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Research article

Building an evidence base for living shorelines: a framework for evaluating the extent and adequacy of post-establishment monitoring programs

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ABSTRACT

Living shorelines are increasingly promoted as a nature-based solution to the growing expense and environmental impacts of conventional engineered coastal protection structures. The coastal ecosystems used in living shorelines increase coastal resilience through wave attenuation and sediment stabilization and offer potential co-benefits such as biodiversity enhancement, productive fisheries, improved water quality and carbon sequestration. Despite the benefits of living shorelines, a suite of technical and socio-political barriers exists to their use as standard practice in coastal management. One barrier is an accessible evidence base on the technical capabilities of living shorelines that provide confidence in their application. Monitoring on-ground projects is a critical component in building the evidence base needed to inform technical guidance. However, monitoring of living shorelines remains neither standardized nor regulated, which can limit the ability to compare outcomes across projects. Here, we present a framework for evaluating the effectiveness of monitoring activities for living shorelines based on eight evaluation metrics - functional design criteria, indicators, monitoring design, sampling periodicity, sampling duration, sustainability, data availability and reporting, and management linkage. We applied this framework to 131 living shorelines projects in Australia. Monitoring activities often scored highly for projects that employed higher-cost techniques to protect valuable infrastructure and were integrated into ongoing coastal asset management programs. In contrast, some long-established techniques had limited routine monitoring data available. Emerging techniques were frequently the subject of scientific studies with robust experimental designs, but their link to management was often weaker. Not all criteria need to be fully met for a project to contribute meaningfully to the evidence base for living shorelines. The framework helps evaluate different aspects of monitoring programs and their influence on project conclusions. When applied across multiple projects, it can provide a standardized assessment of the overall strength of evidence supporting different living shoreline approaches.

1. Introduction

Coastlines support approximately 40 % of the global population, infrastructure for trade and economic growth and ecosystems that provide vital services. Erosion, inundation, and extreme events such as hurricanes and cyclones expose coastal areas to loss of life, damage to infrastructure, and environmental degradation (Kirezci et al., 2020). Widespread armouring of coastlines with conventional engineered structures (e.g., seawalls, breakwaters) that have historically been a common solution to mitigate risk is recognised as not being economically or environmentally viable into the future (Hinkel et al., 2014; Gittman et al., 2016). These engineered structures fragment and replace natural habitats (Chapman, 2003), change connectivity across the land- and sea-scape (Bishop et al., 2017) and can even exacerbate erosion in adjacent shorelines (Fletcher et al., 1997), substantively decreasing coastal amenities and resources. Nature-based solutions (NbS) for coastal protection, also known as “living shorelines” (Bilkovic et al., 2017), that restore habitats (e.g., shellfish reefs, mangrove forests) either with or without support from a structural component (e.g., reef substrate, rock sill) are increasingly being advocated worldwide as a sustainable alternative to conventional engineered structures (Sutton-Grier et al., 2015; Morris et al., 2020).

Akin to natural habitats (Gedan et al., 2011; Narayan et al., 2016), living shorelines provide coastal protection through wave attenuation

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caused by drag and depth-induced wave breaking (Xu et al., 2024) that can promote sediment deposition (Chowdhury et al., 2019), and shoreline stabilization by vegetation (Duarte et al., 2013). Living shorelines may be able to keep pace with changes in climate (e.g., accreting at the rate of sea level rise; Ridge et al., 2015) and self-repair after storm events (Gittman et al., 2014). As well as the potential for sustainable coastal protection, living shorelines can provide a suite of additional benefits that include biodiversity and fisheries enhancement, carbon sequestration and social and cultural opportunities (Chambers et al., 2021; Isdell et al., 2021; Chan et al., 2025). As a result of these co-benefits, there is growing demand to advance the use of living shorelines as standard practice in coastal management. Enabling such transformative change, however, requires overcoming a suite of technical and socio-political barriers to establishing living shorelines at scale (DeLorme et al., 2022; Morris et al., 2024b).

One challenge yet to be addressed is the lack of an accessible evidence base to inform technical guidance for living shorelines (Morris et al., 2024b). Without widely endorsed and locally relevant technical guidance (DeLorme et al., 2022), living shorelines are often not implemented due to a lack of expertise and/or perceived risk in project delivery and ongoing function (DeLorme et al., 2022; Morris et al., 2024b). Experimental evaluation of living shorelines through numerical and physical modelling (e.g., Huang et al., 2024; Huang et al., 2025) and field observations (Bredes et al., 2024) have become more common and provide both predictive and post-installation validation. Simultaneously, coastal practitioners from governmental and non-governmental organizations and community groups in some regions (e.g., in the United States, Europe, Australia) have been increasing practical implementation of living shorelines (Smith et al., 2020; Moraes et al., 2022; Morris et al., 2024a). While some projects have been informed by technical studies (e.g., by consultants), others have grown organically through trial-and-error approaches (Morris et al., 2024a). As policies requiring greater integration of living shorelines into coastal hazard mitigation become more common (Jones and Pippin, 2022), there will be increasing top-down pressure to build the evidence base. To meet this challenge, there is a need to integrate interdisciplinary scientific research with the learnings from innovative coastal-practitioner-led solutions to deliver the technical guidance needed. Monitoring on-ground projects is a critical component of the evidence base that underpins this guidance.

