FINAL REPORT

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Project 1.7

Towards a consolidated and open-science framework for restoration monitoring

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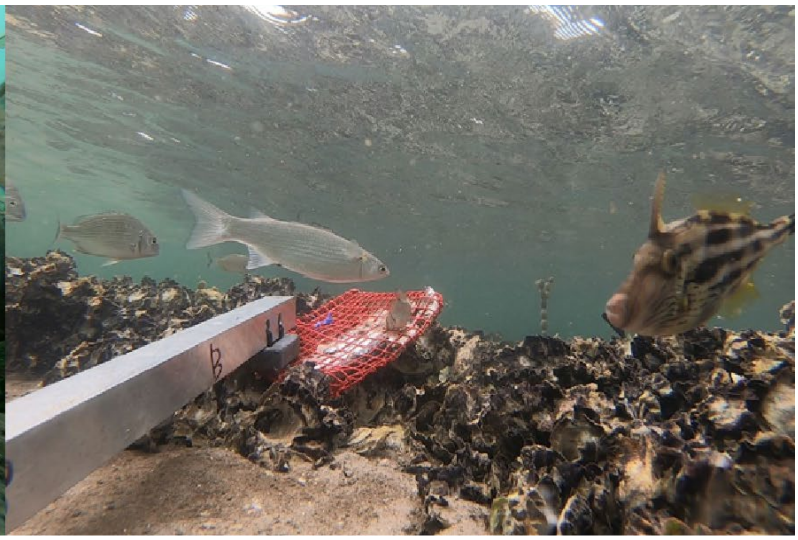

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Executive summary

Coastal habitat restoration is scaling up rapidly in Australia and covers a range of habitats. Every restoration project includes some attempt at monitoring outcomes but currently these are piecemeal, uncoordinated, often poorly funded, and rarely follow Open Science protocols. Previous NESP-funded projects have improved understanding of the ecology and service provision of threatened ecosystems and established targets for repair based on reference conditions (e.g. Marine Biodiversity project B4). They have also established an extensive database of marine and coastal restoration projects (ARCN: project E5), and have supported the development of monitoring, evaluation, reporting and improvement systems (MERI) for various sectors or projects.

This project builds upon these previous projects to synthesise the approaches for monitoring of habitat restoration by combining the knowledge of Australian researchers undertaking monitoring of restoration projects across multiple habitats, with a global literature review. It also explores integration of new technologies, such as automation, artificial intelligence, and eDNA, within monitoring programs to improve efficiency and cost-effectiveness.

Our survey revealed that, within Australia, most restoration projects aim to restore lost habitat and to improve biodiversity. Key habitats which are the focus of restoration projects in Australia are seagrass, kelp, coastal wetlands, mangroves, saltmarsh, *Melaleucas*, shellfish reefs and coral reefs. The variables that are monitored reflect the overarching goals of the projects, and therefore those which are most commonly monitored tend to provide measures of ecosystem or habitat function. Monitoring of physical and social-economic variables is less common. Monitoring programs tend to rely on fieldwork-intensive techniques, and many projects are implementing new, advanced technologies such as drones with high positional accuracy. The incorporation of citizen scientists into monitoring programs was common. Finally, our results show that monitoring data for restoration projects are not often publicly available or straightforward to access.

A literature review of monitoring programs for coastal and marine restoration globally highlighted similar trends, again with a bias toward the measurement of variables relating to ecosystem/habitat function. The uptake of advanced technologies is becoming more common for saltmarsh or seagrass-based restoration programs, however is still rare for other ecosystem types. The availability of monitoring data has historically been restricted to the publication of summaries in papers and reports, but is becoming increasingly accessible in recent years, likely in response to the drive for data availability in scientific publishing.

The final stage of the project was to hold a workshop for key practitioners and scientists involved in nationally recognised restoration projects, to discuss the findings from the survey and literature review, and to draft a guidelines document for monitoring that can be provided to restoration practitioners working across projects, scales and habitats. Workshop participants acknowledged that a single set of monitoring variables will be difficult to apply across projects, and that the overarching objective of individual projects will dictate variables to be measured. Given this, the workshop reached consensus of a small set of universal variables that can be standardly used across restoration projects to facilitate broad comparisons and benchmarking. Measurement of additional goal-based variables and habitat-specific variables should also be considered. It was highlighted that new technologies show promise for increased efficiency of data collection, and that the use of this technology should be facilitated. The group also advocated for public availability of raw data, and the use of standardised definitions and units to facilitate comparison.

The final output of this project is a guidelines document for co-ordinated and open-science monitoring. These guidelines are designed to be used by working groups and practitioners to further refine and standardise monitoring methodologies to streamline development of future restoration projects and ensure that maximum value from monitoring activities is achieved.

1. Introduction

Ecological restoration is defined as the activity of restoring degraded sites, which encompasses multiple forms of intervention (Ableson et al., 2016). Restoration activities can entail amelioration of the physical and chemical characteristics of the substratum to enable a return of vegetation cover, the improvement of the productive capacity of degraded lands by improving acid sulphate soils, or the enhancement of conservation values by removing invasive species or grazers (Hobbs & Norton 1996). Others focus on on-ground activities to assist recovery (for example, transplanting seagrass rhizomes). As the method of restoration defines the restoration goals and subsequent monitoring, it is important to note that we concentrate here on “active restoration” of on-ground activities that focus on biogenic habitat-forming elements (e.g., seagrass, kelp, coastal wetlands, mangroves, saltmarsh, *Melaleucas*, shellfish, and coral).

There is currently a surge of interest in marine and coastal restoration in Australia, with a significant number of projects under way and many more in the planning phase. The Coastal Restoration Database developed by the Australian Coastal Restoration Network lists over 230 individual projects between 1978 and 2020 focused on restoration of biogenic habitat- forming elements, i.e., coral, seagrass, kelp, mangroves, saltmarsh, shellfish reefs, or entire estuaries or wetlands (Purandare 2021). These projects are undertaken by a range of non- government organisations, government agencies, universities, and community groups, and vary in scale, objectives, and resourcing. Despite the current focus on restoration (e.g., the UN Decade on Ecosystem Restoration, www.decadeonrestoration.org) and recent, high profile government investment (e.g., the federally funded AUD20 million ‘Reef Builder’ shellfish restoration program), it is difficult to obtain a clear picture of the scale and benefits of coastal and marine restoration in Australia. This is primarily due to the lack of a consolidated and accessible framework for the reporting and monitoring of these restoration initiatives.

The scale and scope of monitoring programs associated with restoration projects tend to reflect the initial motivations and objectives for the restoration, and these are varied. In a recent study, Bayraktarov and colleagues (2020) found that the most common motivation for restoration projects globally was to develop improved restoration techniques and/or ecological knowledge. The second most common motivation was to enhance biodiversity, and, correspondingly, the variables monitored within these projects tended to focus on monitoring of ecological objectives. Fewer projects were developed to provide ecosystem services or were motivated by social/cultural drivers, and therefore most did not measure progress towards any socio-economic, engineering (e.g. shoreline stabilisation), educational, and/or cultural goals. Current and future projects would benefit from the development of a standardised toolkit of monitoring techniques tailored to address different desired restoration outcomes and available resources for monitoring, including ecological, physical, economic, social, and cultural variables.

