubble. On the other hand, corals outplanted onto other methods like elevated frames and solid structures are less impacted by substrate mobility driven by smaller rubble, provided that the structures are well-anchored. As such, coral cover driven by outplants for these methods was expected to be higher than for flat meshes or grids, thus having greater benefits when the coral cover at the control rubble site remains low over time.

In addition to rubble size, slope angle was another important driver of benefits. Most methods showed higher benefits on moderate to extreme slopes, where rubble is more likely to be unstable. On steeper slopes, avalanches of rubble and sand can occur where rubble continually shifts downslope under the influence of gravity, leading to persistent instability and reduced coral cover (Harmelin-Vivien and Laboute, 1986). Restoring steeper slopes requires strong anchoring to prevent downslope movement; without this, stabilization may be ineffective (Leung et al., 2024). In practice, stabilizing rubble on steep slopes often requires additional resources, specially designed methods, and ongoing maintenance, making it unfeasible in some contexts. For example, on Pom Pom Island in Malaysia, a special design was used for steep slopes, where concrete blocks were secured in a staircase-like arrangement using metal rods to prevent dislodgement of the structures (Stacey, 2020). The relatively high benefits of flat meshes and grids (NOP) on steeper slopes are unexpected, however, as they can be prone to burial by rubble from unprotected upper parts of the slope (Ceccarelli et al., 2020). However, such benefits could be plausible if complementary measures are implemented to reduce burial risk, such as installing barrier fences upslope to prevent rubble from sliding down (Leung et al., 2024). For example, one of the cases in the dataset involved flat meshes with attached outplants in Raja Ampat, Indonesia, where barrier fences were installed on the upper slope to reduce burial risk (Brival, pers. comm.). An increase in coral cover at the site was reported for over four years, suggesting that landscaping considerations can play an important role in restoration outcomes.

Hydrodynamic energy played a key role alongside rubble size and slope angle. The majority of methods deployed at sites with strong hydrodynamic forces achieved greater benefits. Loose rubble is more susceptible to movement in exposed areas with higher hydrodynamic energy (Kenyon et al., 2023b). However, provided structures are securely anchored and rubble is sufficiently stabilized, increased water flow can deliver more nutrients to corals for heterotrophic feeding, while also resuspending deposited sediment and preventing smothering (Jokiel, 1978; Rogers, 1990; Sebens et al., 1998). As such, sites with stronger hydrodynamic forces could yield enhanced benefits for coral recovery. Contrastingly, however, certain methods such as flat and solid structures with outplants show greater recruitment-driven benefits under weak hydrodynamic forces compared to strong forces, opposing the trend observed for outplant-driven coral cover on the same method. This could be driven by the fact that recruits settle onto both the structure and proximal rubble surrounding the structures (spillover), though we lack sufficient data to determine their relative contributions to coral cover. In contrast, outplants are physically attached only to the structures using adhesives, metal wires, or zip ties (Leung et al., 2024). Coral recruits that settle on stabilized rubble can still experience some degree of movement and are, therefore, more vulnerable to damage by loose, surrounding rubble mobilized by strong hydrodynamic forces. In contrast, outplants that are physically attached to structures benefit from a much higher level of stability, making them less vulnerable to displacement or detachment. As a result, outplants are more likely to thrive under strong hydrodynamic forces, while recruits may perform better in weaker forces, as strong forces can be too disruptive for them.

4.1. Limitations and pathways forward for the BBN

Although the BBN provides a good overview of current expert knowledge, the results do not represent all environments or stabilization methods equally (Table 2, Table S5, Table S6, Table S7). There may be greater uncertainty in environments where restoration efforts have rarely taken place. For example, experts tend to avoid initiating projects in conditions where failure is likely, which may have resulted in an overrepresentation of environments that are more favorable for coral recovery, such as relatively sheltered sites. Projects are also often undertaken in more sheltered environments due to logistics relating to site access and diver safety. Additionally, some methods are more represented than others, such as elevated frames, which are popular due to their versatility, affordability, potential for community-led approaches, and include a vast array of different designs (Leung et al., 2024). Despite the limited dataset, the model demonstrated acceptable accuracy in estimating benefits (74 and 69 % accuracy for recruitment-driven and outplant respectively). However, varying accuracy across data subsets suggests potential overfitting (Aguilera et al., 2011; Dietterich, 1995). To improve reliability of the model, additional variables such as geographical location, disturbance regimes, and other outcome metrics of reef resilience could be incorporated. Incorporating more variables would demand substantially more data, which is not available currently, as well as increased computational resources to manage the added complexity of the BBN structure.

