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FINAL REPORT

Project 1.10: A national inventory of implemented nature-based solutions to mitigate coastal hazards

September 2022

Current extent and future opportunities for living shorelines in Australia

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Executive summary

"Living shorelines" or "nature-based coastal defences" have the potential to play an important role in climate adaptation and mitigation because of their ability to reduce the threats of coastal erosion and flooding and provide co-benefits such as carbon sequestration. Australia has a diverse coastline with lots of opportunities for living shorelines using beaches and dunes, saltmarshes, mangroves, seagrasses and shellfish and coral reefs either without ('soft' living shoreline) or with ('hybrid' living shoreline) a structural component (e.g., rock sill). Published scientific studies, however, have indicated little to no use of living shorelines in Australia. Here we combined a national survey of coastal practitioners and a literature search to create a database of living shoreline projects in Australia, which were those that had either a primary or secondary goal of protection of coastal assets from erosion and/or inundation. We presented this database in an online mapping tool (www.livingshorelines.com.au) with the aim to share knowledge among coastal practitioners implementing living shorelines to develop best practice that can be used to inform technical guidelines for different approaches and help focus attention on areas for further research.

We identified 138 living shoreline projects in Australia through the means sampled. These predominantly used beaches, dunes and mangroves, and were most commonly used in the states of New South Wales, Victoria and Queensland. Shellfish reefs are an emerging living shoreline technique in Australia, while more research is needed on integrating saltmarsh and seagrass into coastal protection solutions. Coral reefs and kelp forests were not represented in living shorelines in Australia, which represents a significant knowledge gap, in particular for coral reefs where global research provides evidence for their effectiveness at hazard reduction. Beaches and dunes were more likely to be used to protect built assets, while mangroves, saltmarshes, seagrasses and shellfish reefs were more likely to be used to protect natural assets. Few living shoreline projects were used to protect cultural assets significant to Aboriginal and Torres Strait Islander peoples. A review of 27 Indigenous management plans identified the importance of coastal areas for aboriginal heritage and cultural practices, but little consideration of the impacts of climate change or protection of these cultural assets. One exception was for the Eastern Kuku Yalanji Indigenous Protected Area, which is currently utilising a nature-based solution to protect an important dune system from erosion.

Key recommendations from this work are:

1. Compile commonly used techniques and currently available information, supplemented with additional research where needed, to develop technical guidelines for different methods if they do not exist currently.
2. Identify emerging technologies for research programs to provide the ecological, engineering, and socio-economic information necessary to support broader use. For example, hybrid approaches represent an opportunity for living shorelines in more diverse environmental settings but are less well studied/characterised.
3. Increase the number of living shorelines using ecosystems that are currently not well represented as demonstration projects. Decisions could be aided by a living shorelines options analysis for coastlines.
4. Work with diverse stakeholders, including researchers, practitioners, community and Aboriginal and Torres Strait Islander Organisations to co-design living shoreline projects for built, natural, recreational, and cultural assets.

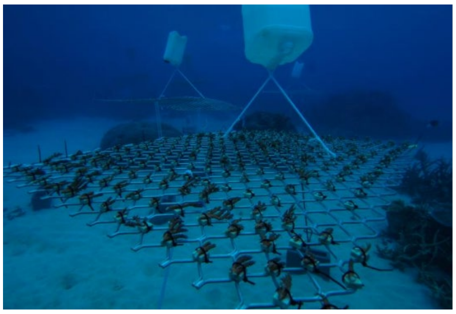
1. Introduction

Climate change and continued coastal population growth are accelerating the demand for coastal structures that mitigate the risk of erosion and flooding (Hinkel et al. 2014; Morris et al. 2020). Coastal hazard risk could increase by 48% by 2100 under future climate change scenarios, driven by sea level rise and a change in the frequency and/or magnitude of storm events (Kirezci et al. 2020). Management of erosion and flooding has commonly used coastal protection structures that include seawalls, revetments and breakwaters. The use of engineered structures has led to significant coastal hardening, and replacement of up to 70% of natural shorelines in some urban areas globally (Bugnot et al. 2021; Claassens et al. 2022; Gittman et al. 2016; Lai et al. 2015). Armouring of natural shorelines has considerable environmental costs as ecosystems such as saltmarshes, mangroves, seagrasses, reefs and dunes are replaced and fragmented (Bishop et al. 2017; Gittman et al. 2016; Goodsell et al. 2007). Hard structures are also non-adaptive; they will need to be replaced or upgraded at considerable economic cost as the physical conditions change, as well as maintained if damaged by severe weather events (Gittman et al. 2014). While hard structures will continue to have a place in coastal protection, alternative methods that are more sustainable and climate-resilient should be more broadly adopted into the future where appropriate.

“Living shorelines” or “nature-based coastal defences” (Bilkovic et al. 2017; Morris et al. 2018; Box 1) have the potential to play important roles in climate adaptation and mitigation because of their ability to reduce the threats of coastal erosion and flooding (Duarte et al. 2013; Ferrario et al. 2014) and provide co-benefits such as carbon sequestration (Carnell et al. 2022). Topographically complex ecosystems created by the habitat-forming species in dunes, saltmarshes, mangroves, seagrasses and biogenic reefs provide coastal protection through wave attenuation, depth-induced wave breaking and sediment stabilisation (Duarte et al. 2013; Morris et al. 2021a). These same ecosystems are increasingly vulnerable to anthropogenic impacts, which include habitat loss through coastal armouring, but also other stressors such as overharvesting and pollution, and are already degraded in many locations (Beck et al. 2011; Goldberg et al. 2020). Living shorelines restore either the habitat alone (“soft” approach) or in combination with engineered structures (“hybrid” approach) for the purpose of habitat recovery and coastal protection (Table 1). Living shoreline structures can have benefits over traditional hard protection structures as they are a living, growing system with the potential to adapt to changes in climate (Rodriguez et al. 2014; Sasmito et al. 2016) and to self-repair after storm events (Gittman et al. 2014).

Table 1. Examples of living shoreline methods applicable to Australia (adapted from Morris et al. 2021). 1a © Teresa Konlechner; 1b © City of Gold Coast; 2a © OzFish; 2b © Fish Habitat Network; 3a and b © Rebecca Morris; 4a © Jennifer Verduin; 4b © Estuary Care.

Ecosystem	**(a) Soft approach**	**(b) Hybrid approach**
(1) Dunes	 Dune planting and fencing (Port Phillip Bay, Melbourne VIC)	 Dune with rock core (the 'A-line', Gold Coast QLD)
(2) Saltmarshes	 Hydrological restoration and fencing (Pitt Water-Orielton Lagoon, TAS)	 Rock fillet protecting saltmarsh (NSW)
(3) Mangroves	 Mangrove planting (Western Port Bay, VIC)	 Mangrove planting in pods (Western Port Bay, VIC)

(4) Seagrasses	 Seagrass cores (Cockburn Sound, WA)	 Seagrass cores behind bagged shell (Port Adelaide River, SA)
(5) Kelp forests	 Juvenile kelp transplants (Port Phillip Bay, VIC)	 Adult kelp transplants onto artificial reef (TAS)
(6) Shellfish reefs	 Oyster shell bags for natural oyster recruitment (NSW)	 Mussels seeded onto reef substrate (Port Phillip Bay, VIC)
(7) Coral reefs	 Coral transplantation (QLD)	 Coral transplanting on artificial reef (Gold Coast, QLD)

Box 1. Terminology

Nature-based Solutions (NbS) are defined as *actions to protect, sustainably manage and restore natural or modified ecosystems to address societal challenges, simultaneously providing human well-being and biodiversity benefits* (Cohen-Shacham et al. 2016). NbS include the ecosystem approach that was endorsed by the Convention of Biological Diversity defined as a *strategy for the integrated management of land, water, and living resources that promotes conservation and sustainable use in an equitable way* (CBD SBSTTA 2000), but NbS is broader in its focus. NbS is an umbrella term that encompasses responses to climate change mitigation and adaptation, disaster risk reduction, economic and social development, human health, food security, water security and biodiversity loss. Living shorelines are a NbS to directly address climate change adaptation and disaster risk reduction, with co-benefits that can contribute to the other societal challenges. Thus, living shorelines can also be considered under the broader NbS term. There are several other terms used in the literature for living shorelines, including: soft and hybrid ecological engineering; nature-based methods, nature-based coastal defence; nature-based features; working with nature; and building with nature. Some of these terms differ in the breadth of approaches are that are included. We have adopted the living shoreline terminology that states that the projects regardless of whether they only use natural habitat elements or also hard materials, should conserve, create or restore natural coastal functions including the provision of defence against storms (Bilkovic, et al. 2017).

Most physical, ecological, and socio-economic research on living shorelines has been focused on North America (Morris et al. 2018; Smith et al. 2020). In comparison, living shorelines demonstration and research in Australia is in its infancy (Smith et al. 2020), with published studies focusing solely on dune management (Morris et al. 2018). This is despite significant opportunity for utilising a variety of ecosystems for hazard mitigation (Morris et al. 2021a; Table 1). Recent public surveys have shown there is support for more ecologically sustainable coastal protection approaches in Australia (Saunders et al. 2022, Strain et al. 2019), and that living shorelines are often perceived to be as effective at coastal defence as traditional structures (Strain et al. 2022). Concomitantly, new policies have prioritised living shorelines over hard protection options (e.g., New South Wales Coastal Management Act 2016 and Victoria Marine and Coastal Policy 2020; Morris et al. 2021a).

Increasing social license and political support has enabled some small-scale trials of living shorelines in Australia (Morris et al. 2019a). Sharing knowledge on the success of implemented living shorelines to develop best practice is a key aspect in supporting living shorelines at scale. Further, to support transformational change in the way communities respond to coastal hazards, understanding potential benefits and barriers perceived by key stakeholder groups is essential (DeLorme et al. 2022). Here we used a combination of stakeholder surveys and interviews and a literature review to (1) develop a national inventory of living shoreline projects; and (2) gain a better understanding of perceived benefits and barriers of different stakeholders to using living shorelines in Australia.

2. Methods

Two methods were used to create a national inventory of living shoreline projects in Australia: (1) surveys and interviews with coastal practitioners; and (2) a literature review. Human ethics approval was obtained for the survey and interviews (2021-14372-24170-5, The University of Melbourne).