The need for a standardised framework for coastal and marine restoration monitoring and reporting has been clearly documented in previous projects and studies (European Commission, 2008; Goergen et al., 2020; Lindenmayer 2020; Mack et al., 2020; Eger et al., 2022). The benefits of implementing standardised reporting include 1) facilitation of comparisons between restoration projects/sites (Goergen et al., 2020), 2) ensuring that future restoration projects can evaluate the effectiveness of previous approaches, improving efficiency and maximising outcomes (Eger et al., 2022) 3) enabling promotion of the collective benefit of habitat restoration (and incentivisation of future projects) (Eger et al., 2022), 4) ensuring that parameters beyond the ecological and physical realms (e.g., socio-economic benefits) are considered (Eger et al., 2022), 5) reducing reporting bias (Eger et al., 2022), 6) facilitation of effective co-operation between stakeholders involved in restoration within the same geographic and/or legislative area (Mack et al., 2020), and 7) ensuring key and cost-effective variables are measured to help determine success of a restoration project. Despite these benefits and documented needs, current monitoring of restoration progress and success varies enormously, with low uptake of technological advances that promote efficiency and comprehensiveness, and large differences in approaches among habitats.

Furthermore, raw data from monitoring programs can be difficult to obtain and are recorded in disparate units and formats, making inter-project comparisons challenging even if similar variables are monitored.

There are a range of comprehensive guidelines for monitoring restoration, most of which are habitat-specific (e.g., Paling et al. 2009, Baggett et al. 2015, Fitzsimons et al. 2019, Eger et al. 2022), or habitat and location-specific (e.g., Fonseca 1998, Van Katwijk et al. 2009, NSW Department of Primary Industries 2021, zu Ermgassen et al. 2021). Eger and colleagues (2022) called on practitioners to develop a restoration reporting framework that includes a standardised set of variables that can be recorded for all marine restoration projects, and presented a roadmap for the development of this framework. An initial step of the roadmap is the co-production of a draft restoration reporting framework by a focal group for one or two ecosystems within one jurisdiction. This initial step aligns with the aim of this project, which is to develop a guidelines document for co-ordinated monitoring of restoration initiatives.

Several activities were designed to inform the development of this document;

1) An online survey of restoration practitioners, scientists, and partners (including Indigenous ranger groups) within Australia to reveal the goals for restoration, and then to identify key elements of current monitoring programs, current data handling and reporting practices, access to equipment and resources (e.g., funding), and key constraints and challenges to obtaining meaningful results.
2) A literature review of strategies that have been implemented globally to monitor progress towards ecological, socio-economic, engineering, and cultural goals of restoration. The review included an investigation of new and emerging technologies (including eDNA, artificial intelligence, remote sensing, drone technology, geo-tagging, app-based surveys), automation, whole-of-ecosystem (rather than taxon-specific) approaches, the use of citizen science, the integration of cultural monitoring, and temporal continuity. The review also built on existing monitoring protocols (e.g., the Society for Ecological Restoration's generic principles and standards guide, Gann et al. 2019) to determine what variables might be monitored as a starting point, and provide the framework for workshop discussions about best-practice monitoring.
3) A workshop for key restoration practitioners, scientists, and partners to discuss the results of the survey and literature review and draft a guidelines document for restoration monitoring. The draft will be critically assessed in the context of current monitoring programs, gaps and challenges, data availability and adoption of new technologies. The guidelines will include monitoring of ecological variables as well as engineering, social, economic, educational, and cultural impacts.

The identification of monitoring goals and protocols applicable across restoration projects will facilitate comparison and benchmarking across projects, based upon desired restoration outcomes. The guidelines document developed by the project will link to the broader policy agenda regarding Nature-based solutions and will follow the guidance provided by IUCN.

2. Online survey of restoration practitioners, scientists, and partners within Australia

2.1 Summary

A survey was targeted to practitioners and scientists within Australia who are involved with coastal and marine restoration. Survey participants were predominately recruited by emails to relevant networks (Australian Coastal Restoration Network; Australian Marine Sciences Association). The survey was designed to determine if the goals, monitoring programs, and uptake of new technologies in Australia reflect global trends in marine and coastal restoration programs, as determined by comparison with a worldwide literature review on monitoring of restoration that was also undertaken (section 3).

2.2 Survey background

Stakeholder online surveys were sent to restoration practitioners, scientists, and partners to understand the goals for restoration and then to identify key elements of current monitoring programs, current data handling and reporting practices, access to equipment and resources (e.g., funding), and key constraints and challenges to obtaining meaningful results.

Specifically, intended survey participants were researchers or natural resource management practitioners who are or have been involved with coastal and/or marine restoration projects in Australia and were able to comment on monitoring programs.

Questions for the survey were developed by all researchers and end-users of the project. The survey (and workshop) was approved by Griffith University's Human Research Ethics Committee (approval number 2021/904) in accordance with the National Statement on Ethical Conduct in Human Research. The surveys were completely anonymous and conducted through the online platform Survey Monkey: https://www.surveymonkey.com/r/8679P8H

The survey aimed to reach all relevant national stakeholders. It was sent directly to the NESP Project 1.7 project team and end users (25 individuals), specific direct invites that were known to involved with restoration projects, and open mail-outs by the Australian Coastal Restoration Network and the Australian Marine Science Association.

After agreeing to the participant information, respondents were led though up to 29 questions, with different subsets of questions depending on responses (Appendix A). Background information on the project was collected to understand whether multiple survey responses were received for the same restoration project (e.g., by multiple collaborators); this information was kept confidential and not used for other purposes. It was observed to be more likely that a single respondent filled in multiple surveys for multiple restoration projects.

The survey results are held confidentially on a secure server at Griffith University. They were analysed with the results of the literature review (section 3) and used to guide the workshop participants in drafting the draft guidelines document (section 4).

2.3 Overview of respondents

A total of 55 separate responses were received from the survey and a broad range of national stakeholders were reached. Based on information from respondents about their projects, 21 were based in Queensland, 16 in New South Wales, 11 from other states, and none from the Northern Territory.

A range of organisations were reached in the survey. The majority of respondents were from universities (21%), local, State or Federal governments (19%), or consultancies (19%). Importantly, most of the respondents (78%) were from organisations that had the primary responsibility for the planning, and implementation of the restoration project.

The majority of respondents targeted shellfish (35%), mangroves (18%), coral (14%), seagrass (14%), saltmarsh (11%), wetlands (7%), and kelp (6%) as the primary habitats for their restoration projects (Figure 1). Other habitats where restoration was targeted (24%) were primarily non-biogenic habitats (e.g., mudflats, dunes, rocky shores). A smaller component of restoration efforts focused on single species restoration (e.g., seahorse hotels, 7%) (Figure 1).

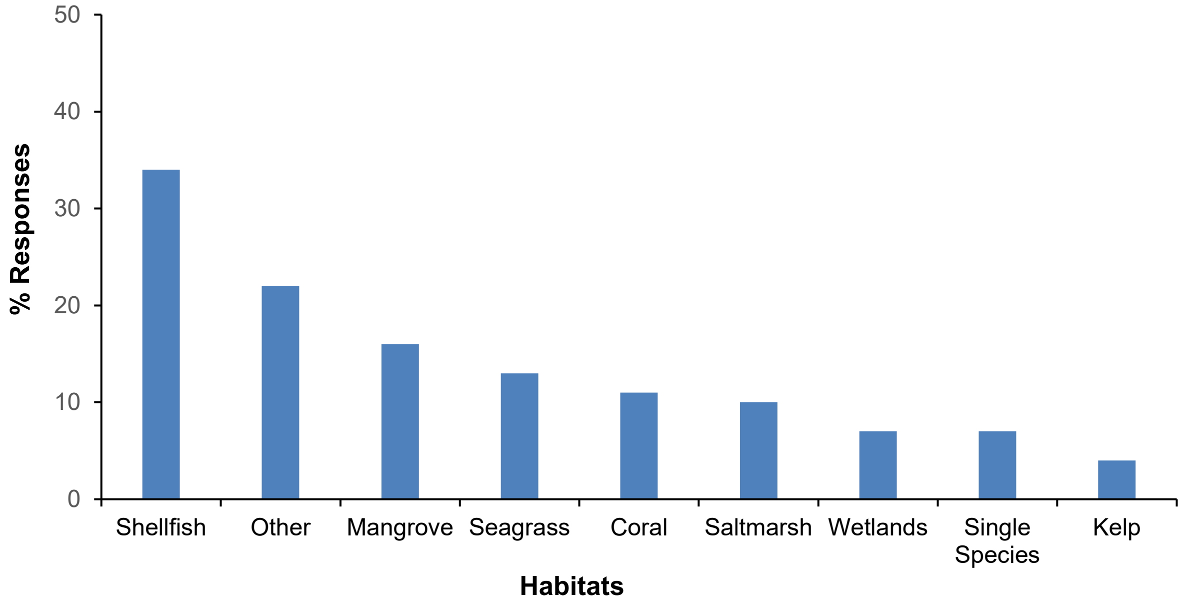

Figure 1. Percentage of responses to the question: What types of marine and coastal habitat is targeted in your project?