The outputs of the BBN tend to show greater uncertainty at later time points, as most projects recorded in the survey were conducted over short periods, typically only one to two years. A recent review indicated that many active coral restoration projects have short monitoring periods, with 60 % of projects reporting less than 18 months of monitoring (Bostrom-Einarsson et al., 2020). As an example, in Indonesia, only 16 % of the 533 projects conducted between 1990 and 2020 reported post-installation monitoring at all (Razak et al., 2022). Moreover, BBN faces challenges due to the subjectivity of expert opinion, particularly regarding the interpretation of environmental conditions and rubble characteristics, which adds to the uncertainty. Currently, rubble-related terminology remains inconsistent, although efforts have been made to characterize different rubble bed types and their implications for stability, binding and recovery outcomes (Kenyon et al., 2024; Leung et al., 2024).

Enhancing the BBN's reliability and value for reef management requires more research, standardized terminology, improved data-sharing, and inclusion of additional benefit metrics and considerations. Further research and long-term monitoring data are required to make reliable predictions about stabilization benefits over longer temporal scales and across broader environmental gradients. In addition, standardizing rubble terminology and classification of environment types would improve future analysis by reducing ambiguity and improving consistency in model predictions. Broader data sharing outside of peer-reviewed literature, as well as the inclusion of unsuccessful efforts and known causes for lack of success, would greatly accelerate these processes. Coral cover is just one of many factors managers must consider when deciding whether to pursue rubble stabilization. Some prioritize ecosystem resilience and therefore focus on metrics such as recruitment rates and larval supply (Anthony et al., 2015; McLeod et al., 2019). Moreover, other considerations, such as logistics, costs, and project scale, are also critical, though beyond the scope of this study. Future efforts could help support decision-making by capturing these dimensions, including the large cost discrepancies between methods. Integrating these factors and addressing remaining data gaps through targeted data collection, inclusion of more metrics, as well as expanding expert input, would further improve the BBN and its practical utility.

Overall, this study represents a foundational step in using BBNs to synthesize current rubble stabilization knowledge from diverse sources and support informed decision-making. Coral reef managers could use the tool to visualize expected outcomes under site-specific conditions, compare the suitability of different methods, and make more informed choices about when and where to intervene. With growing interest in reef restoration, BBNs offer an intuitive approach for incorporating expert judgment and available evidence to guide prioritization and planning efforts worldwide.

CRediT authorship contribution statement

Shu Kiu Leung: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tania M. Kenyon:** Writing – review & editing, Software, Resources, Investigation, Formal analysis, Data curation, Conceptualization. **Laurie J. Raymundo:** Writing – review & editing, Resources, Conceptualization. **Helen E. Fox:** Writing – review & editing, Resources, Conceptualization. **Nathan Cook:** Writing – review & editing, Resources, Conceptualization. **Kailash Cook:** Writing – review & editing, Resources, Conceptualization. **Alasdair J. Edwards:** Writing – review & editing, Resources, Conceptualization. **Eric E. Fisher:** Writing – review & editing, Resources, Conceptualization. **Arnaud J.T. Brival:** Writing – review & editing, Resources, Conceptualization. **Freda E. Nicholson:** Writing – review & editing, Resources, Conceptualization. **Robin W.L. Philippo:** Writing – review & editing, Resources, Conceptualization. **Andrew C.F. Taylor:** Writing – review & editing, Resources, Conceptualization. **Scott E. Bryan:** Writing – review & editing, Resources, Conceptualization. **Brett M. Lewis:** Writing – review & editing, Resources, Conceptualization. **Kee Alfian Bin Abdul Adzis:** Resources, Conceptualization. **John P. Edmondson:** Resources, Conceptualization. **Sean P. Griffin:** Resources, Conceptualization. **Xiubao Li:** Resources, Conceptualization. **Xiangbo Liu:** Resources, Conceptualization. **Hazel A. Oakley:** Resources, Conceptualization. **Tries B. Razak:** Resources, Conceptualization. **Satrio H. Samudra:** Resources, Conceptualization. **Marthen Welly:** Resources, Conceptualization. **Peter J. Mumby:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Funding sources