2.1 Survey and interviews

We used a survey to identify coastal practitioners that had implemented living shorelines across Australia and assessed the reasons why living shorelines had not been implemented in the jurisdictions of some respondents. It used both targeted (coastal practitioners known to the research team to have implemented living shorelines) and convenience sampling (all other coastal practitioners). The survey was distributed online to people aged 18 years or over, and participants were recruited via mailing lists of key coastal organisations or working groups (e.g., Australian Coastal Councils Association; Association of Bayside Municipalities; Coastal Council Adaptation Taskforce [C-CAT]; and the National Committee on Coastal and Ocean Engineering [NCCOE]), or through email lists held by the researchers. The survey was emailed directly to a total of 68 people, however, the number of people the survey reached would have been greater than this due to forwarding of the email. All respondents were provided with access to the plain language statement before agreeing to complete the survey.

The survey was made available online through Qualtrics between 11/01/2022 and 30/06/2022. The survey included eight questions and took no more than five minutes to complete (Supplementary Table 1). The survey included questions with binary (yes, no), multiple-choice, and open answers; the latter allowed participants to expand on their perspectives of the benefits and barriers of living shorelines. Two questions within the survey identified the stakeholder type (e.g., local or state government, consultancy, university) and jurisdiction, two questions identified whether the respondent (or their organisation) had used living shorelines and what type (i.e., soft or hybrid and ecosystem type [beach, dune, saltmarsh, mangrove, seagrass, kelp, shellfish, or coral reef]; Table 1). A further three questions explored the reasons why living shorelines had not been implemented (if this was the case), whether the use of living shorelines was a priority for the individual/organisation and barriers to their use. The last two questions asked whether individuals that had implemented living shorelines would be willing to be contacted for further information about the project(s). A generalised linear model with a binomial distribution was used to test whether individuals that had implemented living shorelines (fixed, 2 levels = yes or no) were more likely to consider them a priority (fixed, 2 levels = yes or no) for future coastal management. Chi square tests of independence were used to test for an association between whether participants had used living shorelines before, and the state in which they worked and the frequency that different barriers were selected.

Where the survey identified coastal practitioners that had implemented living shorelines and had opted to be contacted, they were sent a follow-up email and provided information on the projects they had been involved in either by completing a spreadsheet or communicating the information verbally in an interview, which was then transcribed to a project database (see Data extraction below).

2.2 Literature review

The literature review built on two existing databases on living shoreline (Morris et al. 2018) and beach nourishment (Cooke et al. 2012) projects in Australia. A literature search was done in Web of Science using the same systematic search terms as Cooke et al. (2012) and Morris et al. (2018) (Table 2) to account for any papers that had been published since those reviews between 2011-2022 and 2017-2022, respectively. We also used the reference lists of relevant papers to find additional studies and grey literature. The initial literature search identified 1095 papers for screening, first by title, followed by abstracts, for inclusion in the project database. The papers were then screened for those that reported on field-based living shoreline projects in Australia and the data for each of those projects were extracted. As the number of responses to the survey from traditional owner organisations was low (see results), we also reviewed all publicly available management plans for coastal Indigenous Protected Areas (IPAs) in Australia linked to the North West Atlas (https://northwestatlas.org/node/1703#map). Each management plan was qualitatively scored (low, medium, high) for the following four criteria: (1) importance/extent of the coastal area within the IPA (2) mention of sea level rise/erosion/coastal hazards/climate change (3) potential risk to cultural sites and/or values (4) discussion of adaptation pathways/actions. Plans for 27 of the 42 identified IPAs were reviewed as detailed plans were unavailable for the remaining 15 IPAs.

Table 2. Literature search terms

Search terms	# Results
habitat (oyster* or “oyster reef” or shellfish* or “shellfish reef” or kelp* or seaweed* or macroalgae* or seagrass* or “coral reef” or mangrove* or saltmarsh* or marsh* or dunes*) and (“climate change or adapt*” or “coastal erosion” or risk* or flood* or “sea level rise” or “wave attenuation” or “wave energy” or “wave breaking” or storm* or surge*) and (Australia or “New South Wales” or “Victoria” or “South Australia” or “Western Australia” or “Northern Territory” or Queensland or Tasmania)	364
habitat (oyster* or “oyster reef” or shellfish* or “shellfish reef” or kelp* or seaweed* or macroalgae* or seagrass* or “coral reef” or mangrove* or saltmarsh* or marsh* or dunes*) and (restor* or rehabilitat* or “green engineering” or “eco-engineering” or “ecological engineering” or “green infrastructure”) and (Australia or “New South Wales” or “Victoria” or “South Australia” or “Western Australia” or “Northern Territory” or Queensland or Tasmania)	288
("breakwater" or "groyne" or "revetment" or "seawall" or "riprap") and ("coastal erosion" or risk* or flood* or "sea-level rise" or "wave attenuation" or "wave energy" or "wave breaking" or storm* or surge*) and (Australia or “New South Wales” or “Victoria” or “South Australia” or “Western Australia” or “Northern Territory” or Queensland or Tasmania)	67
(“nourishment” or “replenishment” or “deposition” or "beach enhancement" or "beach skimming" or "beach panning" or "nature assisted beach enhancement" or NABE or "assisted beach recovery" or "beach recycling" or "re-profiling" or "bulldoze/ing" or "sand scrape" or "sand scraping" or "sand push") and (Australia or "New South Wales" or Victoria or "Northern Territory" or Queensland or Tasmania) and (beach or dune)	376

2.3 Data extraction

The following information was recorded from survey respondents and the literature review for all living shoreline projects where available: site name; location [latitude and longitude]; approach used [soft or hybrid and ecosystem type, as before]; primary/secondary objectives of the project; coastal hazard being managed; assets vulnerable to the hazard; geographic context [open coast, estuary]; project approvals required; date of project completion; shoreline length; project area; responsible organisation; funding source; project cost; whether the project was monitored; and any information/reports that resulted from the monitoring. There was then a set of ecosystem-specific variables extracted that focused on specific details about the method used (Supplementary Table 3). Only projects where coastal protection was stated as a primary or secondary objective of the project were included in the database.

Although it is acknowledged that restoration projects that do not have a coastal protection objective may have methods relevant to living shorelines, these projects were not included in the database as the aim was to increase the profile of nature-based methods for coastal hazard resilience. Some projects identified through the literature did not contain all the information needed in one paper or report. In these instances, the Google search engine was used to find more information, which was frequently obtained through council or organisation websites or news articles. Occasionally, this process led to more projects being found incidentally, and these were also included in the database. Projects that were identified, but that were lacking in critical information, were excluded from the database as they were not deemed fit for the purpose of providing a useful example of a living shoreline.

Projects were binned into 5-year intervals from 1970 – 2025 and linear models were used to test how the number of projects using each approach (fixed; 6 levels: beach, dune, mangrove, saltmarsh, seagrass, and shellfish) or in each state (fixed; 6 levels: NSW, VIC, SA, WA, QLD, TAS) varied through time (fixed; 11 levels). Chi square tests of independence were used to test for an association between the approach used and geographic context (open coast, bay, estuary), primary objective (coastal protection, habitat restoration, ecosystem services, safe navigation, test methods), hazard mitigated (erosion, flooding, Sea Level Rise, storms), asset protected (built, cultural, natural, private, recreational) and how the projects were monitored (formal-qualitative, formal-quantitative, informal, no, unsure). Formal monitoring involved reporting of project outcomes, predominantly to government bodies, either through visual assessment of the site (qualitative) or measured variables (quantitative, e.g. m^3 of sand lost or gained). Informal monitoring usually involved visual assessments that were not formally reported (usually community driven projects).

Projects were also categorised in terms of their success (no, somewhat, too early, unsure, yes). Projects were considered successful if they met one of the following criteria: a) they had arrested or significantly mitigated the coastal hazard (on the timescale or to the extent intended); b) they addressed continuing erosion in a long-term sustainable way (e.g. sand pumping pipelines); c) had been explicitly referred to as successful by the organisation responsible. In contrast, projects were considered unsuccessful if they had not succeeded in mitigating the coastal hazard, the effects were very short term, or the organisation responsible considered the project unsustainable in the long run (e.g. some expensive sand carting projects in areas of rapid erosion). A linear mixed model was used to test the effect of the approach used on the length of coastline protected. Project ID was included as a random variable to account for projects that had restored multiple habitats. Project cost was adjusted from the year of completion to 2021 AU$ using the online inflation converter from the Reserve Bank of Australia https://www.rba.gov.au/calculator/annualDecimal.html; e.g., Ferrario *et al*. 2014).

3. Results

3.1 Survey of coastal practitioners

In total, 67 coastal practitioners completed the survey. Most respondents (64.2%) were from local government authorities, while 9.0% of respondents were from community organisations (e.g., Coastcare groups), 7.5% from state government organisations, 6.0% from NRM (Natural Resource Management), and 1.5% each from federal government, engineering consultancy and non-governmental and traditional owner organisations. We also had one respondent from a not-for-profit Aboriginal Charitable Trust, two private coastal landowners, and one respondent that worked at a university. The survey respondents were primarily from South Australia (35.9%), Victoria (18.8%) and Tasmania (17.2%), followed by Queensland (12.5%), New South Wales (12.5%) and Western Australia (3.1%), with no respondents from the Northern Territory.

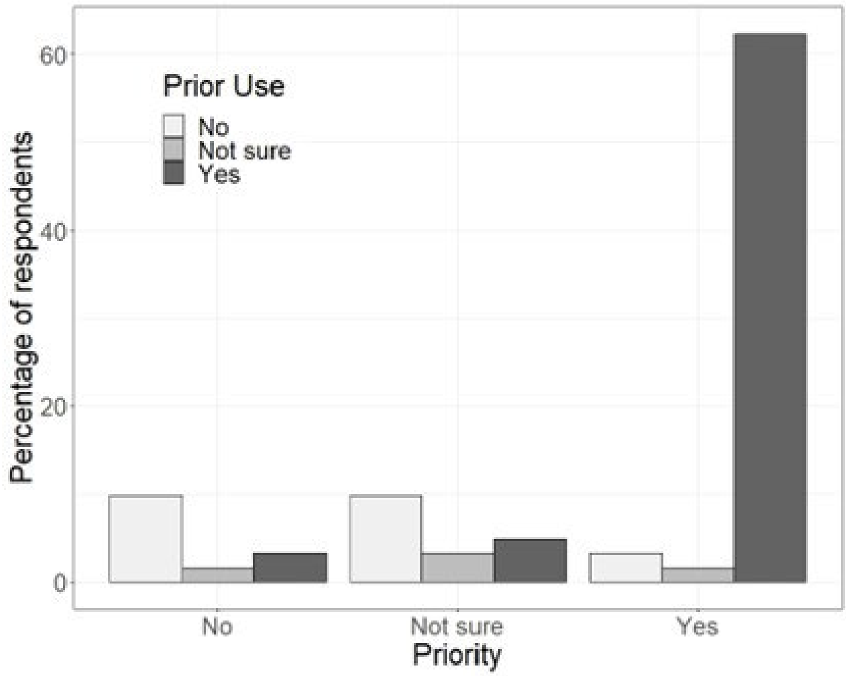


Figure 1. Percentage of respondents that have previously used living shorelines and consider living shorelines a priority for future management of coastal risk.