In habitat restoration and NbS, there has been clear documentation of the need for standardized monitoring and reporting (Findlay et al., 2018; Lindenmayer, 2020; Mack et al., 2020; Eger et al., 2022). Standardized monitoring and reporting can facilitate comparisons between restoration projects/sites, enable the evaluation of the effectiveness of previous approaches that can maximise the outcomes of future projects, and inform adaptive management and adaptation planning pathways (Mack et al., 2020; Eger et al., 2022). A range of guidelines has been developed for monitoring restoration projects, typically tailored to specific habitats or locations (McDougall et al., 2022) and for living shorelines (Findlay et al., 2018). Despite this, restoration monitoring efforts are regularly reported to be piecemeal, uncoordinated, and poorly funded, with large differences across different habitats and approaches (McDougall et al., 2022). Similarly, while there have been recent efforts to collate the extent and distribution of the global evidence base for living shorelines (Paxton et al., 2023), the level of confidence in the evidence (i.e., monitoring quality) has not been evaluated. Much of the evidence base for living shorelines and restoration is not readily available; existing primarily as grey literature on various organizational websites (Morris et al., 2024a). Here, we present a framework for evaluating the effectiveness of monitoring activities for living shorelines. We apply this framework to 131 projects in an Australian database (Living Shorelines Australia; Morris et al., 2024a) to demonstrate how the framework can be used to assess the extent and adequacy of the evidence base for living shorelines. When applied across multiple projects, this framework can help assess the strength of the evidence supporting these different approaches. This framework can be used to evaluate previous projects as well as inform monitoring plans for future living shorelines.

2. Methods

2.1. A framework to evaluate the quality of living shoreline monitoring

The framework is based on a set of eight evaluation metrics – functional design criteria, indicators, monitoring design, sampling periodicity, sampling duration, sustainability, data availability and reporting, and management linkage – the scores assigned to them (from 0 as least good to 5 most adequate; Woinarski, 2018) are described below. These metrics were developed from review of a similar framework for threatened species (Woinarski, 2018) but adapted to living shorelines through integration of existing restoration (e.g., Gann et al., 2019) and living shoreline (e.g., Morris et al., 2019) principles. Further, we drew on a typical coastal protection project design (e.g., Morris et al., 2024b) and monitoring process, recognising that living shorelines are often evaluated as options alongside conventional engineered structures. We note that not all criteria need to be well met for a project to contribute meaningfully to the evidence base for living shorelines. Project managers should consider these various aspects of a monitoring program and how they impact the conclusions drawn from the project, as this can guide adaptive management.

2.1.1. Metric 1: there are clearly defined functional design criteria that can be achieved with a NbS

Functional design is the first stage of the design process for living shorelines (Morris et al., 2024b). This design stage identifies project goals, requirements and constraints with the aim of obtaining agreement among stakeholders on what success looks like and what might affect success. At the end of this stage some high-level concepts may be produced, as well as documentation that forms the first iteration of the Basis of Design, which documents key decisions made throughout the design process. Metric 1 measures how well the project's functional outcomes have been defined and if the criteria to achieve these outcomes have been clearly articulated.

To be successful, a living shoreline must achieve engineering (i.e., coastal protection/management) and ecological (i.e., habitat establishment) outcomes (Morris et al., 2019) (Table 1). A project should have clear engineering functional design criteria that have been established based on an understanding of the site's coastal processes, prevalent hazards (and risk) both presently and projected over the life of the project, as well as any applicable standards related to design or materials. A project should also define successful habitat establishment and how the habitat component will contribute to the coastal protection function of the proposed system. The design criteria must be clearly linked to functional performance, and be measurable, time-limited, and specific. This is akin to setting goals and objectives in restoration projects primarily aimed at habitat recovery (Gann et al., 2019). A project may include additional functional design criteria related to co-benefits of living shorelines, such as water quality improvement, biodiversity or fisheries enhancement, carbon sequestration and social and cultural opportunities (Morris et al., 2018) if these were outcomes identified as project goals. When co-benefits are a project goal, the metrics below may also be used to assess these additional functional design criteria; however, the primary functions of a living shoreline (coastal protection and habitat recovery) must also be monitored.

2.1.2. Metric 2: using appropriate indicators to measure achievement of functional design criteria

Indicators are specific, quantifiable measures of the functional design criteria that directly connect longer-term goals and shorter-term objectives (Gann et al., 2019). Metric 2 measures whether the monitoring protocol effectively applies all relevant indicators that have been

Table 1
Score basis for Metrics 1–8.