The majority of restoration projects (75%) were relatively small scale (<10 ha), but a small percentage (6%) were >5000 ha. Ideally, additional options would be offered for projects less than 10 hectares to have a greater understanding of restoration projects that aim to restore a substantial area of habitat compared to those with an experimental focus.

2.4 Overview of national restoration monitoring

Monitoring and evaluation are recognised as important aspects of restoration projects in Australia. 93% of respondents stated that monitoring and evaluation were included as part of their restoration project.

Importantly, the majority of organisations that were responsible for delivering the monitoring program were also the organisation responsible for overall implementation of the restoration project (67%). Universities and local, State or Federal governments were equally (both 36%) responsible for delivering the monitoring programs for restoration projects, followed by consultancies (25%). A small number of Aboriginal or Torres Strait organisations (8%), and Native Title groups (6%) were responsible for delivering monitoring programs.

The reported cost of monitoring and evaluation for restoration projects is relatively small. For 32% of projects, monitoring ('to date', if project is ongoing) was costed at $10,000-$50,000 (unspecified if it was including salaries or in-kind contributions). Monitoring of a single project was, however, reported to cost over $500,000. Many respondents (39%) believed that the project had adequate access to resources (equipment and funding) to facilitate monitoring, and 25% thought resources were partially adequate. Despite this, 45% of respondents described activities that could have been delivered with additional resources; responses generally included longer term monitoring or a before/after component to the monitoring.

Most projects were monitored for only a relatively short period. Despite the long-term benefits of restoration, the majority of projects were monitored for 2-5 years (33%), with only 13% monitored for 5-10 years. Many projects were, however, reported to have ongoing monitoring programs (27%). The majority of projects (62%) experienced some constraints or challenges with the monitoring of the project. They were generally reported as being delays due to contractors, the COVID-19 pandemic, or difficulty with partners.

2.5 Goals set for restoration

Overall, the primary goal of restoration projects (Figure 2), was to restore the lost habitat (84%). Additional goals included improvement of biodiversity (63%), increasing fisheries productivity (50%), water quality improvement (39%), improvement of cultural/social amenity (25%), and recovery of a threatened species (25%). This response was investigated in further detail to understand whether the goals for restoration differed depending on the habitat focused for restoration. Regardless of the habitat, restoration of lost habitat and improvement of biodiversity ranked highly as restoration goals. Water quality improvement (all but seagrass), increased fisheries productivity (all but for coral), and shoreline stabilisation (for estuarine habitats, i.e., not coral and kelp) also ranked within the top 5 goals for restoration (Table 1).

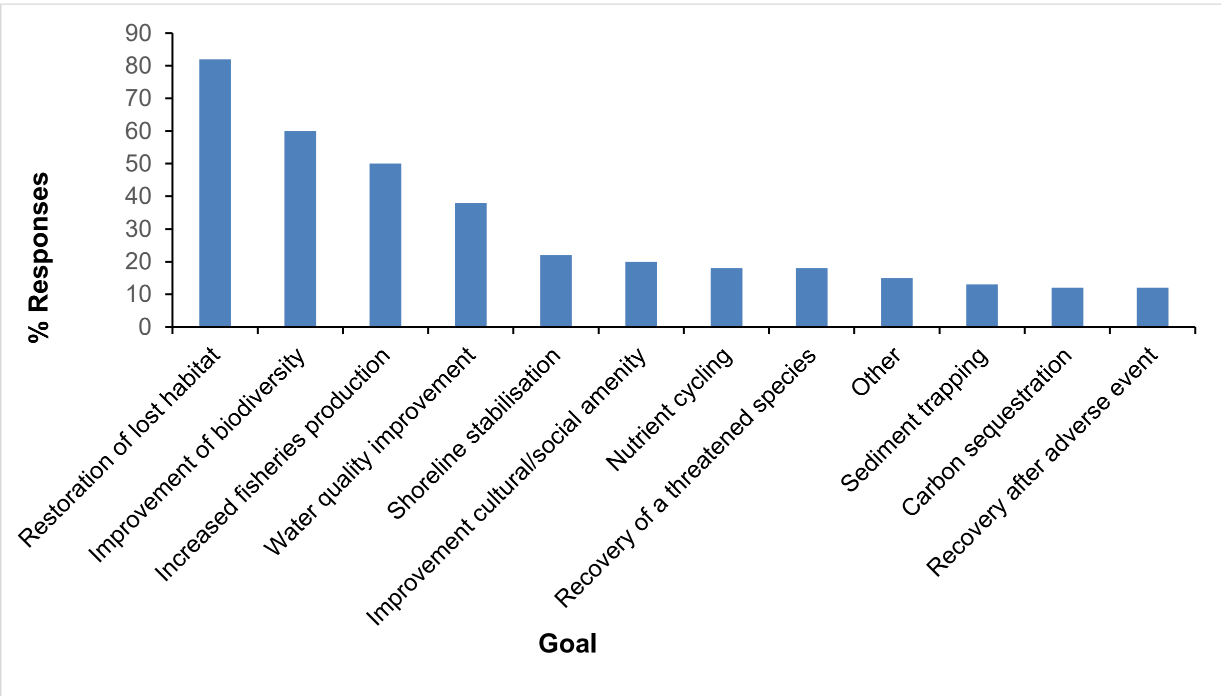

Figure 2. Percentage of responses to the question: What are the primary goals of the restoration project?

Table 1. Filtered by the habitat that was the focus for restoration, top 5 responses (%) to the question: What are the primary goals of the restoration project?

Goal	Shellfish	Coral	Wetlands, mangroves, saltmarsh	Seagrass	Kelp
Restoration of lost habitat	90%	50%	94%	100%	100%
Increased fisheries production	70%		50%	50%	100%
Improvement of biodiversity	70%	50%	63%	63%	67%
Water quality improvement	65%	38%	38%		67%
Shoreline stabilisation	25%		31%	50%	
Recovery of a threatened species		38%			
Carbon sequestration				50%	67%
Tourism and industry resilience		25%			

Although it is well-known that the parameters and variables that are monitored are dependent on the goals of a restoration project, the survey gave a clear overview of the those that are or were monitored in restoration projects in Australia (Figure 3). These were mostly within the broad category of ecosystem or habitat function, e.g., measuring species composition or biodiversity, survivorship or mortality of species, and percentage cover (all ≥ 70%). Physical variables were second to ecosystem or habitat function variables, e.g., temperature, structural diversity/topography, and salinity. Social-economic measures did not rank highly in the priorities for monitoring and evaluation, with community engagement/ awareness the highest at 31%. Assessment of variables reported to be measured in at least 50% of the survey responses per habitat type identified those that can successfully be applied across ecosystems (Table 2). These include survival/mortality and species composition/biodiversity. Most habitat types also commonly monitored percentage cover and growth/productivity.