A total of 44 respondents (68.7%) stated that they or their organisation had used living shorelines, while 23.4% stated that they hadn't used living shorelines and 7.8% were unsure. Forty-one respondents (67.2%) stated that living shorelines were a priority for them or their organisation for future projects to manage the risk of hazards for coastline assets, while 14.8% stated they were not a priority, and 18.0% said they were unsure. Respondents that had used living shorelines previously were more likely to consider them a priority for future risk management ($P<0.001$; Figure 1). There was no effect of prior use of living shorelines (X^2 =

5.10, d.f. = 13, $p > 0.05$) or the state that the respondent worked in ($X^2 = 39.41$, d.f. = 65, $p > 0.05$) on the frequency that different barriers were selected (Figure 2). The top five most selected barriers to implementation were: uncertainty in the level of risk reduction; lack of necessary expertise; planning or regulation barriers; lack of good examples being used; and a lack of clarity in the options available.

Forty respondents that had used living shorelines were willing to be contacted, 26 of which provided information on the living shoreline projects they had been involved in, representing a 65% response rate. After removing projects that did not have a coastal defence objective, the stakeholder survey yielded 52 projects for inclusion in the living shoreline database.

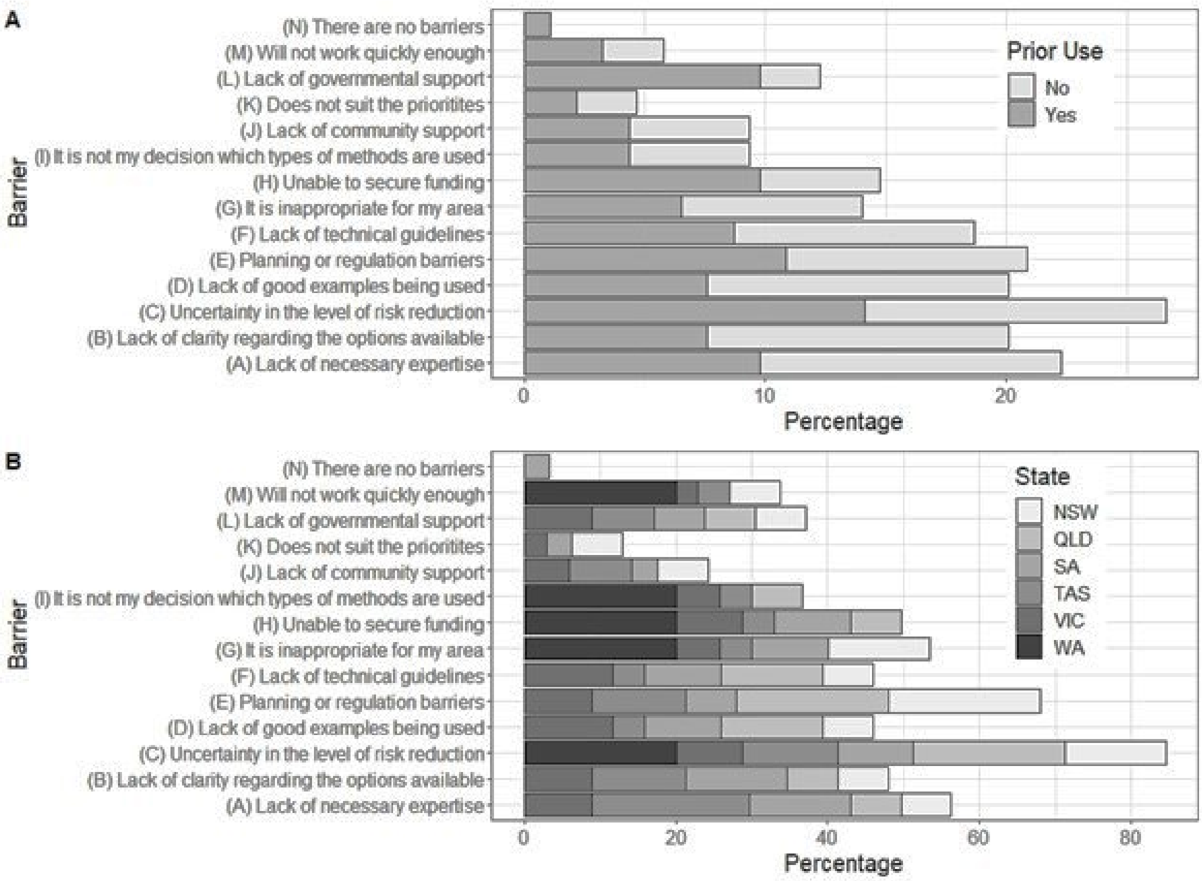


Figure 2. The percentage of respondents that identified barriers to living shorelines depending on (A) prior use of living shorelines (yes or no); and (B) the state in which the participant worked.

3.2 Living shoreline database

Of the initial 1095 papers that were screened from the literature search, four were empirical papers describing relevant projects in Australia, and reference lists were screened in a further five review papers. The total number of living shoreline projects identified through the combined sources of information was 138, as of September 30, 2022 (Supplementary Table 4; www.livingshorelines.com.au). The number of living shoreline projects significantly increased from the period 2006-2010 (Figure 3a; Supplementary Table 6). There were significantly more beach (31.7%), dune (26.2%), and mangrove (26.9%) projects than saltmarsh (4.8%), seagrass (6.9%) or shellfish reef projects (2.7%) (Figure 3a; Supplementary Table 5). No kelp forest or coral reef projects were identified.

Four projects were classified as ‘other’, which included two artificial reefs, the revegetation of a cliff top, and one project that used tea tree log and brushwood groynes. The number of living shoreline projects through time differed by state (Figure 3b; Supplementary Table 6). New South Wales had a higher number of projects implemented in 2001-2015 (Figure 3b). Overall, New South Wales had the greatest percentage of projects (43.9%), followed by Victoria (18.7%) and Queensland (17.9%) (Figure 4). South Australia, Tasmania and Western Australia had 10.6%, 6.5%, and 2.4% of projects respectively. No projects were recorded for the Northern Territory.

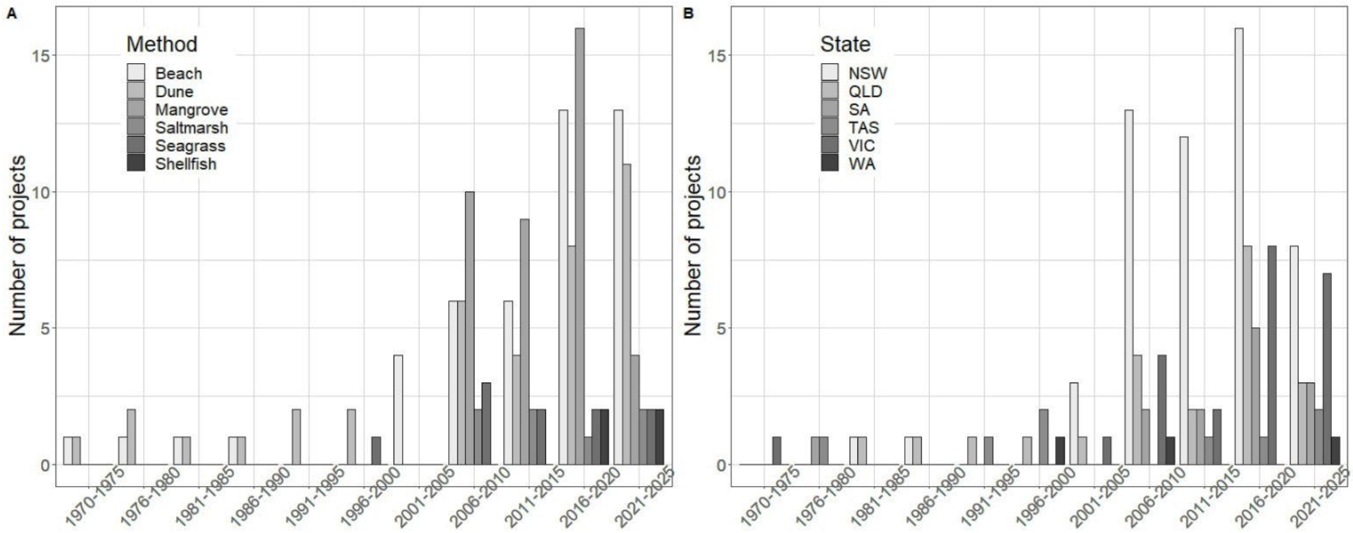


Figure 3. The number of living shoreline projects through time for (A) the approach used and (B) the state implemented.

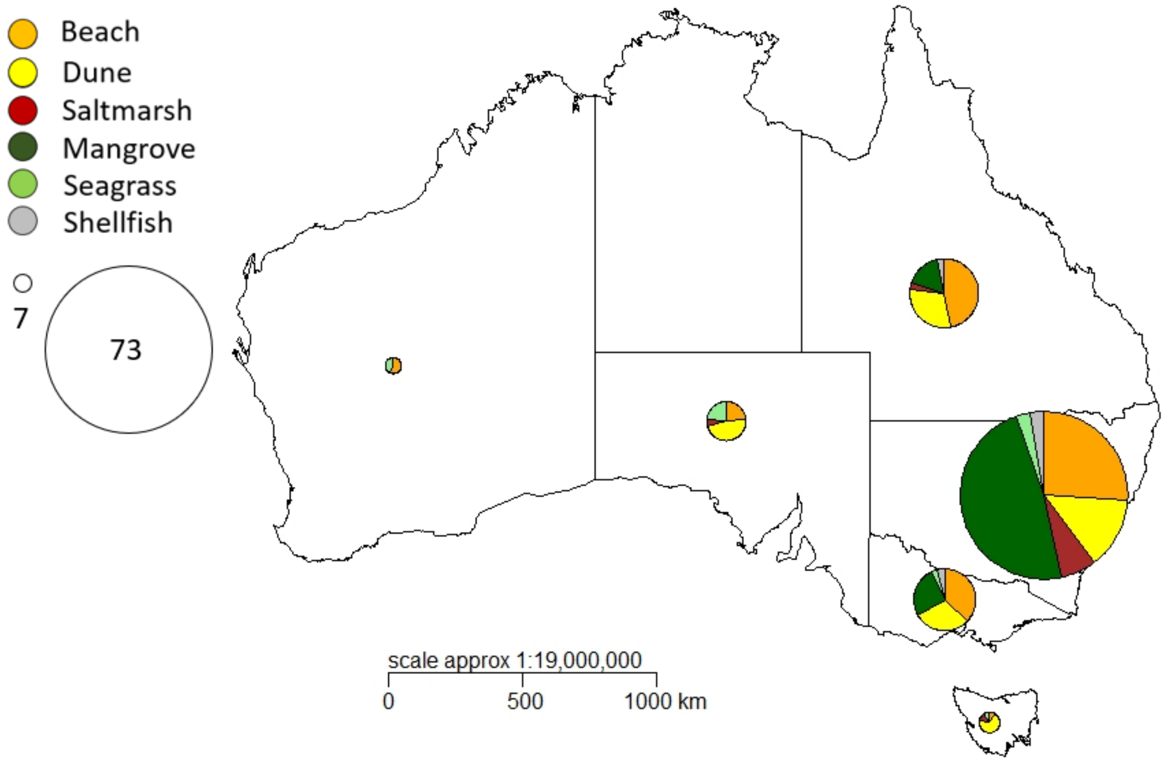


Figure 4. Map of the location and number of living shoreline projects included in the database (n = 138).