Score	Score basis
Metric 1: Clearly defined functional criteria	
Score	*Score basis*
5	All functional design criteria have been clearly stated and include coastal protection, habitat recovery/establishment and performance criteria. The criteria have been informed by an assessment of the coastal processes and hazard being considered, the ecological state of the degraded site and an appropriate reference benchmark. The criteria address the performance required for each attribute, have expected timelines for reaching the benchmark, and include specific and measurable indicators.
4	One or more functional design criteria have been stated. These criteria consider two of habitat recovery/establishment, coastal protection function or performance criteria. The criteria have been informed by an assessment of the coastal hazard being considered, the ecological state of the degraded site and an appropriate reference benchmark. The criteria address key attributes, which include the performance required, timelines, and specific and measurable indicators.
3	One or more functional design criteria have been stated. These criteria only consider one of habitat recovery/establishment, coastal protection function or performance criteria. It is not clear how these criteria were established and if coastal processes and hazards, the ecological state of the degraded site or an appropriate reference benchmark were considered. The criteria address some of key attributes, which include the performance required, timelines, and specific and measurable indicators.
2	One or more functional design criteria have been stated. These criteria only consider one of habitat recovery/establishment, coastal protection function or performance criteria. It is not clear how these criteria were established and if coastal processes and hazards, the ecological state of the degraded site or an appropriate reference model were considered. The criteria address one of the key attributes, which include the performance required, timelines, and and measurable indicators.
1	One or more functional design criteria have been stated. These criteria only consider one of habitat recovery/establishment, coastal protection function or performance criteria. It is not clear how the functional design criteria were established. No specific, measurable indicators or timelines were defined.
0	No functional design criteria have been stated.
Metric 2: Using appropriate indicators	
Score	*Score basis*
5	The monitoring protocol effectively applies all relevant indicators that have been demonstrated to detect changes in the attributes for the living shoreline considered.
4	The monitoring protocol is based on one or more indicators that can reliably detect changes in the attributes for the living shoreline considered
3	The sampling indicators provide some information on the changes in the attributes at a site, but may not capture the changes fully for the living shoreline considered (e.g., species presence but not abundance).
2	It is not known whether the sampling indicators selected will reliably detect changes in the attributes for the living shoreline considered.
1	The sampling indicators are an unreliable approach for demonstrating changes in the attributes for the living shoreline considered.
0	No use of indicators in monitoring.
Metric 3: Monitoring design quality	
Score	*Score basis*
5	Sampling design includes measurement of indicators at multiple reference and/or control sites at multiple times before and after living shoreline implementation (Note: actual method could vary e.g., BACI).
4	Sampling design includes measurement of indicators before and after living shoreline implementation and/or only includes limited reference/control sites.
3	Sampling design measures indicators after living shoreline implementation only, that are compared to multiple reference/control sites.
2	Sampling design measures indicators after living shoreline implementation with comparison to a single reference/control site.
1	Sampling design measures indicators (before and) after living shoreline implementation with no comparison to reference/control site.
0	No monitoring was undertaken.
Metric 4: Monitoring frequency	
Score	*Score basis*
5	Monitoring occurs more than once per year in the establishment phase
4	Monitoring occurs annually
3	Monitoring occurs at 2–5 year intervals
2	Monitoring occurs at >5 year intervals
1	Monitoring occurred once
0	No monitoring occurred
Metric 5: Monitoring duration	
Score	*Score basis*
5	Monitoring for >10 years, and there is an assurance of ongoing commitment
4	Monitoring for >10 years, and there is some indication of ongoing commitment
3	Monitoring for >5 years
2	Monitoring for 1–5 years
1	Monitoring for 1 year with no commitment for future sampling
0	No monitoring was undertaken
Metric 6: Sustainability	
Score	*Score basis*
5	Monitoring program includes detailed assessment of relevant parameters (e.g., recruitment, mortality, accretion), which can identify living shoreline sustainability.
4	Monitoring includes reliable information on at least one relevant parameter.
3	Monitoring includes some consideration of at least one relevant parameter.
2	Monitoring parameters are restricted to incidence of abundance, but in a manner that may allow reasonable inference about some parameters related to living shoreline sustainability.
1	Monitoring parameters are restricted to incidence or abundance.
0	No monitoring was undertaken.
Metric 7: Data availability and reporting	
Score	*Score basis*
5	All raw data are collated, readily available and up to date on well-established and publicly accessible sites, with robust analysis and interpretation.
4	All raw data readily available and up to date on publicly accessible sites.
3	Reasonably easy to find some information on monitoring results, either through websites or published reports or scientific papers.
2	Some information may be available, but difficult to access readily.
1	Monitoring information largely unobtainable by others.
0	No monitoring information available.
Metric 8: Management linkage	
Score	*Score basis*
5	Monitoring closely linked to adaptive management of the NbS with explicit measurements of management actions and inbuilt triggers or review that prompt management responses that may be related to reduced ecosystem survival/establishment, coastal protection function or system performance.
4	Monitoring design explicitly measures the effect of different management actions, there are some links to the relevant management authority but triggers are weakly defined and do not necessarily trigger a management response.
3	Monitoring programs provide some consideration of the effects of different management actions but do not define triggers for adaptive management.
2	Monitoring programs may provide weak inference about management actions, but with no clear links to adaptive management.
1	Monitoring programs do not consider the effects of different management actions.
0	No monitoring was undertaken.