This work was funded by the Reef Restoration and Adaptation Program (RRAP), funded by the partnership between the Australian Government's Reef Trust and the Great Barrier Reef Foundation.

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.

Acknowledgements

We thank the 2023 RRAP Rubble Stabilization Workshop participants, including David Lennon, Darren Cameron, Neil Mattocks, Rolf Voorhuis, Eureka Amadea, Mochyudho Prasetya, Leon Boey, Jens Knauer, and Davidson Rato Nono, for contributing ideas to the formulation of this Bayesian Belief Network and providing critical survey data essential to its development. We also acknowledge the Coral Triangle Center (CTC) staff for their support in hosting the workshop.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.128154.

Data availability

The dataset, including the survey records, R code, and the BBN, is available at https://data.mendeley.com/datasets/rz79dd5t9c/1.

References

Aguilera, P.A., Fernández, A., Fernández, R., Rumí, R., Salmerón, A., 2011. Bayesian networks in environmental modelling. Environ. Model. Software 26 (12), 1376–1388. https://doi.org/10.1016/j.envsoft.2011.06.004.

Alcala, A., Gomez, E.D., 1979. Recolonization and growth of hermatypic corals in dynamite-blasted coral reefs in the Central Visayas, Philippines. In: DSIR Inf. Ser. Proc. Int. Symp. Biogeography and Evolution in the S. Hemisphere, Auckland, New Zealand.

Anthony, K.R.N., Marshall, P.A., Abdulla, A., Beeden, R., Bergh, C., Black, R., Eakin, C. M., Game, E.T., Gooch, M., Graham, N.A.J., Green, A., Heron, S.F., van Hooidonk, R., Knowland, C., Mangubhai, S., Marshall, N., Maynard, J.A., McGinnity, P., McLeod, E., Wear, S., 2015. Operationalizing resilience for adaptive coral reef management under global environmental change. Glob. Change Biol. 21 (1), 48–61. https://doi.org/10.1111/gcb.12700.

Babcock, R., Mundy, C., 1996. Coral recruitment: consequences of settlement choice for early growth and survivorship in two scleractinians. J. Exp. Mar. Biol. Ecol. 206 (1), 179–201. https://doi.org/10.1016/S0022-0981(96)02622-6.

Baldock, T.E., Shabani, B., Callaghan, D.P., 2019. Open access Bayesian Belief Networks for estimating the hydrodynamics and shoreline response behind fringing reefs subject to climate changes and reef degradation. Environ. Model. Software 119, 327–340. https://doi.org/10.1016/j.envsoft.2019.07.001.

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

Boström-Einarsson, L., Ceccarelli, D., Babcock, R.C., Bayraktarov, E., Cook, N., Harrison, P., Hein, M., Shaver, E., Smith, A., Stewart-Sinclair, P.J., 2018. Coral Restoration in a Changing world-a Global Synthesis of Methods and Techniques. Reef and Rainforest Research Centre Ltd.

Brown, B.E., Dunne, R.P., 1988. The environmental impact of coral mining on coral reefs in the Maldives. Environ. Conserv. 15 (2), 159–165. https://doi.org/10.1017/S0376892900028976.

Cameron, C.M., Pausch, R.E., Miller, M.W., 2016. Coral recruitment dynamics and substrate mobility in a rubble-dominated back reef habitat. Bull. Mar. Sci. 92 (1), 123–136.