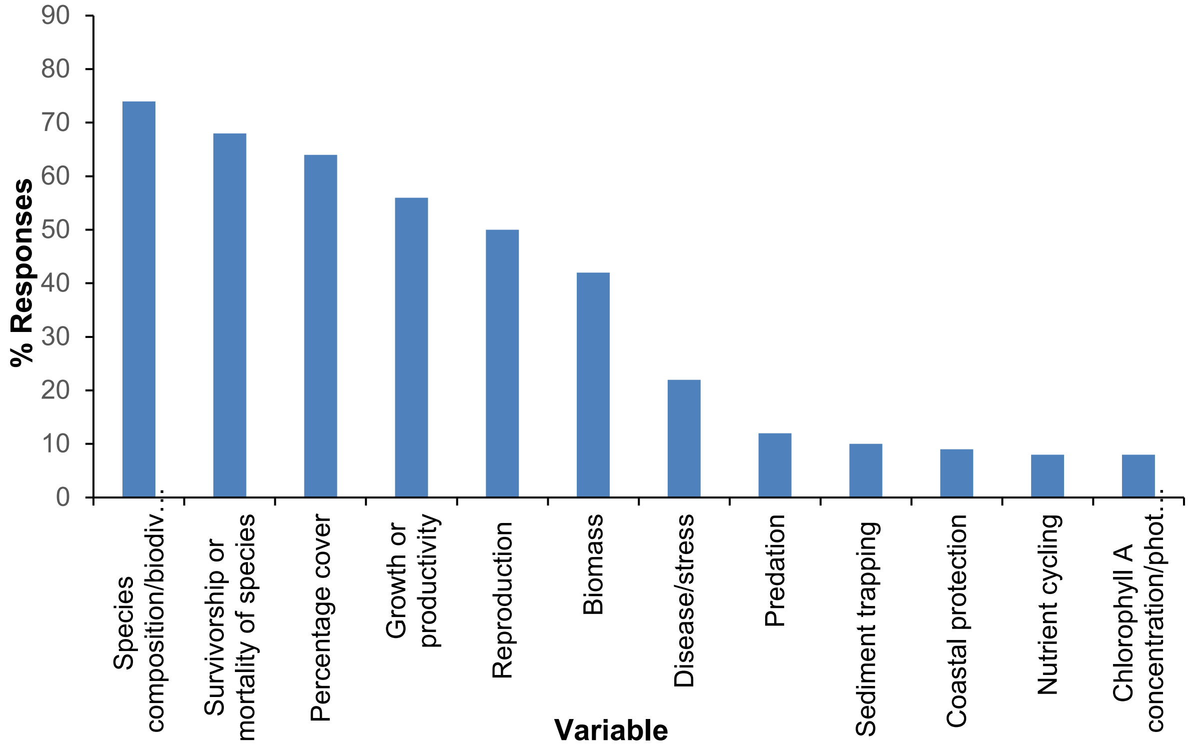

Figure 3. Responses to the question: What parameters/variables are monitored specific to the broad category of ecosystem or habitat function?

2.6 Techniques and methods used in monitoring restoration

The majority of techniques used in monitoring protocols were field-based, for example, visual censuses (71%), or quadrats/transects (69%). Techniques that required considerable post-processing time, such as BRUVs/RUVs (27%), or cores/destructive sampling (20%), were less common. Techniques for measuring water quality were mentioned by a number of respondents, but they were not listed as options in the survey. The survey did not determine the frequency of each of the measurements, e.g., annual or seasonal visual censuses.

Most respondents indicated that non-traditional methods or “new techniques” (which include automation, AI, eDNA, drones, multispectral cameras, hydro-acoustics) were used in their monitoring protocols. Drones (including RTK) were commonly used (31%), followed by artificial intelligence/machine learning/deep learning (19%). Additional methods were mentioned as “new techniques”, such as those utilising genetic techniques including microbiome analysis and metabolomics. Many respondents had no future plans for using new methods in their projects (44%), but this may reflect that many of the projects were complete or nearing completion, rather than a hesitancy to adopt non-traditional methods.

Table 2. Most commonly surveyed variables per habitat type within survey responses. Blue shading indicates variables commonly monitored across all restoration habitat types. Grey shading indicates variables commonly monitored across most restoration habitat types.

Saltmarsh		Mangroves		Coral reef		Shellfish reef		Seagrass		Wetlands		Kelp	
Variable	% studies	Variable	% studies	Variable	% studies	Variable	% studies	Variable	% studies	Variable	% studies	Variable	% studies
Species composition/ biodiversity	100	Percent cover	88	Survival/ Mortality	67	Survival/ Mortality	84	Percent cover	83	Survival/ Mortality	75	Growth/ productivity	100
Percent cover	100	Species composition/ biodiversity	75	Species composition/ biodiversity	56	Species composition/ biodiversity	84	Growth/ productivity	67	Species composition/ biodiversity	75	Survival/ Mortality	100
Growth/ productivity	80	Survival/ Mortality	63			Growth/ productivity	68	Survival/mortality	67	Temperature	75	Reproduction/ recruitment	100
Survival/ Mortality	80					Reproduction/ recruitment	68	Species composition/ biodiversity	67	pH	75	Species composition/ biodiversity	100
						Percent cover	68	Biomass	50	Dissolved oxygen	75	Biomass	100
						Biomass	58	Community engagement/ awareness	50	Growth/ productivity	50	Percentage cover	100
										Nutrient cycling	50	Depth	100
										Percent cover	50	Restoration costs	100
										Turbidity	50	Predation	66
										Salinity	50	Temperature	66
										Depth	50	Structural diversity/topography	-
										Rainfall	50	Nutrients	66
												Community engagement/awareness	-

2.7 Citizen scientist and Aboriginal or Torres Strait Islander involvement

Just under half (42%) of the restoration projects had citizen scientists or volunteers involved with delivering the monitoring. Although citizen scientists were involved with monitoring of similar variables to the organisations leading the monitoring projects, fewer measured species composition and biodiversity (41% by citizen scientists compared to 77% for leads). Citizen scientists were primarily reported as monitoring survivorship or mortality of a species (59%), reproduction (including recruitment), and species composition biodiversity (both 41%).

Few projects (19%) had Aboriginal or Torres Strait Islander involvement in delivering the monitoring. For those that did, 50% measured survivorship or mortality of a species, growth or productivity, and percentage cover (both 40%).

2.8 Availability of reports and monitoring data

Reports on monitoring restoration projects are not all easily available: 29% of studies had project reports that were publicly available, and a further 29% had reports that were partly available. Moreover, monitoring data for restoration projects generally did not meet FAIR data principles of findability, accessibility, interoperability, and reusability. Only 24% of monitoring data are publicly available, and 33% partly available. Of those that considered their data to be available, they were generally available on institutional, government or company websites or databases (41%), project specific websites/databases (34%), or public repositories (31%). A large percentage of the data were also available through other means, i.e., within scientific publications or presentations (34%). 52% of respondents stated the data would be available on request. Despite many projects' data not being available, 49% would be willing to consider adding their data to a free, easy access platform, with a further 31% being unsure.

2.9 Discussion

More than 90% respondents to the survey stated that their restoration initiatives have monitoring and evaluation as part of the restoration project. The primary goals of restoration projects revealed in the survey were to restore lost habitat and to improve biodiversity. As such, variables that are/were monitored in restoration projects fell within the broad category of ecosystem or habitat function. Notably, the majority of social-economic measures did not rank highly in the priorities for monitoring and evaluation. We recommend inclusion of social scientists in future discussions on monitoring methodologies.