demonstrated to detect changes in the design criteria of the living shoreline considered (Table 1). Ecological indicators are variables that are measured to assess changes in the physical (e.g. turbidity units), chemical (e.g. nutrient concentration), or biotic (e.g. species abundance) ecosystem attributes as guided by the reference benchmark and design criteria. Coastal protection indicators include reduction in physical processes (e.g., waves), hazards (e.g., inundation) and/or risk (e.g., averted property damages). The performance indicators should reflect the importance of achieving both the ecological and coastal protection functions to the long-term success of a living shoreline.

2.1.3. Metric 3: monitoring design quality

This metric evaluates if the sampling design is appropriate to the functional design criteria that were established (Table 1). The success of restoration projects is generally informed by a target that is compared to the restoration site. A target may include one or more of the following: (1) a reference site that has an intact, undisturbed (or best available) natural habitat; (2) a historical reference that may be described in the scientific literature or historical records, or have been documented prior to a disturbance event; (3) a baseline where variables have been measured prior to restoration actions; or (4) a control site that has not been restored (Gann et al., 2019). Ideal goal-based monitoring of restoration has been described as monitoring not just of the restoration site but also reference and control sites, before and after on-ground works (i.e., a Before-After Control-Impact [BACI] design). In this way, the interaction between spatial and temporal components of variation can be tested against a variable background to robustly attribute any outcome to the restoration action (Seger et al., 2021). This monitoring design, while more often applied to measuring ecological indicators, equally applies to variables measured for engineering outcomes of living shorelines such as the rate of shoreline change or wave attenuation. In contrast, initial monitoring of conventional engineered structures typically focuses on verifying that construction aligns with the design intent. After construction, a limited defect liability period may be prescribed, during which the structure's condition and performance are assessed before formal handover to the owner. Periodic assessments may be made to ensure structural integrity, safety and continued performance against coastal hazards, especially towards the end of a structure's design life. A key difference in the approach of monitoring conventional engineering structures compared to NbS is a focus on detecting damage rather than adaptive performance.

2.1.4. Metric 4: monitoring frequency

This metric evaluates the intensiveness of monitoring of ecosystem establishment, coastal protection function, and system performance (the ability for the system to truly act as a living shoreline over time; Table 1). The monitoring frequency should be informed by the life histories of the target organism(s) and the expected timeframe for exhibiting the responses (ecological and physical). Typically, though, projects may require more frequent sampling in the establishment phase, as this can help determine factors influencing survival of individuals of the target habitat and inform adaptive management. Monitoring frequency may then be able to be reduced in the post-establishment phase as the system matures and becomes more stable. Targeted sampling may also occur around disturbance events such as storms. In contrast, for engineered structures the most intensive monitoring typically occurs during construction and can range from daily to weekly. Once constructed, the frequency tends to decrease substantially (every few years to decades) as most coastal management and protection structures are typically designed for specific design lives and with limited condition or response monitoring prescribed over the design life of the structure. Typically, as the structure ages, degrades or approaches its end of design life, it will be subjected to increased monitoring and higher frequency (e.g., yearly to several years). Targeted monitoring may occur when the structure is exposed to extreme conditions.

2.1.5. Metric 5: monitoring duration

The monitoring duration of a project should be informed by the expected timeframe to meet the functional design criteria (Table 1). A lack of evidence for long-term performance of living shorelines is one barrier to their implementation (Morris et al., 2024b). Overcoming this barrier, as well as the trajectory of restoration for some habitats (e.g., 15+ years for mangrove restoration; Salmo et al., 2013) supports the importance of commitment to long-term monitoring of living shorelines. In contrast, once conventional engineered structures are constructed and handed over to the owner, monitoring is often governed by asset management strategies. These strategies may consider the risk of failure as well as the consequences of such failures, available resources for monitoring and the general rate of structural degradation. For many structures, high level visual condition assessments occur at regular intervals throughout the design life of the structure, which are only elevated to detailed engineering review if specific defects are noted. Typically, as the structure ages, degrades or approaches its end of design life, it will be subjected to increased and more frequent monitoring.