There was a significant difference in the geographic context (X^2 = 112.13, d.f. = 12, $p < 0.001$), primary objective (X^2 = 113.58, d.f. = 24, $p < 0.001$), hazard mitigated (X^2 = 30.71, d.f. = 18, $p < 0.05$) and asset protected (X^2 = 89.42, d.f. = 24, $p < 0.001$) among the living shoreline approaches. Mangrove, saltmarsh, and shellfish reef living shorelines were used more frequently in estuaries, while seagrass was used most frequently in bays. Beach nourishment and dune management more commonly occurred on the open coast and in bays (Figure 5a). Beach, dune, and mangroves had a high percentage (> 70%) of projects where the primary objective was coastal protection (Figure 5b). For saltmarsh, seagrass, and shellfish reefs there was a greater number of projects where the primary objective was habitat restoration, with a secondary objective of coastal protection (Figure 5b), and 45% of seagrass projects had the primary objective of testing methods for restoration.

Almost all projects (except one) were installed for erosion mitigation, 23% of projects additionally aimed to mitigate storms, flooding, or inundation as well as erosion. Beach, dunes, and shellfish reefs were more commonly implemented to protect against storms (Figure 5c). Protection against flooding and SLR were less frequently cited as the reason for living shoreline implementation (Figure 5c). Mangroves, saltmarsh, seagrass, and shellfish reefs were most frequently implemented to protect natural assets, while beaches and dunes were used to protect built and recreational assets (Figure 5d). Only 2.5% of responses stated that living shorelines were used to protect cultural assets, and all used either beach nourishment or dune management (Figure 5d).

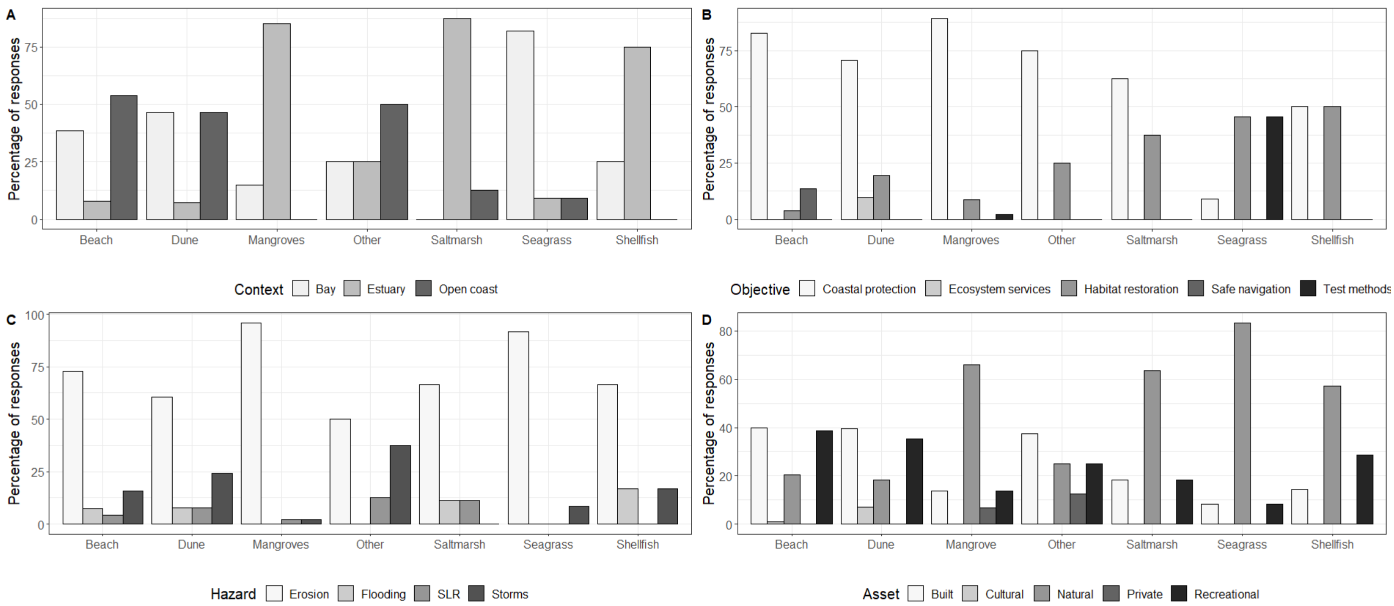


Figure 5. The percentage of responses for the (A) geographic context; (B) primary objective; (C) hazard mitigated; and (D) asset protected for the different living shoreline approaches.

Overall, the living shorelines were considered successful in 59% of the projects recorded. Thirteen percent of projects were deemed somewhat or not successful, while the remaining percentage were either unsure of success or the projects had been implemented too recently for results. Formal monitoring was undertaken for just over half of the projects (53.6%), and this was either quantitative (30.1%) or qualitative (24.1%). Informal monitoring has occurred at 16.3% of the projects, while 3.6% of the projects were unmonitored. For 25.9% of the projects, there was no information about whether the projects have been monitored or not. Whether projects were considered a success ($X^2 = 37.26$, d.f. = 24, $p < 0.05$) and how they were monitored ($X^2 = 89.05$, d.f. = 24, $p < 0.001$) significantly differed among living shoreline approaches (Figure 6). No saltmarsh or shellfish reef projects were considered unsuccessful (Figure 6a), however, a greater percentage of projects from these approaches were also unknown or considered too early to tell. No seagrass projects were classed as being successful and most of these projects (63.4%) were listed as unsure of success. More than 60% of beach, dune and mangrove living shorelines were considered successful (Figure 6a). Beach, dune, and shellfish reef living shorelines received the most formal quantitative monitoring (Figure 6b). A higher percentage of saltmarsh projects received formal qualitative monitoring, while no seagrass projects received formal quantitative monitoring, and a higher percentage of seagrass projects were either informally or not monitored (Figure 6b). The monitoring status for a high percentage (51%) of mangrove projects was unknown (Figure 6b).

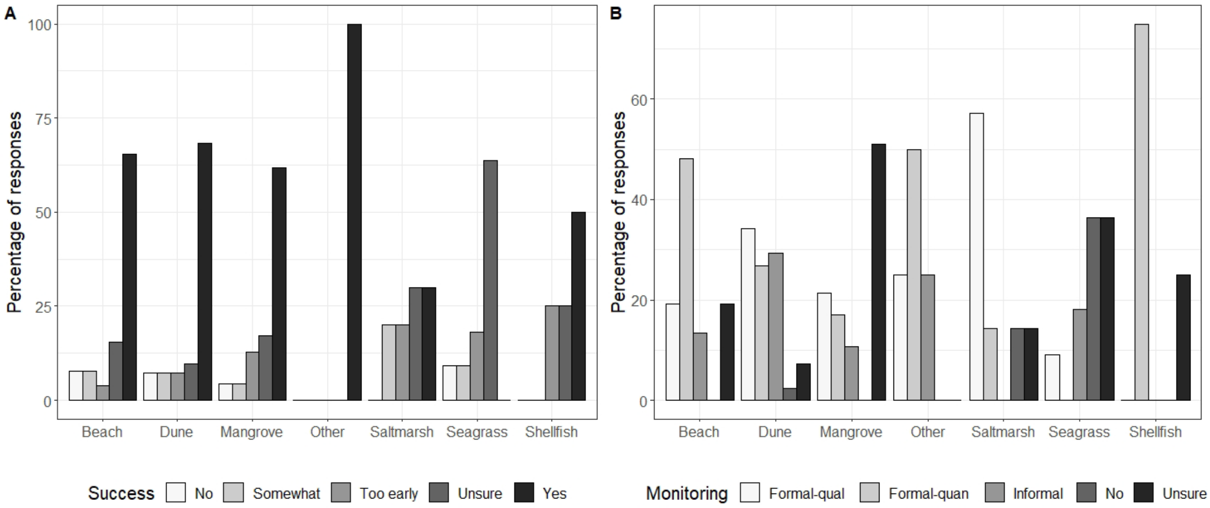


Figure 6. The percentage of responses for the (A) success and (B) monitoring of different living shoreline approaches.

In total, 178.2 km of Australia's linear coastline has been protected with living shorelines, which was greatest in New South Wales where living shorelines had been applied to 3.1% of the coast compared to 0.88% in Victoria, 0.83% in South Australia, 0.22% in Tasmania, 0.19% in Queensland and 0.06% in Western Australia. The average length of shoreline protected by living shorelines was 1,781 m, and ranged from 80 – 36,000 m with a median of 690 m. The length of shoreline protected per project did not differ among living shoreline approaches (Figure 7; $F_{2,100} = 3.06$, $P > 0.05$).

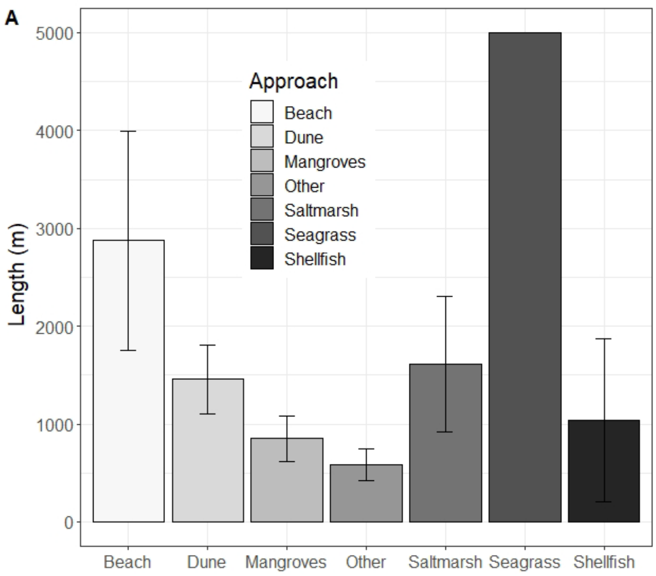


Figure 7. The mean (±S.E.) shoreline length (m) protected for different living shoreline approaches. Note seagrass was not included in the analysis as there was only one project.