Ceccarelli, D.M., McLeod, I.M., Bostrom-Einarsson, L., Bryan, S.E., Chartrand, K.M., Emslie, M.J., Gibbs, M.T., Gonzalez Rivero, M., Hein, M.Y., Heyward, A., Kenyon, T. M., Lewis, B.M., Mattocks, N., Newlands, M., Schlappy, M.L., Suggett, D.J., Bay, L.K., 2020. Substrate stabilisation and small structures in coral restoration: state of knowledge, and considerations for management and implementation. PLoS One 15 (10), e0240846. https://doi.org/10.1371/journal.pone.0240846.

Cheal, A.J., MacNeil, M.A., Emslie, M.J., Sweatman, H., 2017. The threat to coral reefs from more intense cyclones under climate change. Glob. Change Biol. 23 (4), 1511–1524. https://doi.org/10.1111/gcb.13593.

Chen, S.Y., Chelliah, A.J., Lau, C.M., Nadhirah, R., Hyde, J., 2018. Reef Rehabilitation Experiments Edition 2: a Review of Various Approaches. R. C. Malaysia. https://www.reefcheck.org.my/S/Reef-Rehabilitation-Experiments-Edition-2-A-Review-of-various-Approaches.PDF.

Chong-Seng, K.M., Graham, N.A.J., Pratchett, M.S., 2014. Bottlenecks to coral recovery in the Seychelles. Coral Reefs 33 (2), 449–461. https://doi.org/10.1007/s00338-014-1137-2.

Clark, S., Edwards, A.J., 1994. Use of artificial reef structures to rehabilitate reef flats degraded by coral mining in the Maldives. Bull. Mar. Sci. 55 (2–3), 724–744.

Clark, S., Edwards, A.J., 1995. Coral transplantation as an aid to reef rehabilitation: evaluation of a case study in the Maldive Islands. Coral Reefs 14 (4), 201–213. https://doi.org/10.1007/bf00334342.

Clark, S., Edwards, A.J., 1999. An evaluation of artificial reef structures as tools for marine habitat rehabilitation in the Maldives. Aquat. Conserv. Mar. Freshw. Ecosyst. 9 (1), 5–21. https://doi.org/10.1002/(SICI)1099-0755(199901/02)9:1<5::AID-AQC330>3.0.CO;2-U.

Cruz, D.W.d., Villanueva, R.D., Baria, M.V.B., 2014. Community-based, low-tech method of restoring a lost thicket of Acropora corals. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 71 (7), 1866–1875. https://doi.org/10.1093/icesjms/fst228.

Dietterich, T., 1995. Overfitting and undercomputing in machine learning. ACM Comput. Surv. 27 (3), 326–327.

Dollar, S.J., Tribble, G.W., 1993. Recurrent storm disturbance and recovery: a long-term study of coral communities in Hawaii. Coral Reefs 12 (3–4), 223–233. https://doi.org/10.1007/bf00334481.

Edmunds, P.J., Bruno, J.F., Carlon, D.B., 2004. Effects of depth and microhabitat on growth and survivorship of juvenile corals in the Florida Keys. Mar. Ecol. Prog. Ser. 278, 115–124. https://www.int-res.com/abstracts/meps/v278/p115-124/.

Edwards, A., Gomez, E., 2007. Reef Restoration Concepts & Guidelines: making sensible management choices in the face of uncertainty. Coral Reef Targeted Research & Capacity Building for Management Programme. pp. 9–10, 26–27.

Edwards, A.J., 2010. Reef rehabilitation manual. Coral Reef Targeted Research & Capacity Building for Management Program, pp. 12–14.

Edwards, A.J., Clark, S., 1994. Data Handbook of Current, Salinity, Water Temperature, and Sediment Information for Galu Falhu Faro, North Male Atoll, Republic of Maldives, pp. 1–33.

Fox, H.E., Caldwell, R.L., 2006. Recovery from blast fishing on coral reefs: a tale of two scales. Ecol. Appl. 16 (5), 1631–1635. https://doi.org/10.1890/1051-0761(2006)016[1631:RFBFOC]2.0.CO;2.