2.1.6. Metric 6: evaluation of living shoreline sustainability

The persistence of ecosystem service delivery through a resilient and adaptable system (referred to as ‘sustainability’) is a fundamental component of living shorelines (Mitchell and Bilkovic, 2019). Metric 6 assesses how well the monitoring has evaluated living shoreline sustainability (Table 1). For the biogenic component, life-history and demographic parameters (e.g., recruitment, mortality) are important to identify whether the habitat is likely to be self-sustaining. The resilience of the habitat, as well as the overall performance of the system in the provision of coastal protection may be informed through measures of sediment supply, or rate of accretion and/or retreat (Mitchell and Bilkovic, 2019). For (bio)geomorphic systems, monitoring should include an evaluation of replenishment changes over time. A self-sustaining living shoreline should rely less on the structural component (if present) over time and rely more on the ecological component to provide coastal protection. Monitoring will inform the expected degree of additional intervention (i.e., maintenance) required (e.g., the need to re-nourish, re-seed or re-plant).

2.1.7. Metric 7: data availability and reporting

For monitoring to have the greatest impact on living shoreline standard practice, the data needs to be accessible, analysed, interpreted and shared (Table 1). Scientific publications remain the primary method of research dissemination among academics; however, they are often not accessible or easily discoverable by other stakeholders such as coastal managers, community groups, or policymakers. Similarly, technical reports commissioned by coastal managers are frequently inaccessible to external stakeholders—either not publicly released, difficult to locate, or only available on request—hindering the wider sharing of monitoring insights. Such barriers to data sharing can result in best practice being achieved only when experienced practitioners collaborate, preventing the consistent performance needed to make it standard practice. To overcome this barrier, there have been calls for nationally coordinated databases and technical guidance to support the use of NbS across jurisdictions (Morris et al., 2024b).

2.1.8. Metric 8: management linkage

Effective monitoring is central to adaptive management where actions are implemented, outcomes are monitored and the interventions are adjusted in response to new information or changing conditions (Thom, 2000, Table 1). Trigger points for adaptive management that are informed by the functional performance criteria should be identified as well as the appropriate management response to this (e.g., wait for conditions to improve, apply corrective actions, reevaluate goals; Thom, 2000). Adaptive management is closely linked to coastal adaptation pathways planning, which provides a long-term strategic framework for identifying and sequencing potential adaptation actions with decision points (Barnett et al., 2014). Adaptive management operationalises this framework by providing a process for implementing and adjusting those actions over time and refining the adaptation pathway. When applied together, coastal adaptation pathways planning and adaptive management enable coastal managers to remain flexible as environmental and socio-economic conditions change, while still working towards desired outcomes.

2.2. Application of the framework to Australian living shorelines

The monitoring framework was applied to living shoreline projects listed in the Living Shorelines Australia (LSA) database (Morris et al., 2024a). The projects within the LSA database were compiled through a review of published and grey literature, and a survey of coastal practitioners in Australia to identify living shorelines in 2022. Since the publication of the initial 138 projects in the LSA database (Morris et al., 2024a), an additional 74 projects have been added, bringing the total to 212 projects used in this analysis (Fig. 1). The projects spanned most coastal ecosystems including beaches, dunes, saltmarshes, mangroves, seagrasses and shellfish reefs singularly and together (termed “living shoreline mosaics” [LSM]). To evaluate monitoring for each project, publicly available datasets, publications, reports, and other sources (e.g., websites) were compiled. For projects lacking publicly available monitoring information, the listed contact person or organization was emailed to request any available data. In Australia, state governments