3.3 Techniques within the living shoreline approaches

Dune and saltmarsh living shoreline projects used predominantly soft approaches, whereas beaches, mangroves and seagrass used a combination of soft and hybrid approaches, and shellfish reefs were all hybrid projects (Figure 8). Shellfish reefs were considered hybrid if there had been substrate addition. Table 2 provides examples of the techniques used for soft and hybrid approaches within each ecosystem.

The average cost per linear metre of all living shoreline approaches was AU$4,238, however this had a large range from AU$10 m^{-1} to AU$102,033 m^{-1}, with hybrid approaches more expensive than soft approaches (Table 2). The median cost was AU$207 m^{-1}. Projects were most often funded through state (64.8%) or local (36.2%) governments. Other sources of funding were the federal government (13.3%), community grants (7.6%), research grants (4.8%) and the private sector (2.9%).

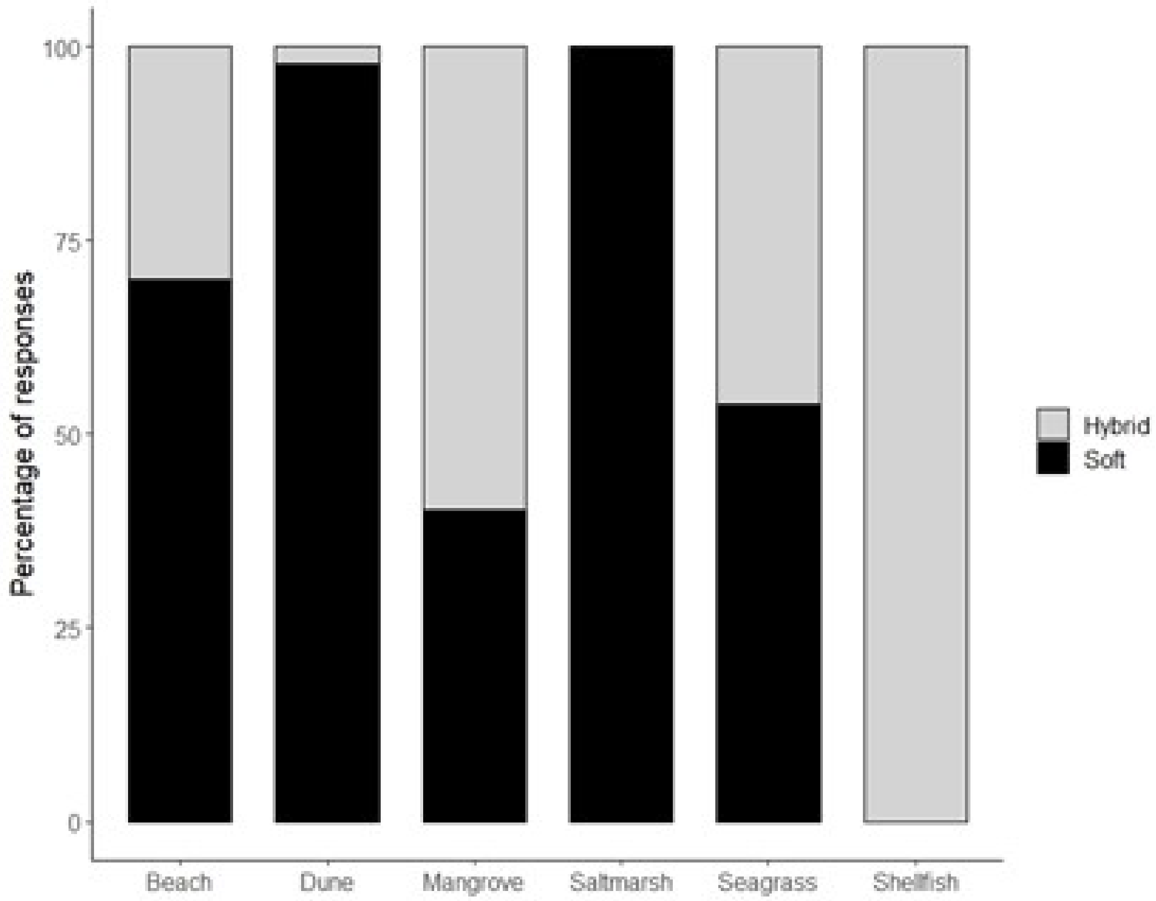


Figure 8. The percentage of soft and hybrid approaches per ecosystem.

Table 3. Median length of coastline protected and median cost ($AUD) per linear metre of living shoreline approaches for “soft” and “hybrid” techniques. Costs were adjusted for inflation before calculation.

Approach	Technique	Example	Length (m)	Cost (m^{-1})
Beach	Soft	Artificial nourishment, replenishment or scraping	690	356
	Hybrid	Sand pumping, sand bypassing	1000	5235
Dune	Soft	Restricting access, revegetation, reshaping, sand fencing	800	46.5
	Hybrid	Dune with rock core	550	4000
Mangrove	Soft	Planting seeds or seedlings	2750	60
	Hybrid	Rock fillet/sill, wooden logs or pilings	407.5	158
Saltmarsh	Soft	Restricting access, hydrological restoration, revegetation	1000	10
	Hybrid	-		
Seagrass	Soft	Planting seeds or fragments	5000	Unknown
	Hybrid	Metal pins, sediment stabilising matting	Unknown	Unknown
Shellfish	Soft	-		
	Hybrid	Rock or shell consolidated or unconsolidated	1037.5	1396.5

3.4 Recognition of coastal hazard risks in Sea Country management plans

79% of the IMPs reviewed had medium or high focus on the coastal area within their IPA, however only 27% discussed climate change related hazards in any detail, and only 21% explicitly identified climate change as being a risk to cultural values or sites (Figure 9). Importantly, 45% of plans described cultural values or sites that, to our reviewer, were obviously at risk of destruction or degradation as a result of coastal hazards, but these hazards were not explicitly identified by the plan (these were deemed “medium”) (Supplementary Table 7). Only 2 plans (7%) discussed specific actions that are being or will be taken to mitigate coastal hazards; one plan is currently undertaking dune revegetation and vehicle exclusion to protect dune systems from erosion, and the other plan details how a coastal resilience program for the area will be created.

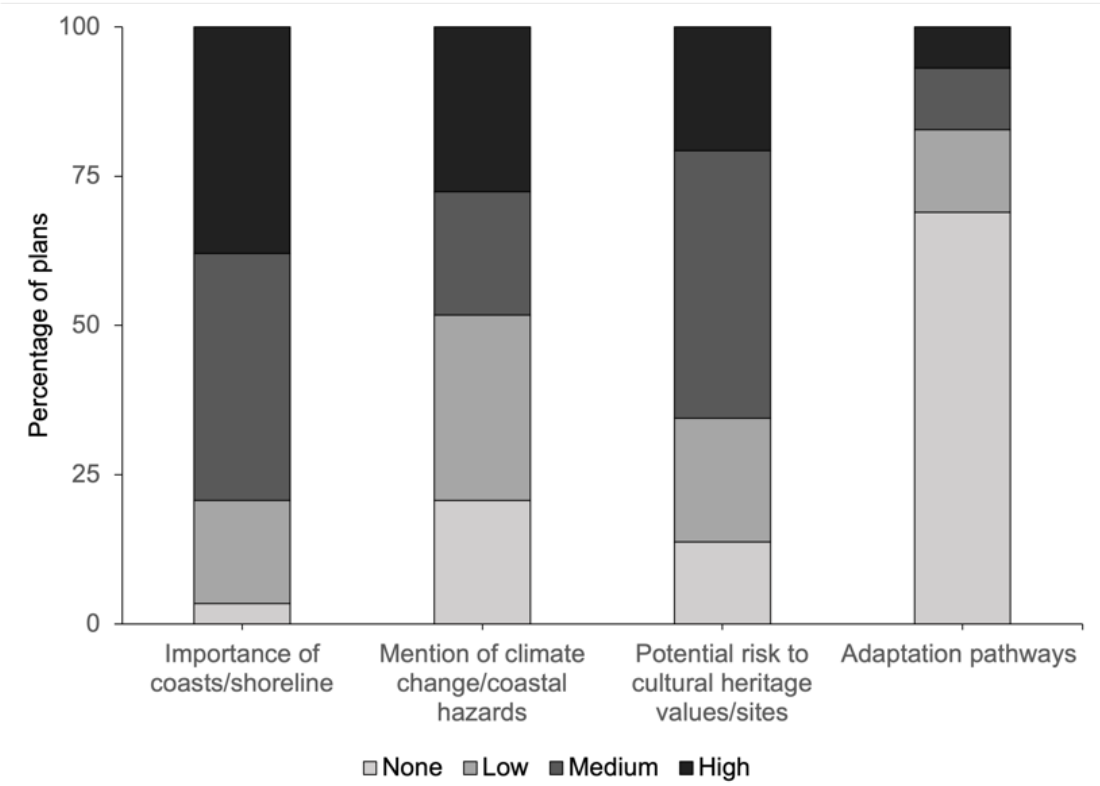


Figure 9. Percentage of management plans addressing the four criteria.

4. Discussion

Previous reviews of the scientific literature identified little (Morris et al. 2018) to no (Smith et al. 2020) use of living shorelines in Australia (although note that these previous studies excluded beach nourishment). Predominantly through stakeholder surveys, we have shown that the use of living shorelines dates back as far as the 1970's for beach and dune management but has also been emerging over the last 25 years for saltmarsh, mangroves, and seagrass, and 5 years for shellfish reefs. Despite this, the number of projects for ecosystems other than beaches and dunes is still low in most states, except for mangroves in New South Wales, and the use of living shorelines is far from standard practice. Living shoreline projects are often run by local or state governments or community groups, so results do not frequently get published in the scientific literature. Encouragingly, more than half of the projects have been formally monitored, either quantitatively or qualitatively. However, for projects where data have not been collected and written up in a robust and defensible manner, and are not publicly available, it can limit the extent to which the project can be used as precedent for future living shoreline applications. The National Living Shorelines Database aimed to fill this gap in the transfer of knowledge among coastal practitioners implementing living shorelines to develop best practice that can be used to inform technical guidelines for different approaches.