Fox, H.E., Harris, J.L., Darling, E.S., Ahmadia, G.N., Estradivari, Razak, T.B., 2019. Rebuilding coral reefs: success (and failure) 16 years after low-cost, low-tech restoration. Restor. Ecol. 27 (4), 862–869. https://doi.org/10.1111/rec.12935.

Fox, H.E., Mous, P.J., Pet, J.S., Muljadi, A.H., Caldwell, R.L., 2005. Experimental assessment of coral Reef rehabilitation following blast fishing. Conserv. Biol. 19 (1), 98–107. https://doi.org/10.1111/j.1523-1739.2005.00261.x.

Fox, H.E., Pet, J.S., Dahuri, R., Caldwell, R.L., 2003. Recovery in rubble fields: long-term impacts of blast fishing. Mar. Pollut. Bull. 46 (8), 1024–1031. https://doi.org/10.1016/S0025-326X(03)00246-7.

Frys, C., Saint-Amand, A., Le Hénaff, M., Figueiredo, J., Kuba, A., Walker, B., Lambrechts, J., Vallaeys, V., Vincent, D., Hanert, E., 2020. Fine-Scale Coral Connectivity Pathways in the Florida Reef Tract: Implications for Conservation and Restoration [Original Research]. Front. Mar. Sci. 7, 2020. https://doi.org/10.3389/fmars.2020.00312.

Gischler, E., Ginsburg, R.N., 1996. Cavity dwellers (coelobites) under coral rubble in southern Belize barrier and atoll reefs. Bull. Mar. Sci. 58 (2), 570–589.

Gladfelter, E.H., Monahan, R.K., Gladfelter, W.B., 1978. Growth rates of five reef-building corals in the northeastern Caribbean. Bull. Mar. Sci. 28 (4), 728–734.

Goergen, E.A., Gilliam, D.S., 2018. Outplanting technique, host genotype, and site affect the initial success of outplanted Acropora cervicornis. PeerJ 6, e4433. https://doi.org/10.7717/peerj.4433.

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

Harmelin-Vivien, M.L., Laboute, P., 1986. Catastrophic impact of hurricanes on atoll outer reef slopes in the Tuamotu (French Polynesia). Coral Reefs 5 (2), 55–62. https://doi.org/10.1007/bf00270353.

Hernández-Delgado, E.A., Mercado-Molina, A.E., Suleimán-Ramos, S.E., 2018. Multi-Disciplinary lessons learned from low-tech coral farming and Reef rehabilitation: I. Best management practices. In: Duque, C., Tello Camacho, E. (Eds.), Corals in a Changing World. IntechOpen. https://doi.org/10.5772/intechopen.73151.

Hoegh-Guldberg, O., 1999. Climate change, coral bleaching and the future of the world's coral reefs. Mar. Freshw. Res. 50. https://doi.org/10.1071/MF99078.

Howlett, L., Camp, E.F., Edmondson, J., Henderson, N., Suggett, D.J., 2021. Coral growth, survivorship and return-on-effort within nurseries at high-value sites on the Great Barrier Reef. PLoS One 16 (1), e0244961. https://doi.org/10.1371/journal.pone.0244961.

Hughes, T.P., Anderson, K.D., Connolly, S.R., Heron, S.F., Kerry, J.T., Lough, J.M., Baird, A.H., Baum, J.K., Berumen, M.L., Bridge, T.C., Claar, D.C., Eakin, C.M., Gilmour, J.P., Graham, N.A.J., Harrison, H., Hobbs, J.-P.A., Hoey, A.S., Hoogenboom, M., Lowe, R.J., Wilson, S.K., 2018. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. science 359 (6371), 80–83. https://doi.org/10.1126/science.aan8048.

Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B., Kleypas, J., 2003. Climate change, human impacts, and the resilience of coral reefs. science 301 (5635), 929–933. https://doi.org/10.1126/science.1085046.