The majority of techniques used for restoration monitoring are relatively field intensive, e.g. visual censuses and quadrats/transects. Methods that required post-field work processing were less common, e.g. BRUVs/RUVs, cores/destructive sampling. Given that most projects reported to spend \$10,000–\$50,000 on monitoring, it is unlikely that more labour-intensive methods will be used. Many respondents reported utilisation of non-traditional methods (identified here to include automation, AI, eDNA, drones, multispectral cameras, hydro-acoustics) in their projects, with drones (including Real Time Kinematic) most commonly used. Despite this, few respondents had plans to use new methods in their projects in the future.

Many restoration projects involved citizen scientists in monitoring, particularly to monitor species survivorship or mortality. Fewer citizen scientists were involved with monitoring species composition/biodiversity compared to universities and government departments. It is unclear how monitoring by citizen scientists fits with new technologies in terms of facilitating their involvement.

Finally, our results show that monitoring data for restoration projects do not generally meet the FAIR data principles of findability, accessibility, interoperability, and reusability. It is clear that not all monitoring data (and reports) are publicly available, and, for those that are, they are only available on request or are difficult to locate on a range of different websites.

Despite few projects' data being currently available, there was interest in adding their data if there was a free, easy access platform available.

3. Literature review of global strategies for monitoring progress towards marine and coastal restoration goals

3.1 Summary

The aim of this literature review was to evaluate strategies that have been implemented globally to monitor progress towards the restoration goals (ecological, socio-economic, engineering and/or cultural) of marine and coastal restoration projects. The review also aimed to evaluate whether new and emerging technologies are being incorporated into monitoring programs, and to assess how easily monitoring data from these projects are available. The overall objective is to compare the results with that of the survey of Australian coastal and marine restoration practitioners to determine whether Australian monitoring programs align with current international practice, and to inform the development of best- practice guidelines.

3.2 Methodology

The methodology used for this literature review builds upon that used by Bayraktarov and colleagues (2016, 2020), in which the Web of Science and Scopus databases were searched for restoration publications using the search terms "ecosystem* and restor*", or "ecosystem* and rehab*" within the title, where the word 'ecosystem' was replaced by different words describing coastal ecosystems (including coral reef, seagrass, mangrove, saltmarsh, and shellfish reef). The papers were further refined to include only studies that described a specific restoration project (secondary sources, reviews, and papers that focused on the development of guidelines were removed). The database produced by these previous surveys (including papers published up to 2018) was downloaded and references imported into a shared library using the 'Zotero' reference management software. This Zotero database was expanded to include studies published since the generation of the imported database (2018 and onwards), as well as studies relating to the additional habitat types "mussel reefs" and "kelp". Studies were restricted to those published in English. References from Bayraktarov and colleagues (2020) that were in Spanish or for which full text was unavailable were removed.

Once the expanded Zotero database was complete, studies were filed according to habitat type ('oyster', 'shellfish' and 'mussel' restoration were grouped into 'shellfish'). Secondary literature, guideline documents or papers not focused on restoration were removed. Primary restoration literature was further divided into those that documented pilot studies or experiments, and those that reported on bona fide restoration projects. For this purpose, pilot studies and experiments were defined as studies where no work was performed in the habitat intending to be restored (e.g., lab/ aquarium/ mesocosm studies), and/or where the scale of the work was not sufficient for benefits or ecosystem services to be expected. Restoration projects were defined as studies in which the primary goal was to restore habitat and ecosystem function, however studies where the primary goal was to test approaches and that were conducted at scales large enough for benefits/ecosystem function gains to be observed were also included. Only studies that were classed as bona fide restoration projects were investigated further.

3.2.1 Monitoring programs and data availability

Each study in the final database was assessed to determine whether a monitoring program was described for the restoration project. If so, the study was inspected to determine whether, where and how the monitoring data is available. Based on this the study was given one of the following tags within Zotero: “raw data fully available in paper”, “raw data fully downloadable from repository”, “data partly available (summaries)”, “data partly available (available upon request)” or “no data reported/available”. “Data partly available (summaries)” includes publications in which monitoring data may be presented within the paper within figures or tables, but that do not provide the raw monitoring data.

3.2.2 Adoption of advanced technologies

Studies in the final database were searched using the following text strings within the full text to determine whether advanced monitoring techniques are used within monitoring programs: “drone”, “eDNA”, “environmental DNA”, “automat”, “artificial intelligence”, “machine learning”, “deep learning”, “real time kinematic”, “multispectral camera”, “hydroacoust”, “metagenom”, “metabarc”, “16S”. Any matches were manually checked to ensure the technique was used in the study. If accurate, the study was given the corresponding tag within Zotero.

3.2.3 Variables monitored

The full list of monitoring parameters from the database from Bayraktarov and colleagues (2020) were extracted and assembled into an excel spreadsheet. The number of studies that reported monitoring of each variable was calculated for each habitat type. Variables that were deemed to be very similar were grouped for analysis (e.g., survival and mortality; arial cover, benthic cover, and percent cover; species presence, species richness, and species diversity).

3.3 Results

3.3.1 Overview of primary restoration studies

Our final database of primary marine and coastal restoration project literature consisted of 485 publications. Studies focusing on seagrass habitats had the highest representation among the literature (~30% of publications), whereas kelp was the least represented (~4%) (Figure 4). The earliest publications in our database were published in 1976, however the number of published studies on marine and coastal restoration remained low until 1996, where a clear increase in the number of publications per year was observed, regardless of habitat type (Figure 4). An additional increase in publications is observed from 2019 onward.

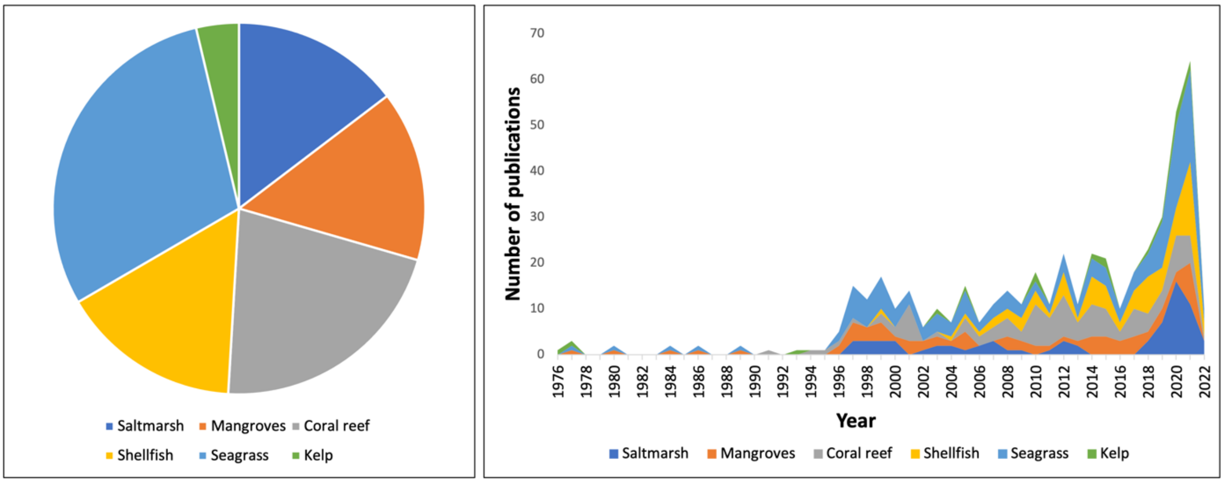

Figure 4. Summary of marine and coastal restoration studies identified in this literature review. The chart on the left shows the distribution of studies by habitat type. The largest proportion of studies focus on seagrass restoration, and the smallest proportion on kelp. The graph on the right shows publication trends since 1976. There was a clear increase in published marine and coastal restoration studies in the mid-1990s, and another in 2019–2021.