A previous assessment of barriers to living shorelines identified them as being function-based or related to public perception or acceptance (DeLorme et al. 2022). Function-related barriers include uncertainty in the level of risk reduction provided, potentially from a lack of evidence on performance. Public perception related challenges include a lack of community or government support, misalignment of public values to the processes and functions of living shorelines, and the potential financial cost (DeLorme et al. 2022). In our survey, the function-related challenges were most frequently cited as uncertainty in the level of risk reduction provided being the primary barrier, followed by a lack of necessary expertise, clarity in the options available and good examples being used. Planning or regulation barriers were also regarded as a significant challenge to the implementation of living shorelines. While these responses largely came from local government representatives who were the main stakeholder group represented in the survey, the function-related barriers to living shorelines align with that of policy makers in state and federal government (Morris et al. 2021a). The policy makers, however, considered that the current Australian coastal policy landscape supports the implementation of living shorelines, for example nature-based methods are explicitly preferred to grey infrastructure where appropriate in the NSW Coastal Management Act 2016 and VIC Marine and Coastal Policy 2020. This potential discrepancy between policy, and planning and regulation barriers to delivering on-ground solutions needs further exploration.

One stakeholder group that was notably missing from the survey was coastal engineering or environmental consultants. Consultants are often employed by government agencies to advise, design, and deliver coastal protection projects. While the projects delivered by consultants may have been captured in the database through local and state government representatives, identifying the barriers to delivering living shorelines by engineering and environmental consultants (Scheres and Schüttrumpf 2020; Saunders et al. 2022) will be important to understand as they will be one of the primary pathways of expertise accessed by coastal managers. Across the states and territories, Western Australia and Northern Territory were particularly underrepresented in survey respondents. These states and territories also had one of the lowest number of projects. What is unclear is whether this is the case or if the low survey response rate in these areas has led to a lower likelihood of detecting living shoreline projects.

The development of a National Living Shorelines Database is a step towards sharing examples of living shorelines in action. A synthesis of the projects included in the database can help guide the context for the use of different living shoreline approaches. However, to increase expertise in this area technical guidelines need to be developed for different methods to inform use at scale. The inventory of projects can be used to identify methods that may have enough on-ground demonstration to build an evidence base that would support technical guidance through existing resources or additional data collection. The database can also be used to identify emerging technologies that can be supported by programs of research that include ecological, engineering, and socio-economic evaluation (e.g., Gijón Mancheño et al. 2021; Gittman et al. 2014; Morris et al. 2021b; Strain et al. 2022).

Beaches and dunes have the longest history of being used for coastal protection, and projects often received either formal or informal monitoring that could be used to determine success. The use of mangroves for coastal protection has accelerated since 2000, particularly in NSW estuaries where hybrid approaches (using rock or timber fillets to produce a hydrodynamically sheltered area for mangroves to re-establish) have been widely used for erosion control (Jenkins and Russell 2017). Despite the broad use of mangrove rock fillets, quantitative assessments of success are few but necessary to inform the effective design and implementation of this technique (Morris et al. in review).

Standardised monitoring protocols for living shorelines in Australia would increase our ability to compare and evaluate different techniques for success. Success may be defined differently depending on the perspective of the stakeholder and should include assessment of the coastal protection provided and extent of habitat establishment; but may also evaluate co-benefits or trade-offs with other services. Shellfish reefs have been widely used for erosion control in the United States (La Peyre et al. 2014; Morris et al. 2021b), but have only been used in Australia in the last five years and mostly not for coastal protection. Shellfish reefs are an attractive hybrid method for coastal protection as the reef forming substrate can be similarly parameterised to submerged breakwaters in the engineering literature (Webb and Allen 2015). However, this can lead to over-engineering and projects need to focus on integrating the species' ecology with engineering principles to achieve success in establishing a shellfish living shoreline (Morris et al. 2019b).

Saltmarsh has a high percentage of projects that were quantitatively monitored, however, with only three projects using saltmarsh alone and four in combination with other habitats, it was not well-represented as an ecosystem for living shorelines in Australia. This contrasts with other areas globally such as the United States (Morris et al. 2018) and Europe (Kosmalla et al. 2022) where saltmarsh is a predominant ecosystem used in living shorelines. Saltmarsh occurs higher in the intertidal zone in Australia compared to many other places around the world (e.g. USA), and therefore has the potential to provide significant protection from storm surge and waves (Duarte et al. 2013). The saltmarsh communities in Australia need specific research, however, as they often differ ecologically and morphologically from the grass-type saltmarsh (e.g., *Spartina*) that has been studied in other areas of the world. Few Australian living shorelines used seagrass and there was a gap in formal monitoring of the projects implemented. This is common globally, where the evidence for seagrass-associated processes effecting erosion control has recently been identified as weak (Twomey et al. 2022). Therefore, more research is needed in this area. Similarly, no projects have used coral reefs or kelp forests for coastal defence, despite strong evidence that coral reefs, at least, are effective at hazard risk reduction and adaptation (Ferrario et al. 2014). However, the less common use of these ecosystems for coastal defence in Australia may be simply a reflection of the extent of their natural distribution when compared to other countries. Although most living shoreline projects focused on one ecosystem, 20.6% of projects used multiple habitats (Figure 10). Multi-habitat living shorelines are another emerging technique which may increase infrastructure resilience, maximise co-benefits and provide protection under a wider range of conditions (Bouma et al. 2014; Moody et al. 2022).

Built assets were more often protected using beaches and dunes, while mangroves, saltmarsh, seagrass and shellfish reefs were implemented to protect natural assets. This likely reflects the greater confidence and history of using beaches and dunes in hazard risk mitigation, or potentially the public perception of coastal vegetation and shellfish reefs near built infrastructure where people are located (e.g., mangroves can be negatively received by the public due to blocking views or water access). With greater use and technical guidance for coastal vegetation and shellfish reefs it would be expected that these techniques should also be used to protect built as well as natural assets. Only six projects were installed to protect cultural assets. There are many recorded Aboriginal sites on the Australian coast, most of which are shell middens but also burials and rock engravings (Aboriginal Heritage Office, 2019). Many of these sites are experiencing significant coastal erosion, for example a third of foreshore middens in North Sydney (Aboriginal Heritage Office, 2019).

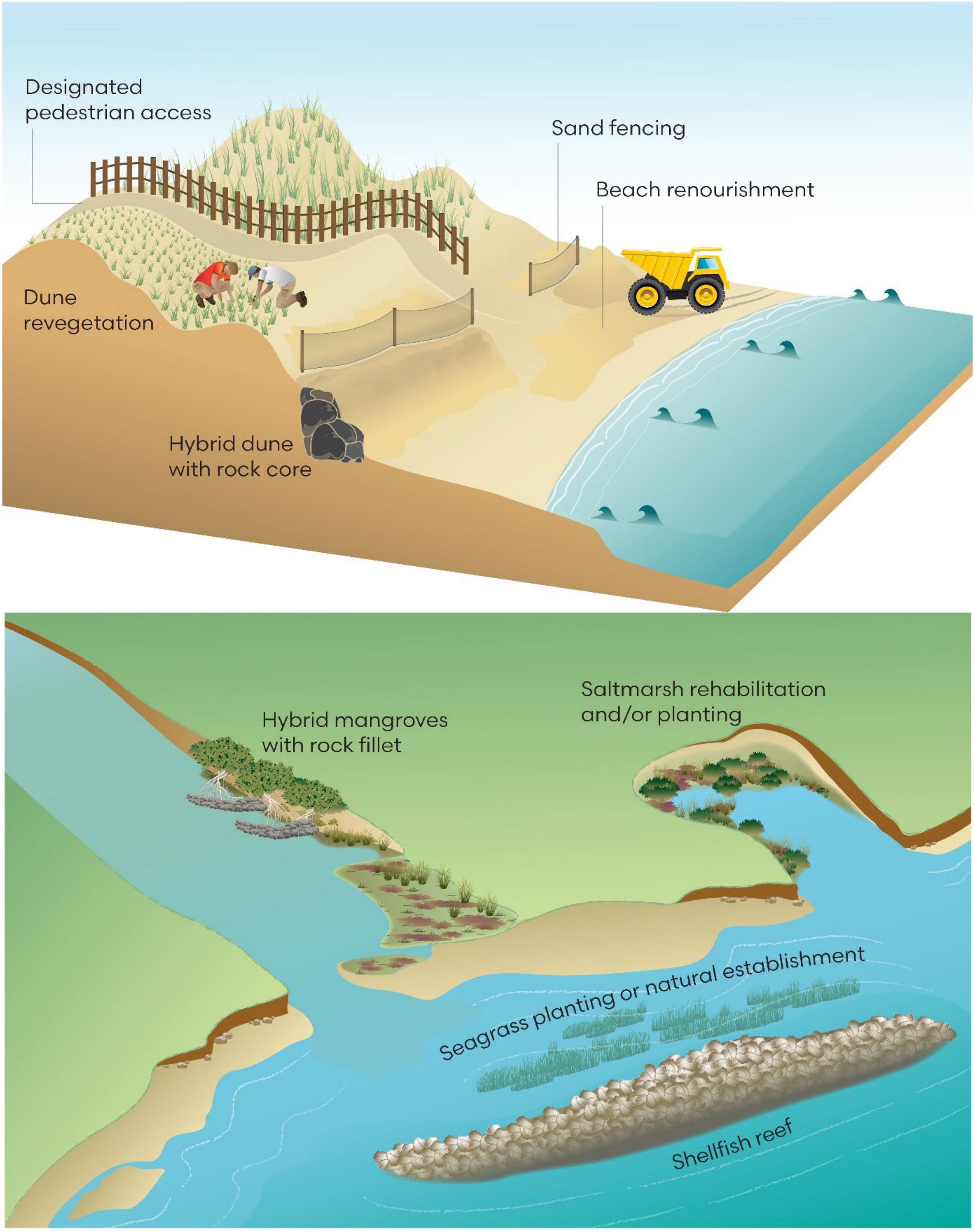


Figure 10 Example of multi-habitat approaches to living shorelines for open coasts (top) and bays and estuaries (below).