Hughes, T.P., Kerry, J.T., Alvarez-Noriega, M., Alvarez-Romero, J.G., Anderson, K.D., Baird, A.H., Babcock, R.C., Beger, M., Bellwood, D.R., Berkelmans, R., Bridge, T.C., Butler, I.R., Byrne, M., Cantin, N.E., Comeau, S., Connolly, S.R., Cumming, G.S., Dalton, S.J., Diaz-Pulido, G., Wilson, S.K., 2017. Global warming and recurrent mass bleaching of corals. Nature 543 (7645), 373–377. https://doi.org/10.1038/nature21707.

Jokiel, P.L., 1978. Effects of water motion on reef corals. J. Exp. Mar. Biol. Ecol. 35 (1), 87–97.

Kassambara, A., 2023. In: Ggpubr: 'Ggplot2' Based Publication Ready Plots. https://CRAN.R-project.org/package=ggpubr.

Kenyon, T.M., Doropoulos, C., Dove, S., Webb, G.E., Newman, S.P., Sim, C.W.H., Arzan, M., Mumby, P.J., 2020. The effects of rubble mobilisation on coral fragment survival, partial mortality and growth. J. Exp. Mar. Biol. Ecol. 533, 151467. https://doi.org/10.1016/j.jembe.2020.151467.

Kenyon, T.M., Doropoulos, C., Wolfe, K., Webb, G.E., Dove, S., Harris, D., Mumby, P.J., 2023a. Coral rubble dynamics in the Anthropocene and implications for reef recovery. Limnol. Oceanogr. 68 (1), 110–147. https://doi.org/10.1002/lno.12254.

Kenyon, T.M., Eigeland, K., Wolfe, K., Paewai-Huggins, R., Rowell, D., Dodgen, T., Mumby, P.J., 2024. Material legacies on coral reefs: rubble length and bed thickness are key drivers of rubble bed recovery. Glob. Change Biol. 30 (11), e17574. https://doi.org/10.1111/gcb.17574.

Kenyon, T.M., Harris, D., Baldock, T., Callaghan, D., Doropoulos, C., Webb, G., Newman, S.P., Mumby, P.J., 2023b. Mobilisation thresholds for coral rubble and consequences for windows of reef recovery. Biogeosci. Discuss. 2023, 1–28. https://doi.org/10.5194/bg-2023-2.

Kenyon, T.M., Jones, C., Rissik, D., Brassil, W., Callaghan, D., Mattocks, N., Baldock, T.E., 2025. Bio-degradable 'reef bags' used for rubble stabilisation and their impact on rubble stability, binding, coral recruitment and fish occupancy. Ecol. Eng. 210, 107433. https://doi.org/10.1016/j.ecoleng.2024.107433.

Ladd, M.C., Shantz, A.A., Nedimyer, K., Burkepile, D.E., 2016. Density Dependence Drives Habitat Production and Survivorship of Acropora cervicornis Used for Restoration on a Caribbean Coral Reef [Original Research]. Front. Mar. Sci. 3. https://doi.org/10.3389/fmars.2016.00261.

Landuyt, D., Broekx, S., D'hondt, R., Engelen, G., Aertsens, J., Goethals, P.L.M., 2013. A review of Bayesian belief networks in ecosystem service modelling. Environ. Model. Software 46, 1–11. https://doi.org/10.1016/j.envsoft.2013.03.011.

Leung, S.K., Kenyon, T.M., Brival, A., Bryan, S., Cameron, D., Cheung, M., Cook, N., Dodgen, T., Edmondson, J., Edwards, A., Eigeland, K., Griffin, S., Keppens, M., Lennon, D., Lewis, B., Lowe, R., Mattocks, N., Nicholson, F., Paewai-Huggins, R.,