3.3.2 Availability of monitoring data

We restricted our analysis of data availability to studies published in the last five years, as the push for open data and the availability of hosting platforms is relatively recent. Overall, approximately 19% of studies published since 2018 had raw data fully available, and 46% provided summaries of data (e.g., figures within publications) or had data available on request. No data was available for 35% of the studies. Studies on coral reef restoration had the highest proportion of papers with fully accessible data (approximately 30%), and the lowest proportion of studies that provided no access to monitoring data (Figure 5). In contrast, over 50% of studies on seagrass restoration did not make monitoring data available. These results show that monitoring data is not accessible for over one-third of recent marine and coastal restoration projects.

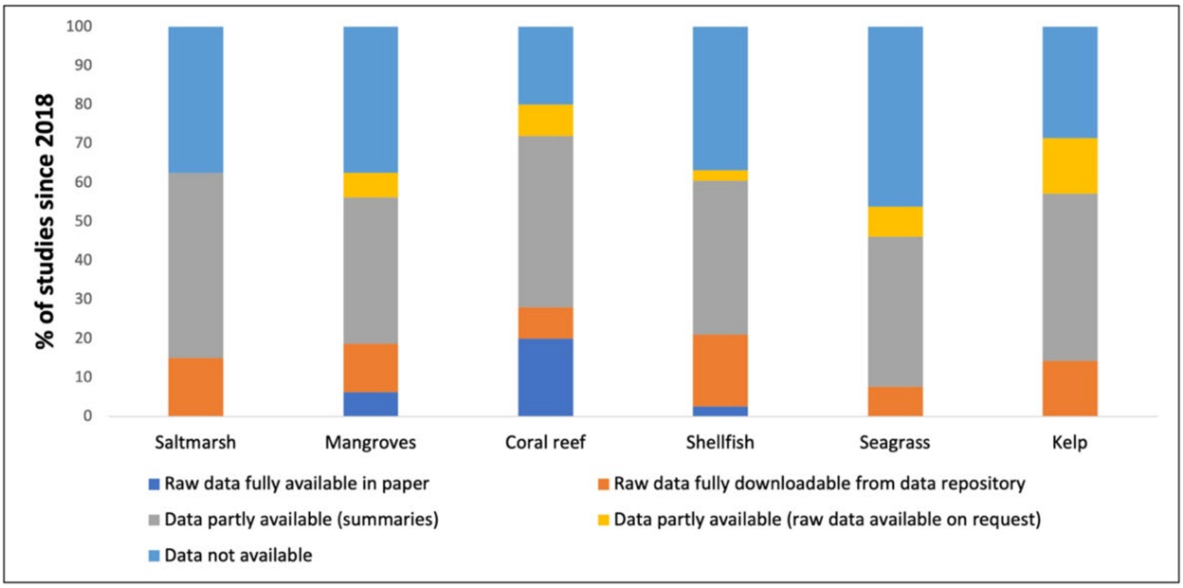

Figure 5. Availability of monitoring data for marine and coastal restoration studies published since 2018.

3.3.3 Adoption of advanced technologies within coastal and marine restoration monitoring

Relatively few studies reported the use of advanced techniques within restoration monitoring programs (Figure 6). The most commonly used method was Real-Time-Kinematic technology for highly accurate positioning; this was predominately used within studies focused on saltmarsh. The second most commonly used technique was drone use (used in saltmarsh, shellfish reef, and kelp monitoring programs), followed by the use of automation (within saltmarsh and coral reef studies). No studies reported the use of environmental DNA (eDNA) techniques, artificial intelligence, deep learning, or hydroacoustic techniques.

While not classed as an 'advanced technology', we also searched papers and reports for the involvement of citizen scientists in restoration monitoring programs. Only four studies (three on shellfish reef restoration and one on coral reef restoration) reported the involvement of citizen science.

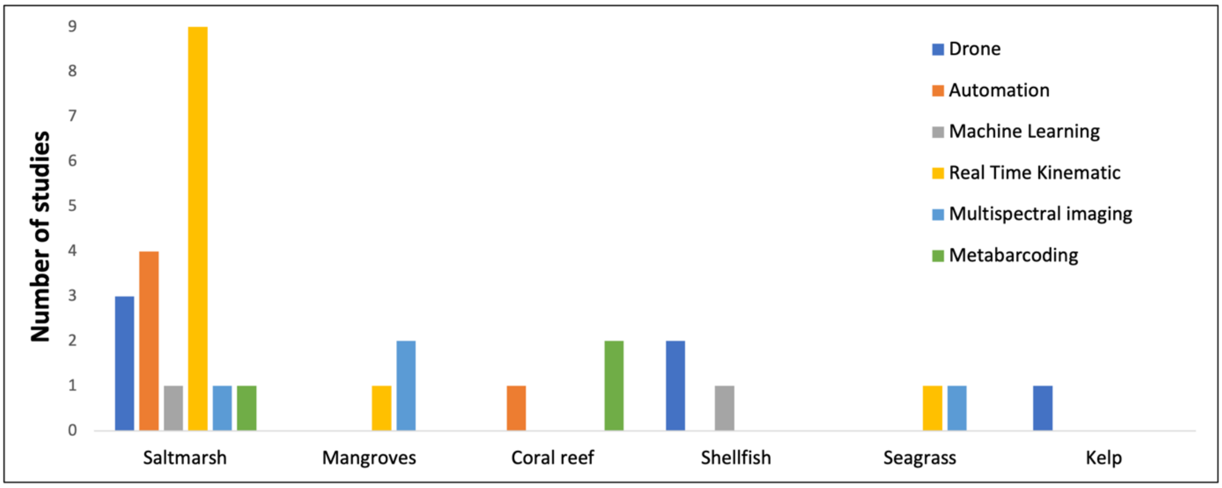

Figure 6. Number of studies reporting the use of advanced monitoring techniques per habitat type.

3.3.4 Variables monitored per habitat type

A number of variables were commonly monitored across restoration projects regardless of habitat type (Table 3). Survival/mortality, percent cover/aerial coverage, biodiversity (e.g., species richness/ observed), recruitment, and size (e.g., height/length/radius), were commonly measured in some form across each of the habitats assessed. Density, growth rate, and salinity were also commonly measured in most, but not all, of the habitats.

Table 3. Most commonly surveyed variables per habitat type within papers identified in the literature review. Blue shading indicates variables that are commonly monitored across all restoration habitat types. Grey shading indicates variables that are commonly monitored across most restoration habitat types.