The extent to which living shorelines could be used as part of a coastal erosion strategy for aboriginal heritage needs further work, which should be led or co-designed with traditional owners. In our assessment of the Sea Country IPA management plans, we identified an overall lack of explicit reference to climate change related coastal hazards in most plans, with little to no mention of potential adaptation or mitigation pathways. This is despite many plans identifying important cultural sites that, due to their location, are likely to be at risk from coastal hazards, particularly from sea level rise and storm-related erosion. For example, the Yanyuwa Sea Country Plan details the importance of sacred sites such as sand dune systems and beach-based rookeries that are located on the open coast of the Gulf of Carpentaria. These sites are likely exposed to sea level rise and increased storm activity, however no mention of climate change is made in the Plan at all. Additionally, many plans made clear that the ecology and natural values of the area in themselves are important culturally, and damage or degradation of these will have cultural impacts on the traditional owners. Thus, it is important that coastal hazard risks to the natural assets of traditional owner-managed areas are considered as important as protecting more obvious cultural assets, such as middens or sacred sites.

The IMPs that did discuss climate change and coastal hazard risks often stated that they are beyond the capacity of their management to address. However, a single plan, for the Eastern Kuku Yalanji IPA, is currently utilising a nature-based solution to protect an important dune system from erosion. On top of this, several plans, while not stipulating any specific action, discuss the fact that ancestors of today's traditional owners experienced significant sea level rise and non-anthropogenic climate change. Therefore, consultation with elders on ancestral knowledge of these experiences may be beneficial for successful adaptation actions today. It is clear that further engagement with traditional owners regarding the reality of climate change threats, and the potential for soft and culturally appropriate adaptation strategies, is needed to prevent damage to culturally important areas in the future.

5. Conclusions and recommendations

The outcome of this project was to create a living shorelines database for sharing knowledge on different approaches being used in Australia. The database should be used as a starting point for upscaling the use of living shorelines as standard practice for coastal hazard risk management. The database contributes to addressing some of the major barriers experienced by coastal practitioners on living shorelines implementation by providing examples and experience. Key future directions of this work are:

1. Compile commonly used techniques and currently available information, supplemented with additional research where needed, to develop technical guidelines for different methods if they do not exist currently.
2. Identify emerging technologies for research programs to provide the ecological, engineering, and socio-economic information necessary to support broader use. For example, hybrid approaches represent an opportunity for living shorelines in more diverse environmental settings but are less well studied/characterised.
3. Increase the number of living shorelines using ecosystems that are currently not well represented as demonstration projects. Decisions could be aided by a living shorelines options analysis for coastlines (e.g., Nunez et al. 2022).
4. Work with diverse stakeholders, including researchers, practitioners, community and Aboriginal and Torres Strait Islander Organisations to co-design living shoreline projects for built, natural, recreational, and cultural assets.

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Appendix

Supplementary Table 1. Questions for the online survey.

Question #	Question	Question type
1	What is your organisation?	**Check box** • Local Government Authority • State Government Organisation • Federal Government Organisation • Coastal Crownland Manager • Local Land Services • NRM • Land Council • National Landcare Program • Catchment Management Authority • Engineering Consultancy • Environmental Consultancy • Non-governmental Organisation • Community-led Organisation • Traditional Owner Group • Other………
2	In which jurisdiction or local government area do you do most of your work (State, Area, *e.g. Victoria, Wellington Shire)*?	**Short Answer**
The following questions ask about the use of nature-based methods for coastal hazard risk reduction. Nature-based methods defined here are the creation or restoration of coastal habitats for hazard risk reduction. This includes the rehabilitation of existing degraded habitats, restoration of those historically present, or the creation of new habitats in ecologically suitable areas. Nature-based defences can restore the habitat alone ("soft" approach), or in combination with hard structures that support habitat establishment ("hybrid" approaches).		
3	Have you (or your team/organisation) used nature-based methods to reduce the risk of hazards for coastline assets (regardless of whether this was a primary or secondary objective of the project)?	**Check Box** • Yes • No • Not sure
4a	What nature-based methods have you (or your team/organisation) used previously? Please select all that apply.	**Check Box (if yes to [3])** • Beach renourishment • Dune replanting or construction • Mangroves • Mangroves with hard structures • Saltmarshes • Saltmarshes with hard structures • Seagrasses • Seagrasses with hard structures • Shellfish reefs

		● Coral reefs ● Other** If other, please elaborate
4b	What are the reason(s) you (or your team/organisation) have not used nature-based methods in your area (the same area indicated in Question 1)? Please select all that apply.	**Check Box (if no to [3])** ● Unable to secure funding ● Lack of necessary expertise ● Lack of technical guidelines ● Lack of clarity regarding the options available ● Lack of good examples being used ● Uncertainty in the level of risk reduction ● It is inappropriate for my area ● It is not my decision which types of methods are used ● Does not suit the priorities ● Will not work quickly enough ● Planning or regulation barriers ● Lack of governmental support ● Lack of community support ● Other **If other please elaborate
5	Is the use of nature-based methods a priority for (your organisation) future projects to manage the risk of hazards for coastline assets?	**Check Box** • Yes • No • Not sure
6	What, if any, are the current barriers to nature-based methods for coastal protection being used in your area (the same area indicated in Question 1)? Please select all that apply.	**Check Box (only for those that ticked yes to [3])** ● There are no barriers ● Available funding ● Lack of necessary expertise ● Lack of technical guidelines ● Lack of clarity regarding the options available ● Lack of good examples being used ● Uncertainty in the level of risk reduction ● It is inappropriate for my area ● It is not my decision which types of methods are used ● Does not suit the priorities ● Will not work quickly enough ● Planning or regulation barriers ● Lack of governmental support ● Lack of community support ● Other **If other please elaborate

You selected “yes” for implementing nature-based methods in Question 3. The purpose of this survey is to identify individuals (or teams/organisations) that have implemented nature-based methods for coastal protection (completed or planned) to create an online inventory of all projects for the purpose of creating a community of practice, sharing knowledge, and identifying best practice.

7	Would you be willing to be contacted for further information about the projects you have implemented for inclusion in the database?	**Check Box** • Yes • No
8	Please provide your contact details.	**Short answer (if yes to [7])** Name: Email: Phone (optional):

Supplementary Table 2. Literature search terms.

Search terms	# Results
habitat (oyster* or "oyster reef" or shellfish* or "shellfish reef" or kelp* or seaweed* or macroalgae* or seagrass* or "coral reef" or mangrove* or saltmarsh* or marsh* or dunes*) and ("climate change or adapt*" or "coastal erosion" or risk* or flood* or "sea level rise" or "wave attenuation" or "wave energy" or "wave breaking" or storm* or surge*) and (Australia or "New South Wales" or "Victoria" or "South Australia" or "Western Australia" or "Northern Territory" or Queensland or Tasmania)	364
habitat (oyster* or "oyster reef" or shellfish* or "shellfish reef" or kelp* or seaweed* or macroalgae* or seagrass* or "coral reef" or mangrove* or saltmarsh* or marsh* or dunes*) and (restor* or rehabilitat* or "green engineering" or "eco-engineering" or "ecological engineering" or "green infrastructure") and (Australia or "New South Wales" or "Victoria" or "South Australia" or "Western Australia" or "Northern Territory" or Queensland or Tasmania)	288
("breakwater" or "groyne" or "revetment" or "seawall" or "riprap") and ("coastal erosion" or risk* or flood* or "sea-level rise" or "wave attenuation" or "wave energy" or "wave breaking" or storm* or surge*) and (Australia or "New South Wales" or "Victoria" or "South Australia" or "Western Australia" or "Northern Territory" or Queensland or Tasmania)	67
("nourishment" or "replenishment" or "deposition" or "beach enhancement" or "beach skimming" or "beach panning" or "nature assisted beach enhancement" or NABE or "assisted beach recovery" or "beach recycling" or "re-profiling" or "bulldoze/ing" or "sand scrape" or "sand scraping" or "sand push") and (Australia or "New South Wales" or Victoria or "Northern Territory" or Queensland or Tasmania) and (beach or dune)	376

Supplementary Table 3. Ecosystem specific variables for the database.

Ecosystem	Data	Options
Beach	Method	Artificially nourished Replenished

		Scraped Sand bypass/backpass (hybrid) Sand pumping (hybrid)
	Sediment source	Same sediment compartment Quarry Offshore River Building site Other dredged material Other
	Sand volume (m^3)	Short answer
	Sediment placement	Dune area Visible beach Swash to breaking Profile Offshore bar Full profile
	Frequency of renourishment (years)	Short answer
	Date of first renourishment	dd/mm/yyyy
	Date of last renourishment	dd/mm/yyyy
Dune	Method	Rehabilitation (see below) Revegetation Sand fences Mechanical reconstruction or reshaping Hybrid dune with core Other
	Rehabilitation – method	Restrict pedestrian access Restrict vehicle access Weed control Vertebrate trampling/grazer control Educational signage New access points
	Vegetation species	Short answer
	Planting density	Short answer
	Sand fence - material	Wood Plastic Jute Branches or brush Other
	Sand fence - configuration	Straight Zig zag Alongshore Diagonal to shore Perpendicular to shore Single row Multiple row Other
	Sand fence - porosity	Short answer

	Sand fence – height (m)	Short answer
	Sand fence – width (m)	Short answer
	Sand fence – length (m)	Short answer
	Dune construction – width (m)	Short answer
	Dune construction – height (m)	Short answer
	Hybrid dune – core material	Geotextile Rock Gabions Other
Saltmarsh	Method	Rehabilitation (see below) Hydrological restoration Planting Hybrid Other
	Rehabilitation – method	Restrict pedestrian access Restrict vehicle access Weed control Vertebrate trampling/grazer control Educational signage New access points
	Hydrological restoration - method	Removal of dikes/levees Breaching of dikes/levees Sediment removal Sediment addition Other
	Saltmarsh species	Short answer
	Planting density	Short answer
	Hybrid structure	Rock fillet/sill Offshore structure - rock Offshore structure - wood Coir logs Smart gates Other
	Hybrid structure – width (m)	Short answer
	Hybrid structure – height (m)	Short answer
	Hybrid structure – length (m)	Short answer
Mangrove	Method	Hydrological restoration Rehabilitation (see below) Planting: direct seeding Planting: nursery reared Hybrid Supplementary revegetation (with other riparian species) Other
	Rehabilitation – method	Restrict pedestrian access

		Restrict vehicle access Weed control Vertebrate trampling/grazer control Educational signage New access points
	Supplementary revegetation	Short answer
	Hydrological restoration method	Removal of dikes/levees Breaching of dikes/levees Sediment removal Sediment addition Rebattering Other
	Mangrove species	Short answer
	Planting density	Short answer
	Seedling age at planting (months)	Short answer
	Hybrid structure	Rock fillet/sill Hardwood logs or pins Offshore structure - rock Offshore structure - wood Coir logs Other
	Hybrid structure – width (m)	Short answer
	Hybrid structure – height (m)	Short answer
	Hybrid structure – length (m)	Short answer
Seagrass	Method	Planting: rhizome fragments Planting: seed Hybrid Other
	Seagrass species	Short answer
	Planting density	Short answer
	Hybrid structure	Offshore structure - rock Offshore structure - wood Coir logs Sediment stabilising matting Metal pins Environmentally friendly moorings Other
	Hybrid structure – width (m)	Short answer
	Hybrid structure – height (m)	Short answer
	Hybrid structure – length (m)	Short answer
Kelp forest	Method	Assisted establishment Transplantation - adults Transplantation - juveniles Seeding Substrate addition