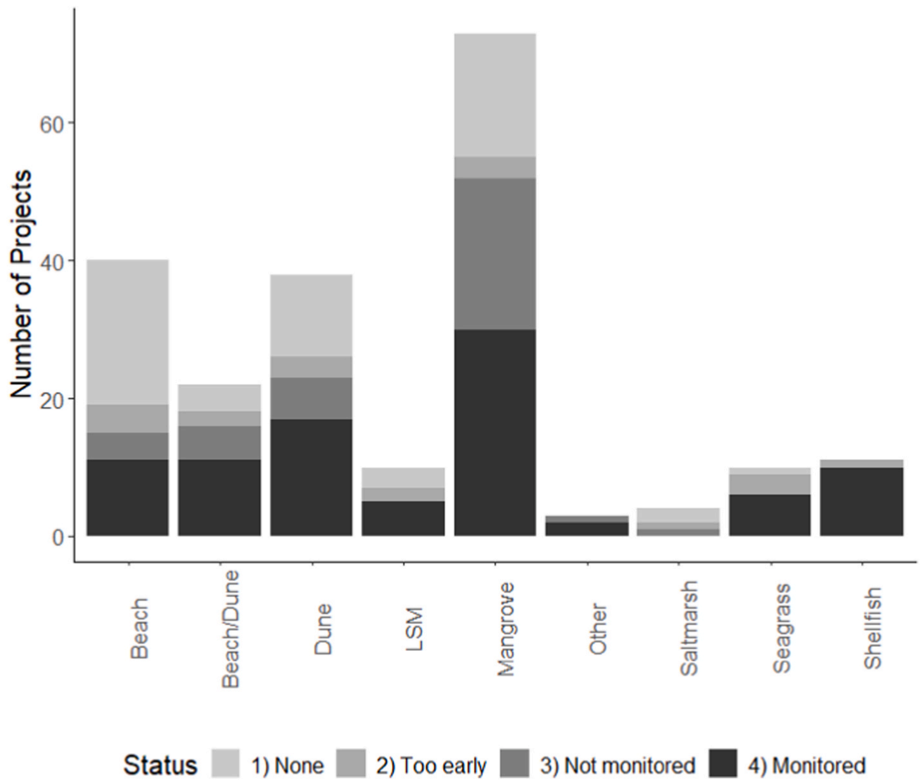

Fig. 1. The number of projects for different living shoreline methods included in the Living Shorelines Australia database and their monitoring status. Projects were categorized as having available datasets, publications, reports or other sources (e.g., websites; black bars), not being monitored (dark grey bars), too early to have monitoring data available (mid grey bars) or none (light grey bars). Projects categorized as "None" predominantly referred to those where the listed project contacts did not respond to a request for data, but also includes projects where data were not available to be shared. LSM = Living Shoreline Mosaic.

hold primary decision-making authority over coastal development and management, while local land managers implement coastal plans and land-use planning decisions within state regulatory frameworks, often drawing on expert advice from consultants and academics (Morris et al., 2024b). Therefore, government agencies commonly held project ownership or served as the primary point of contact, but the reports or publications reviewed may have been delivered by consultancies or academic institutions. Traditional Owners are key rightsholders in Australia with landowner and land manager roles and are custodians of Sea Country. Further, the local land manager and elected councillors need to engage with the community as the primary end users for a socially accepted solution (Morris et al., 2024b). Some of the projects are therefore in partnership with Traditional Owners, community groups, as well as not-for-profit, non-governmental organizations (e.g., The Nature Conservancy, OzFish).

Out of the 212 projects, monitoring information was available, or a response was received from the person or organization responsible for 163 projects. Of the 163 projects, 56 % of the projects had been monitored, 24 % had not been monitored, 12 % were too recent for monitoring data to be available, and for the remaining 8 %, data were not publicly available or accessible to the person now responsible for the project (Fig. 1). Projects with monitoring information (n = 131) were scored according to the eight monitoring metrics described above using the score basis in Table 1 to assign each project a score of 0–5 for each metric, predominantly using information synthesised in publications or reports.

3. Results and discussion

There was variation in the mean scores among monitoring metrics within an ecosystem, as well as across different ecosystems (Fig. 2). For Metric 1, most coastal ecosystems scored a mean of 4 or higher for setting clearly defined functional design criteria that can be achieved with a NbS (Fig. 2). Many projects were informed by detailed technical studies or coastal management strategies that guided their design and implementation. Such studies are often a prerequisite for permitting coastal structures, whether using conventional engineering or living shorelines. Some documentation included recommendations for monitoring programs; however, in practice, monitoring, when required, is often contracted separately from the initial concept, detailed design, and on-ground construction, as different marine contractors with specialised skill sets typically deliver each project stage. Inadequate funding for monitoring leading to monitoring that is absent, poorly designed, or limited to short timeframes is a consistently cited barrier to effective evaluation of restoration, particularly in marine and coastal ecosystems (Abelson et al., 2020). This may be a contribution to the mean metric scores being more varied within and among the ecosystems beyond Metric 1.

For managed beaches the mean scores were >3 for each metric (Fig. 2a). These projects were typically large-scale, high-profile, and often involved more costly, engineered solutions such as sand bypass and back-passing systems (e.g., Adelaide coastline, South Australia; and northern Gold Coast beaches in Queensland) or mass nourishments (e.g., Gold Coast Beach Nourishment Project), as well as beach scraping (Figure S1). Retaining beach width is not only important for coastal resilience but also protecting beach amenities. For example, the recreational value of Gold Coast's beaches is estimated at >$500 million per year (Zhang et al., 2015). During Tropical Cyclone Alfred in February 2025, over 3 million cubic metres of sand were lost from the Gold Coast beaches. A large-scale restoration effort is now underway, with beach volumes expected to take three years to recover to their pre-Alfred state (City of Gold Coast, 2025). Likely reflecting the high socio-economic risks of management failure, monitoring scoring indicates that these beach management programs prioritize funding for monitoring. These