Mumby, P.J., 2024. A Practical Guide to Restoration and Rehabilitation of Rubble Fields on Coral Reefs. Reef Restoration and Adaptation Program/University of Queensland.
Lewis, B.M., Suggett, D.S., Prentis, P.J., Nothdurft, L.D., 2022. Cellular adaptations leading to coral fragment attachment on artificial substrates in Acropora millepora (Am-CAM). Sci. Rep. 12 (1), 18431. https://doi.org/10.1038/s41598-022-23134-8.
Liu, X., Zhu, W., Chen, R., Rinkevich, B., Shafir, S., Xia, J., Zhu, M., Chen, R., Wang, A., Li, X., 2024. Framed reef modules: a new and cost-effective tool for coral restoration. Restor. Ecol. 32 (1), e13997. https://doi.org/10.1111/rec.13997.
McLeod, E., Anthony, K.R.N., Mumby, P.J., Maynard, J., Beeden, R., Graham, N.A.J., Heron, S.F., Hoegh-Guldberg, O., Jupiter, S., MacGowan, P., Mangubhai, S., Marshall, N., Marshall, P.A., McClanahan, T.R., McLeod, K., Nyström, M., Obura, D., Parker, B., Possingham, H.P., Tamelander, J., 2019. The future of resilience-based management in coral reef ecosystems. J. Environ. Manag. 233, 291–301. https://doi.org/10.1016/j.jenvman.2018.11.034.
McWhorter, J.K., Halloran, P.R., Roff, G., Skirving, W.J., Perry, C.T., Mumby, P.J., 2022. The importance of 1.5°C warming for the Great Barrier Reef. Glob. Change Biol. 28 (4), 1332–1341. https://doi.org/10.1111/gcb.15994.
Moerland, M.S., Scott, C.M., Hoeksema, B.W., Huang, D., 2016. Prey selection of corallivorous muricids at Koh Tao (Gulf of Thailand) four years after a major coral bleaching event. Contrib. Zool. 85 (3), 291–309. https://doi.org/10.1163/18759866-08503003.
Morton, B., Blackmore, G., 2009. Seasonal variations in the density of and corallivory by Drupella rugosa and Cronia margariticola (Caenogastropoda: muricidae) from the coastal waters of Hong Kong: 'plagues' or 'aggregations'? J. Mar. Biol. Assoc. U. K. 89 (1), 147–159. https://doi.org/10.1017/S002531540800218X.
Norsys Software Corporation, 2024. Netica version 7.01. https://www.norsys.com/download.html.
Norsys Software Corporation. (n.d). Netica help. https://www.norsys.com/WebHelp/NETICA.htm.
R Core Team, 2023. R: a Language and Environment for Statistical Computin. R Foundation for Statistical Computing. https://www.R-project.org/.
Raymundo, L.J., Maypa, A.P., Gomez, E.D., Cadiz, P., 2007. Can dynamite-blasted reefs recover? A novel, low-tech approach to stimulating natural recovery in fish and coral populations. Mar. Pollut. Bull. 54 (7), 1009–1019. https://doi.org/10.1016/j.marpolbul.2007.02.006.
Riegl, B.M., 2001. Degradation of Reef structure, coral and fish communities in the Red Sea by ship groundings and dynamite fisheries. Bull. Mar. Sci. 69, 595–611.
Rinkevich, B., 2014. Rebuilding coral reefs: does active reef restoration lead to sustainable reefs? Curr. Opin. Environ. Sustain. 7, 28–36. https://doi.org/10.1016/j.cosust.2013.11.018.
Roff, G., Ledlie, M.H., Ortiz, J.C., Mumby, P.J., 2011. Spatial patterns of parrotfish corallivory in the Caribbean: the importance of coral taxa, density and size. PLoS One 6 (12), e29133. https://doi.org/10.1371/journal.pone.0029133.
Roff, G., Mumby, P.J., 2012. Global disparity in the resilience of coral reefs. Trends Ecol. Evol. 27 (7), 404–413. https://doi.org/10.1016/j.tree.2012.04.007.
Rogers, C.S., 1990. Responses of coral reefs and reef organisms to sedimentation. Marine ecology progress series. Oldendorf 62 (1), 185–202.
Rojas Jr., P., Raymundo, L., Myers, R., 2008. Coral transplants as rubble stabilizers: a technique to rehabilitate damaged reefs. In: Proceedings of the 11th International Coral Reef Symposium, Ft. Lauderdale, Florida.