Saltmarsh		Mangroves		Coral reef		Shellfish reef		Seagrass	
Variable	**% studies**	**Variable**	**% studies**	**Variable**	**% studies**	**Variable**	**% studies**	**Variable**	**% studies**
Aerial coverage/ percent cover	54	Survival	67	Survival/ mortality	82	Recruitment/ live spat density	70	Survival	81
Survival	46	Height	41	Growth/ extension	62	Survival/ mortality	65	Recruitment	35
Species richness/ species present/ species diversity/ species observed/ fauna observed/ fish population	46	Recruitment	33	Attachment/ recruitment	36	Live oyster shell height/ width/ length / weight/ live spat size/ dry oyster shell or tissue weight/ wet oyster shell or tissue weight	60	Aerial coverage/ percent cover	32
Sediment elevation	42	Species present/ fauna observed/ species observed	23	Colony size: Height/width/length/mean radius	19	Live oyster density/ oyster abundance/ spat abundance	55	Shoot density	26
Recruitment	33	Aerial coverage/ percent cover	23	Species richness/ species present/ species diversity/ species observed/ fauna observed/ fish population	16	Salinity	35	Rhizome length	19
Biomass (above ground)/ Biomass (above ground) (of more than one species)	29	Salinity	21	Percent cover/ benthic cover	16	Water temperature	35	Stem density	19
Height	25	Stem density	18	Detachment	15	Dissolved oxygen	35	Erosion	19
Soil / pore water salinity	21	Community engagement	18	Bleaching	14	Aerial cover/ percent cover/ percent shell cover	30	Species present/ fauna observed/ species richness/ species observed	19

Table 3 continued…

Salinity	21	Leaves per plant	18	Sedimentation	12	Species richness/ species present/ species diversity/ species observed/ fauna observed/ fish population	25	Height	16
Biomass (below ground)	17	Tidal flows	15	Percent live tissue	12	Dead oyster density/ dead spat density	20	Number of shoots per plant	16
Stem density	17	Main stem length	10	Predation	11	Disease prevalence/ disease intensity	15	Leaf length	16
Soil organic matter	17	Flower production	8	Water temperature	11	Live oyster growth/ growth rate	15	Storm events	13
Invasive species	17	Capacity building	8	Genotype	10	Dead oyster shell height/ dead oyster shell width/ dead oyster shell length/ dead oyster weight/ dead spat size	15	Water depth	13
Tidal range	13	Creation of income-	8	Salinity	8	Water depth	15	Sediment	13
Erosion	13	Environmental awareness	8	Settlement rate	7	Sediment elevation	15	Biomass (roots/ rhizomes/ shoots)	10
Rainfall	13	Fisheries harvest size	8	Macroinvertebrates (abundance)	7			Sediment type	10
		Growth (vertical)/ Growth rate	8	Disease	7			Reproductive shoot production	10
		Sediment elevation	8					Plant health / 'stress'	10

3.4 Discussion

3.4.1 An overview of current international practice for restoration monitoring

The results of this study provide an overview of restoration monitoring programs around the world, although we note that studies from non-English speaking countries are likely underrepresented. Seagrass restoration studies are the most numerous, however there was relatively low uptake of advanced technologies and open-data practices within projects focusing on this habitat type. This suggests that a larger research community does not necessarily lead to a more rapid uptake of new techniques. Adoption of advanced technologies was highest within saltmarsh restoration monitoring, both in the number of studies reporting their use and in the diversity of technologies used. Real Time Kinematic technology and drones were the most commonly used technologies reported in literature, however, the uptake of advanced technologies is quite low overall. There was also a very low proportion of studies that reported the involvement of citizen scientists in monitoring.

These results contrast with those of the survey of Australian restoration practitioners (see section 2). The highest proportion of respondents were involved in shellfish reef restoration projects, followed by mangroves, pointing to a possible regional difference in habitat restoration priorities. Most survey respondents indicated that advanced technologies were used in the monitoring programs for the projects they are involved in, and just under half reported the involvement of citizen science. These differences may reflect true differences between restoration monitoring in Australia and elsewhere, or perhaps a bias in reporting. Given that advanced technologies and the push for citizen science are fairly recent, this may, alternatively, represent a lag in publication. Australian restoration practitioners also reported a higher proportion of projects with monitoring data freely available (31% of projects have data available in public repositories, in contrast to 19% of published studies), but also a significant proportion of projects with data available on request (52%, possibly because studies were still in progress at the time of the survey).

3.4.2 Commonly monitored variables guide development of guidelines document for restoration monitoring

While some differences between current international practice and restoration monitoring within Australia, there was a clear alignment of the variables that are commonly included in monitoring programs. Survival/mortality, species composition/biodiversity, percent cover, and growth/productivity are clearly variables that are broadly used to measure progress towards restoration goals in a broad range of coastal and marine habitats. Additional variables, for example, measures of recruitment, density, size, biomass, or salinity are also common.

These variables represent clear candidates for inclusion in any guidelines for restoration monitoring. The literature review also identified variables that are commonly used within one or a small number of habitat types, including sediment elevation, temperature, and dissolved oxygen; the identification of these variables will be useful for the development of more specific guidelines tailored to different habitat types, or to different restoration project goals.

3.5 Conclusion

This literature review has identified trends in restoration monitoring programs globally. Combining the results of the review with those of the survey of Australian coastal and marine restoration practitioners allows the identification of several variables that are routinely included in monitoring of restoration projects across habitat types and geographical regions. Co-ordinating reporting of these variables could therefore enable broad-scale analysis and reporting of restoration outcomes, as long as the challenge of poor data availability is overcome.

4. Workshop and guidelines for a universal approach to marine and coastal restoration monitoring

4.1 Summary

A workshop for key practitioners and scientists involved in nationally recognised restoration projects provided a platform for the researchers and end-users of NESP Project 1.7 to develop a draft guidelines document for marine and coastal monitoring. Findings from the survey and preliminary results from the literature review were reported. Over the workshop, monitoring practices and priorities were investigated in greater detail than was gained from the survey.

A draft document on the guidelines for a universal approach to marine and coastal restoration monitoring in Australia was produced and discussed. The guidelines included outlining the important considerations for designing and implementing a monitoring program, and recommended variables for measuring success of restoration.

4.2 Workshop background

A workshop was held for key practitioners and scientists involved in nationally recognised restoration projects. The workshop was designed to provide a platform for the researchers and end-users of NESP Project 1.7 to develop a draft guidelines document for marine and coastal monitoring. Targeted invites were, therefore, sent to all the researchers and end- users of NESP Project 1.7 (including the Australian Department of Agriculture, Water and Environment, DAWE), and researchers leading (or co-leads) of other NESP Ecosystem Restoration and related projects (e.g., wetlands).

The workshop (and survey) was approved by Griffith University's Human Research Ethics Committee (approval number 2021/904) in accordance with the National Statement on Ethical Conduct in Human Research. Participants signed their consent in the workshop prior to taking part.

Initially, the workshop was planned as an in-person (or hybrid) event at Port Stephens Fisheries Institute run by NSW Department of Primary Industries Fisheries (NSW DPI). Unfortunately, with COVID and extreme flooding in New South Wales and Queensland, it was decided by the project leads that the workshop would be completely online. The workshop was therefore conducted through the Microsoft Teams application hosted by NSW DPI. It was also recorded in Teams for note taking purposes but not for distribution. After the workshop, the minutes were disseminated to all invitees, including those that were unable to attend.

Over the two days (3-4 March 2022), there were 20 participants to the workshop. Participants included the research team from Griffith University, NSW DPI, University of Western Australia, Macquarie University, James Cook University and University of NSW. Research end-users that were present included DAWE, NSW DPI, The Nature Conservancy, Sydney Institute of Marine Science, and South Australia Department for Environment and Water.

Researchers leading (or co-leads) of restoration NESP projects (1.5, 1.6, 1.8, 1.10) were also present.

4.3 Workshop with key practitioners and scientists

The workshop provided an opportunity to report the findings from the survey and preliminary results from the literature review. Over the workshop, monitoring practices and priorities were investigated in greater detail than was gained from the survey. Project participants split into three groups based on ecosystem type. The three ecosystem types were: 1) seagrass and kelp; 2) coastal wetlands, mangroves, saltmarsh and Melaleucas; and 3) shellfish and coral. The primary objective was to discuss the most commonly measured parameters or variables for the habitat and identify those that are most relevant across marine and coastal restoration projects broadly (e.g., other ecosystem types).