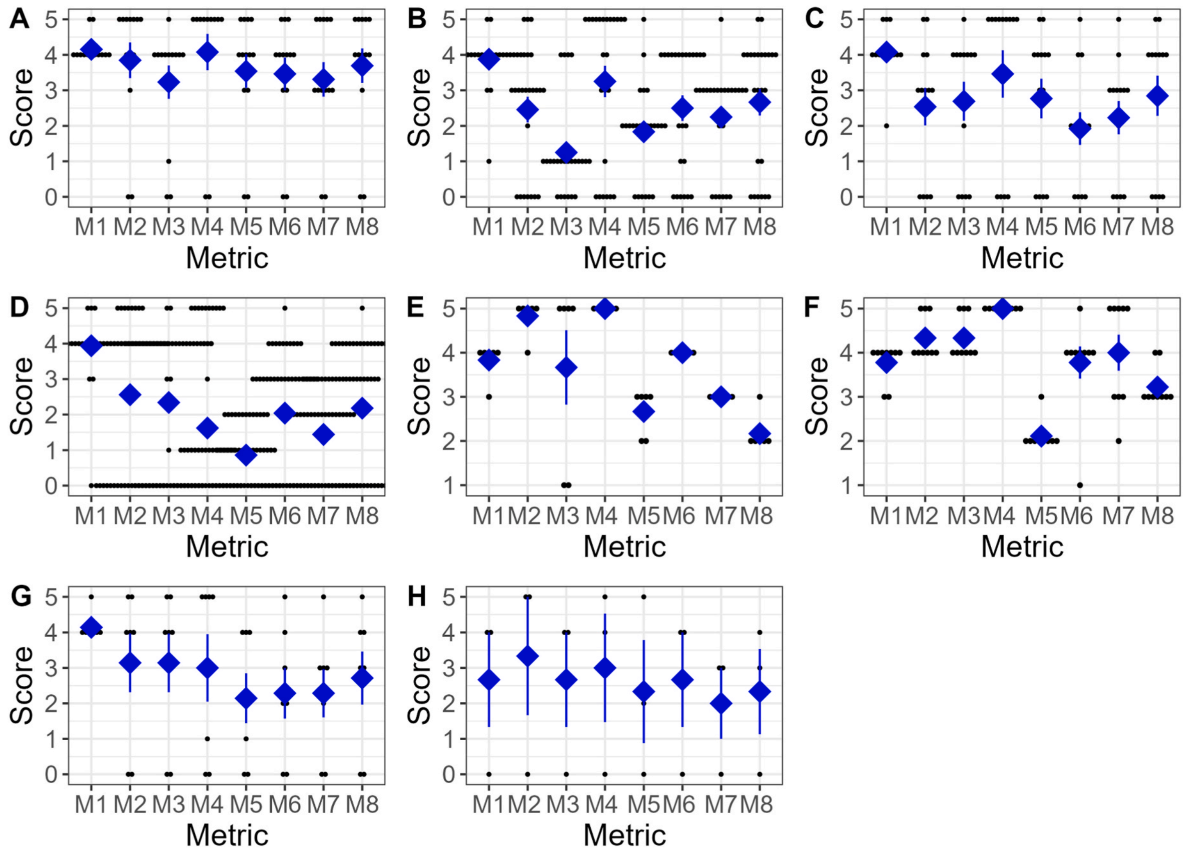

Fig. 2. Mean ± S.E. score for each of the eight monitoring metrics for a) Beach, b) Dune, c) Beach/Dune, d) Mangrove, e) Seagrass, f) Shellfish, g) Living Shoreline Mosaic, and h) Other. Note saltmarsh is not included as a single habitat due to only one project with monitoring information, which was not monitored.

programs also provide good examples of adaptive management. For instance, Adelaide's beaches are annually replenished to compensate for the impact of coastal infrastructure on the natural northward movement of sand from wind and waves that results in erosion of the central and southern beaches in the metropolitan region (Bluecoast Consulting Engineers, 2023). The volume of sand placed in different locations is informed by regular beach monitoring e.g., through beach profiles (Bluecoast Consulting Engineers, 2023). In comparison to managed beaches, projects that included dunes or a combination of dune and beach ecosystems had lower mean scores for the monitoring metrics (Fig. 2b and c, Figure S2). One reason for this could be due to the way that these projects are funded. Projects involving dunes were often community- or grant-funded, with a greater focus on implementation than on monitoring (Muurmans et al., 2017). As a result, monitoring, if conducted at all, was often ad hoc and relied on less quantitative or standardized methods. In contrast beach management often sits within ongoing coastal asset management programs.

Mangroves showed mean monitoring scores that ranged from 1 - <3 for Metrics 2–8 (Fig. 2 b). The lower scores for mangrove projects were driven by a large number of bank stabilization works using rock fillets (Jenkins and Russell, 2017) or other nearshore structures (e.g., wood or geotextiles) that have received little or no monitoring to date (Figure S3). Many of these projects were obtained from a new database connected to a field app created by the Hunter Local Land Services to support more frequent and standardized monitoring and reporting of estuary bank works in the region. Given this is a new tool, only baselines were established for many projects and long-term monitoring has yet to be developed. These baseline surveys have been used to guide priorities for estuary management (Fruition, 2024). Standardized monitoring tools that are easy for coastal practitioners to apply present a future opportunity to build long-term evidence bases for living shorelines. These should be co-developed with relevant stakeholders in living shorelines to enhance uptake. These tools would likewise address a technical barrier for living shorelines where limited guidance on monitoring and evaluation of their performance results in a lack of clarity on whether and when the living shoreline is working or has still yet to be fully established (Morris et al., 2024b).