Sebens, K., Grace, S., Helmuth, B., Maney Jr, E., Miles, J., 1998. Water flow and prey capture by three scleractinian corals, Madracis mirabilis, Montastrea cavernosa and Porites porites, in a field enclosure. Marine Biology 131, 347–360.
Shaver, E.C., Courtney, C.A., West, J.M., Maynard, J., Hein, M., Wagner, C., Philibotte, J., MacGowan, P., McLeod, I., Böstrom-Einarsson, L., Bucchianeri, K., Johnston, L., Koss, J., 2020. A Manager's Guide to Coral Reef Restoration Planning and Design, vol. 36. NOAA Technical Memorandum CRCP. https://doi.org/10.25923/vht9-tv39 [Technical Memorandum].
Stacey, A., 2020. Pom Pom Island rubble to Reef marine conservation. https://www.scubadivermag.com/pom-pom-island-rubble-to-reef/.
Suggett, D.J., Guest, J., Camp, E.F., Edwards, A., Goergen, L., Hein, M., Humanes, A., Levy, J.S., Montoya-Maya, P.H., Smith, D.J., Vardi, T., Winters, R.S., Moore, T., 2024. Restoration as a meaningful aid to ecological recovery of coral reefs. npj Ocean Sustainability 3 (1), 20. https://doi.org/10.1038/s44183-024-00056-8.
Uusitalo, L., 2007. Advantages and challenges of Bayesian networks in environmental modelling. Ecol. Model. 203 (3), 312–318. https://doi.org/10.1016/j.ecolmodel.2006.11.033.
Venables, W.N., Ripley, B.D., 2002. Modern Applied Statistics with S. Springer. https://www.stats.ox.ac.uk/pub/MASS4/.
Victor, S., 2008. Stability of reef framework and post settlement mortality as the structuring factor for recovery of Malakal Bay Reef, Palau, Micronesia: 25 years after a severe COTS outbreak. Estuar. Coast Shelf Sci. 77 (1), 175–180. https://doi.org/10.1016/j.ecss.2007.09.009.
Vida, R.T., Razak, T.B., Mogg, A.O.M., Roche, R., Lynch, J., Williams, B., Team, M.C.R.P. M., Alisa, C.A.G., Subhan, B., Agus, S.B., Graham, N.A.J., Lamont, T.A.C., 2024. Impacts of "Reef Star" coral restoration on multiple metrics of habitat complexity. Restor. Ecol. 32 (8), e14263. https://doi.org/10.1111/rec.14263.
Viehman, T.S., Hench, J.L., Griffin, S.P., Malhotra, A., Egan, K., Halpin, P.N., 2018. Understanding differential patterns in coral reef recovery chronic hydrodynamic disturbance as a limiting mechanism for coral colonization. Mar. Ecol. Prog. Ser. 605, 135–150. https://doi.org/10.3354/meps12714.
Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York. https://ggplot2.tidyverse.org.
Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., Yutani, H., 2019. Welcome to the tidyverse. J. Open Source Softw. 4 (43). https://doi.org/10.21105/joss.01686.
Wilke, C.O., 2024. In: Cowplot: Streamlined Plot Theme and Plot Annotations for 'Ggplot2'. https://CRAN.R-project.org/package=cowplot.
Williams, S.L., Sur, C., Janetski, N., Hollarsmith, J.A., Rapi, S., Barron, L., Heatwole, S.J., Yusuf, A.M., Yusuf, S., Jompa, J., Mars, F., 2019. Large-scale coral reef rehabilitation after blast fishing in Indonesia. Restor. Ecol. 27 (2), 447–456. https://doi.org/10.1111/rec.12866.
Yadav, S., Rathod, P., Alcoverro, T., Arthur, R., 2015. "Choice" and destiny: the substrate composition and mechanical stability of settlement structures can mediate coral recruit fate in post-bleached reefs. Coral Reefs 35 (1), 211–222. https://doi.org/10.1007/s00338-015-1358-z.
Yakob, L., Mumby, P.J., 2011. Climate change induces demographic resistance to disease in novel coral assemblages. Proc. Natl. Acad. Sci. U. S. A. 108 (5), 1967–1969. https://doi.org/10.1073/pnas.1015443108.