		Other
	Assisted establishment - method	Marine Protected Areas Catchment Management Pest management Other
	Kelp species	Short answer
	Seeding density	Short answer
	Hybrid structure	Artificial reef - natural rock Artificial reef - concrete Other
	Hybrid structure – width (m)	Short answer
	Hybrid structure – height (m)	Short answer
	Hybrid structure – length (m)	Short answer
Coral reef	Method	Assisted establishment Substratum stabilisation Substratum addition Substratum enhancement Transplanting fragments Larval enhancement Assisted gene flow technology Assisted evolution/synthetic biology Other
	Assisted establishment – method	Marine Protected Areas Catchment Management Pest management Other
	Coral species	Short answer
	Transplant/seeding density	Short answer
	Hybrid structure	Artificial reef- natural rock Artificial reef- concrete Other
	Hybrid structure – width (m)	Short answer
	Hybrid structure – height (m)	Short answer
	Hybrid structure – length (m)	Short answer
Shellfish reef	Method	Substrate provision Seeding - aquaculture Seeding - wild stocks Other
	Oyster species	Short answer
	Seeding density	Short answer
	Hybrid structure	Natural rock Unconsolidated shell Consolidated shell (e.g., bags, cages)

		Concrete structures Other
	Hybrid structure – width (m)	Short answer
	Hybrid structure – height (m)	Short answer
	Hybrid structure – length (m)	Short answer

Supplementary Table 4. Number of living shoreline projects by information source.

Source	Number of projects
All sources	**138**
Survey respondents	52
Literature search	4
Reference lists	8
Cooke et al. (2011) review	15
Morris et al. (2018) review	1
BMT Benchmark Report*	11
ACRN Project Database†	2
Personal communication	33
Google searches	12

> *BMT NbS Benchmark Assessment Report, prepared for Caitlin Ziviani and Scott Hardy; †https://www.acrn.org.au/database

Supplementary Table 5. Results from type III ANOVA testing for the effect of a) time, approach and time*approach interaction and b) time, state, and time*state interaction on the number of living shoreline projects identified.

	df	SS	MS	F	p
Number of projects by time and approach					
Time	10	67.35	6.73	6.95	<0.001 *
Approach	6	40.06	6.68	6.90	<0.001 *
Time*Approach	60	74.69	1.24	1.28	0.09
Residual error	315	305.27	0.97		
Number of projects by time and state					
Time	10	55.47	5.55	7.88	<0.001 *
State	5	29.46	5.89	8.37	<0.001 *
Time*State	50	57.02	1.14	1.62	<0.001 *
Residual error	270	190.03	0.70		

Supplementary table 6. List of management plans evaluated for their discussion of climate change related coastal hazard risks to cultural values and/or sites.

IPA	State	Name of plan	Document type	Time span	Importance of coasts/ shores	Mention of climate change/ coastal hazards	Potential risk to cultural heritage values or sites	Mention of adaptation pathways	Notes
Nyangumarta Warrarn and Karajarri IPA	WA	Eighty Mile Beach Marine Park	State management plan	2014-2024	High	High	Medium	None	
Karajarri IPA	WA	Karajarri Healthy Country Plan 2013-2023	Indigenous Healthy Country Plan	2013-2023	Medium	Low	Medium	None	
Yawuru IPA	WA	Yawuru Nagulagun/Roebuck Bay Marine Park	Joint Management Plan		Low	Medium	Low	Low	Some discussion of undertaking local adaptive management to mitigate climate related threats.
Bardi Jawi IPA	WA	Bardi-Jawi Indigenous Protected Area Management Plan	Indigenous Healthy Country Plan	2013-2023	Low	Low	Low	None	

Dambimangari IPA	WA	Dambimangari Healthy Country Plan 2012-2022	Indigenous Healthy Country Plan	2012-2022	Medium	High	High	Low	Some recognition of the need to adapt to climate change in the future.
		Lalang/Garram/Camden Sound Marine Park Management Plan 2013-2023	Joint Management Plan	2013-2023	High	Low	Medium	None	
Uunguu IPA	WA	Uunguu Indigenous Protected Area: Wundaagu (saltwater) Indicative Plan of Management 2016-2020	Indigenous Healthy Country Plan	2016-2020	Low	Low	Medium	None	

		Wunanbal Gaambera Healthy Country Plan	Indigenous Healthy Country Plan		Medium	High	High	None	Plan explicitly lays out climate change related threats to coastal habitats as well as cultural areas, however no indication of any action planned to mitigate these threats.
Balanggarra IPA	WA	Balanggarra Healthy Country Plan 2012-2022	Indigenous Health Country Plan	2012-2022	Low	Medium	Low	None	
Nyangumarta Warrarn IPA	WA	Nyangumarta Warrarn Indigenous Protected Area Plan of Management 2015 to 2020	Indigenous Management Plan	2015-2020	Medium	None	None	None	

Mayala Baaliboor – Mayala	WA	2019-2029 Mayala Country Plan	Country Plan	2019-2029	High	Medium	High	Medium	Plan highlights that the traditional owners of this Country lived through sea level rise events in the past, and suggests that consulting with traditional knowledge for mitigation strategies would be highly beneficial.
Anindilyakwa IPA	NT	Anindilyakwa Indigenous Protected Area Plan of Management 2016	Indigenous Management Plan	2016-2026	Medium	Medium	Low	None	

Dhimurru IPA	NT	Dhimurra Indigenous Protected Area Management Plan 2015-2022	Indigenous Management Plan	2015-2022	High	High	High	None	Plan explicitly identifies cultural sites including middens, artefact scatters and sacred sites that are at risk from sea level rise and storm damage. No discussion of adaptation strategies follows, however.
Laynhapuy IPA	NT	Yirralka Rangers Business Plan 2013-2016	Indigenous strategic business plan	2013-2016	Low	None	None	None	
Yanyuwa IPA	NT	Barni-Wardimantha Awara Yanyuwa Sea Country Plan	Indigenous Management Plan	2007	High	None	Medium	None	While the area clearly holds a lot of cultural value, and some sites will likely be impacted by climate change, there is no explicit mention of CC-related threats.

Nijinda Durlga IPA	QLD	Nijinda Durlga (Gangalidda) Indigenous Protected Area Management Plan	Indigenous Management Plan	High	High	Medium	None	The area is of significant cultural and natural significance and the plan describes in detail the threats to the area from climate change due to the extremely low topography of the region and proximity to frequent cyclone events. Despite this, no mention of adaptation strategies is made.
Thuwathu-Bujimulla (Wellesley Islands) IPA	QLD	Thuwathu/Bujimulla Indigenous Protected Area Management Plan	Indigenous Management Plan	High	Medium	Low	None	

Pormpuraaw Rangers (Land in Trust)	QLD	Pormpuraaw Land and Sea Country CNRM Plan 2010-2015	Indigenous Management Plan	2010-2015	Medium	High	High	Medium	Explicit mention of tidal inundation and coastal erosion as a result of climate change. Some discussion of the need for adaptation/mitigation, including suggestions for working with traditional owner knowledge of past sea level rise events.

Eastern Kuku Yalanji IPA	QLD	Eastern Kuku Yalanji Indigenous Protected Area Management Plan Stage 2 - Jalunjii-Warra Land and Sea Country	Indigenous Manageme nt Plan	2012+	Medium	Medium	High	High	Explicit mention of climate stressors affecting the natural heritage of the area, as well as acknowledgem ent of the need to protect dune systems to mitigate erosion and flooding. Clear indication that nature-based measures including vehicle access exclusion and revegetation are being used for dune management.
Mandingalb ay IPA	QLD	Strategic Plan for Mandingalba y Yidinji Country	Indigenous Strategic Plan	2009+	Medium	None	None	None	

Gunggandii Land and Sea Rangers	QLD	Gunggandji Land and Sea Country Plan	Indigenous Strategic Plan	2013+	Medium	High	Medium	Medium	"Our ancestors have lived through a 100m rise in sea level, great changes in rainfall…we want to continue this long tradition of successful adaptation by learning more about current climate change threats and contributing to solutions for the benefit of Hunhhandji People and other residents of the region. Through the implementation of this Land and Sea Country Plan we seek to be involved in monitoring and minimising the impacts of climate change and collaborating with our

									management partners to find adaptive solutions where necessary.”
Girrigngun IPA	QLD	Girringun Region Indigenous Protected Areas Management Plan 2013-2023	Indigenous Management Plan	2013-2023	High	Low	Medium	None	

Eastern Kuku Yalanji, Mandingalbay and Girringun IPA	QLD	Wet Tropics Aboriginal Cultural and Natural Resource Management Plan	Indigenous Management Plan	2005+	Medium	Low	Medium	None
Pulu IPA	Torres Strait	Pulu Indigenous Protected Area Plan of Management	Indigenous Management Plan	2009	High	Low	Medium	None

Putalina IPA	TAS	Putalina Management Plan	Indigenous Manageme nt Plan	2020+	Medium	None	Medium	None	Despite no mention of coastal hazards threatening them, an abundance of culturally important sites including middens and quarry rock outcrops are located close to shore.
Premingha na IPA	TAS	Preminghana Healthy Country Plan 2015	Indigenous Healthy Country Plan	2015	High	High	Medium	None	Despite significant discussion of the potential impacts of climate change on culturally important coastal habitat, no mention of adaptation is made.

lungatalanana IPA, Babel Island IPA & Big Dog Island IPA	TAS	lungtalanana, Babel Island & Big Dog Island Healthy Country Plan 2015	Indigenous Healthy Country Plan	2015	Medium	Low	Low	Low	Some mention is made of planting tussock grass to stop erosion, however it is unclear the context the erosion is occurring in.
Wardang Island IPA	SA	Conservation Action Planning June 2015 Summary Southern Yorke Peninsula	Government Report	2015	High	Low	Medium	High	Report includes a detailed action plan for assessing, planning for, and increasing resilience to climate change and sea level rise risks.
Yalata IPA	SA	Yalata Indigenous Protected Area Draft MERI Plan – Monitoring, Evaluation, Reporting, Improvement (2011-2016)	Indigenous Healthy Country Draft Plan	2011-2016	None	None	None	None	No mention of the coast is made despite it being a large part of the IPA.

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