There were fewer shellfish and seagrass projects in the LSA database compared to the other ecosystems and there were no saltmarsh projects with monitoring data (Fig. 1). The seagrass projects were all extracted from published scientific literature, which was reflected through high scores for monitoring design, frequency and indicators used (Fig. 2e). Seagrass projects, however, were more recently constructed—reflected in lower scores for Metric 5: Monitoring Duration—and, due to their experimental nature, tended to have weaker linkages to management. Shellfish reefs scored similarly to seagrass, having high scores for monitoring design, frequency and indicators but a lower score for duration due to their recent construction (Fig. 2f). However, in contrast to seagrass, the monitoring scores were predominantly based on technical reports as well as scientific studies that had a stronger link to management, meaning they were more likely to inform adaptive decision-making (Fig. 2f). Living Shoreline Mosaics and other methods received average scores across the monitoring metrics; however, these results are based on a limited number of projects in the database.

Overall, the application of the monitoring framework to Australian living shorelines showed that methods used to protect high value assets had monitoring programs that scored relatively highly using the criteria developed (e.g., managed beaches). Other ecosystems with a larger number of projects in the database and longer history of use (e.g., >50 years for dune restoration, and 25 years for rock filleted mangroves) scored comparatively lower for their monitoring programs. This suggests that the precedence of certain techniques, combined with practitioner knowledge in specific regions, has likely driven their adoption and ongoing use in lieu of any formal, accessible evidence base. In recent years, there has been increasing interest in innovative restoration approaches for other ecosystems for coastal protection, particularly shellfish reefs (Morris et al., 2024a). There has been a focus on growing a strong evidence base to support technical guidance and scaling of their use that is reflected in the higher monitoring scores compared to some of the more established NbS techniques. The next step will be to combine the monitoring scores with an evaluation of project outcomes. Together, these can help identify what is known (and what remains uncertain) about the effectiveness of different NbS techniques.

3.1. Adoption of a living shoreline monitoring framework

At the project level, monitoring is essential for informing maintenance and adaptive management of living shorelines. When aggregated across multiple projects, these data can build the evidence base needed to support the upscaling of different living shoreline techniques. The monitoring framework can support project managers in navigating trade-offs when designing resource-limited monitoring programs, helping to prioritize decisions that align with project goals. Combined across projects, the scores resulting from this framework can also inform our evaluation of expected outcomes from living shoreline techniques. Similar frameworks have been adopted in other fields, such as monitoring of threatened species (Woinarski, 2018). Reverse-engineered, this framework could also be used as a basis to create a standardized living shoreline monitoring protocol that could be implemented globally, such as that for reef biodiversity through the Reef Life Survey (Edgar and Stuart-Smith, 2014). When co-designed with the end-users commonly responsible for living shoreline projects, such standardized monitoring protocols may help increase the proportion of monitored projects and the knowledge base needed to inform technical guidance and accelerate transformative change in coastal environmental management.

This framework has been developed on the assumption that investigative monitoring is important to fill in the technical gaps that currently exist for many living shoreline techniques (Morris et al., 2024b). Investigative monitoring uses complex monitoring techniques that allow for greater understanding of the underlying causes of living shoreline project outcomes (England et al., 2021). In contrast, confirmatory monitoring uses simpler monitoring techniques only to verify expected outcomes and is more comparable to condition assessments undertaken for conventional engineered structures. Another distinction between conventional and nature-based approaches is the frequency of monitoring throughout the life of a structure. For living shorelines, monitoring effort is greater in the early years of the project while the target habitat is established. As the habitat matures and stabilizes the frequency of monitoring can be reduced. In contrast, for a conventional engineered structure, beyond the defect period, monitoring effort is low but increases towards the end of the structure's design life. For living shorelines, it may be appropriate to switch to confirmative monitoring in the longer-term, although it will be important to provide evidence for long-term resilience of living shorelines (Mitchell and Bilkovic, 2019; Morris et al., 2024b). Similarly, confirmatory monitoring may be sufficient when living shoreline methods are well-established and their performance expectations are already understood. If expected outcomes aren't met, monitoring can be switched to investigative to identify underlying causes. While we did not differentiate between investigative and confirmatory monitoring here, on the score basis presented, confirmatory approaches may have lower scores. Monitoring frameworks should therefore be designed to evolve over time, reflecting the growing evidence base and technical knowledge for living shorelines, enabling more informed conclusions about their performance and suitability.

CRediT authorship contribution statement

Rebecca L. Morris: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Andrew W.M. Pomeroy:** Writing – original draft, Methodology, Conceptualization. **Roma Bodycomb:** Writing – review & editing, Investigation, Data curation. **Stephen E. Swearer:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

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.2026.128684.

Data availability

Data will be made available on request.

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