It was clear from the survey and a review of preliminary literature that different variables are measured in projects focused on different habitat types, for example disparate variables for measuring restoration of kelp and shellfish reefs (Table 4). Therefore, a primary objective of the workshop was to discuss the most commonly measured parameters or variables for the habitat and identify those that are most relevant across marine and coastal restoration projects broadly (e.g., other ecosystem types). If time allowed, participants were also asked to discuss what spatial scales restoration are generally attempted, the duration of monitoring programs, and whether advanced technologies show promise for use in the future.

All groups identified that the purpose of restoration will dictate variables to be measured, but listed variables that were commonly measured or considered to be important (Table 5, detailed discussion is detailed below). The workshop reached consensus of variables that can be standardly used across restoration projects to facilitate broad comparisons and benchmarking. There was also a clear promise of significant gain from adoption of new technology. The discussion of open data highlighted the need for data from monitoring to be available. It was agreed upon that there was no need for a specific database for restoration monitoring due to the prevalence of other platforms.

Table 4. Example variables for measuring restoration of kelp and shellfish reefs – adapted from The Nature Conservancy Kelp Restoration Guidebook Restoration (Eger et al. 2022) and Guidelines for Shellfish Reefs (Fitzsimons et al. 2019). *Units provided for shellfish reefs only.

Variables for measuring restoration of kelp
Kelp-specific
• Area or percent cover of kelp canopy
• Height, density, biomass, or survivorship of individuals
• Recruitment of juveniles
• Presence/quantity of reproductive tissue (i.e., Sori/ sporophylls)
• Indicators of health (e.g., fouling, pigmentation)
Associated community
• Mobile organisms (e.g., fishes, large invertebrates)
• Sessile and/or benthic organisms (e.g., other seaweeds, sessile invertebrates)
• Epiphytes, micro-organisms
• Particular species of interest
» Positive (e.g., commercially valuable species)
» Negative (e.g., destructive grazers/herbivores)
• Community production (i.e., nutrient and carbon cycling)
Environmental/physical factors
• Hydrodynamics (e.g., water flow, currents, wave action)
• Subcanopy light levels
• Sedimentation
• Turbidity
• Water quality (especially nutrient levels)
• Water temperature

Variables for measuring restoration of shellfish reefs (and recommended units*)
• Reef aerial dimension
»Project footprint (m^2)
»Reef area (m^2)
• Reef height (m)
• Oyster density (individuals/ m^2)
• Size-frequency distribution (mm (size), number or % per bin (size distribution)

Table 5. Variables listed as commonly measured for restoration of specific habitats. The three ecosystem types were: 1) Seagrass and Kelp; 2) Coastal Wetlands, Mangroves, Saltmarsh and Melaleucas; and 3) Shellfish and Coral.

	Seagrass & Kelp	*Coastal Wetlands, Mangroves, Saltmarsh & Melaleucas*	**Shellfish (& Coral)**
Ecosystem /habitat function			
	Growth or productivity /biomass proxies /percentage cover /density		
	Survivorship or mortality		Survivorship or mortality
	Reproduction		Recruitment
	Species composition /biodiversity	Species composition/biodiversity	
	Disease /stress – morbidity /fouling		Health or condition e.g. physiology, filtration
	Total restored area		Define what a restored habitat looks like, e.g. area and density as defined for EPBC threatened ecological communities
Physical variables			
	Salinity	Salinity	Salinity
	Temperature	Temperature	Temperature
	Depth	Depth	
	Irradiance		
		pH	pH Turbidity
		Dissolved oxygen	
		Hydrology / hydro-period,	
		Connectivity across flood plains	
		Residence time	

Table 5 continued

Socio-economic			
	Restoration costs		Restoration costs
		Cultural benefits	Indigenous/Cultural knowledge
	Community capacity building	Educational learning on country (Indigenous and non)	
	Community engagement/awareness	How community use these areas, conflicting views/uses, identified benefits from restoration, early engagement important, develop a shared vision for restoration project. Level of where you start depends on community awareness of habitat/issue and level of community/individual attachment to these areas – including non-material benefits.	Change in public perception over time
	Employment/jobs	Volunteering groups, citizen scientists	Socio-econ jobs (# volunteers, #/FTE of local contractors)
		Recreational benefits for community	Use of area by public
			Economic $ value based on ecosystem services

4.3.1 Seagrass and kelp

It was clearly identified that the purpose of restoration will dictate variables to be measured. Nevertheless, variables that were often utilised for monitoring seagrass or kelp restoration included measures for ecosystem/habitat function: growth or productivity /biomass proxies / percent cover / density (it was noted that destructive sampling is uncommon for seagrasses); survivorship or mortality; reproduction; species composition/biodiversity; disease/stress – morbidity / fouling; total restored area. Measurements of physical variables included: salinity, but only in specific cases where extremes are likely; temperature; depth; irradiance. Socio- economic monitoring was specific to some projects and often only rarely performed and included restoration costs; community capacity building; community engagement/awareness; employment/jobs.

Monitoring of seagrass and/or kelp was ideally 10 years or even multiple decades in duration, especially for slow growing species. The temporal scale also was dependent on the method of restoration, e.g., replanting compared to natural colonization (after removing disturbances). It was recognised that monitoring periods for most projects were less than three years, and often for 6 to 18 months.

Novel methods for monitoring seagrass or kelp used photogrammetry to measure coverage and spread of the restored habitat. Additional technologies are being explored, e.g., remote sensing possibilities, but limitations for subtidal habitats, especially estuaries, are acknowledged.

4.3.2 Coastal Wetlands, Mangroves, Saltmarsh and *Melaleucas*

It was clearly identified that the monitoring parameters were determined by the initial restoration goal, but similar key variables are often measured for these habitats. Species composition/biodiversity was identified as a common measure for an ecosystem/habitat function variable for restoration of coastal wetlands, mangroves, saltmarsh, and Melaleucas. Many physical variables are monitored but they often vary depending on project: salinity; temperature; pH; dissolved oxygen; hydrology or hydroperiod, including connectivity across floodplains, residence time, depth of water.

Socio-economic monitoring is currently limited, but is possibly increasing. It was recognised that there is a significant gap in understanding the cultural benefits of restoration. Ideas were discussed on how the community use these areas, conflicting views and uses, and benefits from restoration. It was acknowledged that early engagement is important, with the community being involved in the development of a shared vision for the restoration project. The initial level of engagement for a restoration project depends on community awareness of the habitat or issue and the level of community/individual attachment to these areas (including non-material benefits). Although recognised as important in future restoration projects, further consideration is required to understand how these can be measured and reported, e.g. educational learning on country (Indigenous and broader community), volunteering groups, citizen science, recreational benefits for community.

Novel methods for monitoring were supported with enthusiasm. Promising technology includes increasing the accessibility of monitoring data to stakeholders, e.g., live water level and salinity monitoring. Remote technology for data collection also was seen as a benefit for safer collection. Community and stakeholder surveys of social, economic are also immediately accessible.

4.3.3 Shellfish (and Coral)

No coral restoration representative was able to be present at the workshop, but input was included in the surveys. Similar to all other ecosystem types, it was recognised that the variables that are measured depend on the goal of the project. Ecosystem level and habitat function measures and habitat function are monitored for restoration of shellfish reefs: length/density; measurement of the health or condition of a habitat e.g., filtration, physiology, recruitment; measurement of a restored habitat in terms of area and/or density. It was suggested that a clear consistency in reporting is required, for example, defining ‘successful restoration’, as is consistency of terminology to describe the total area of restored areas (‘footprint’ has a different meaning in different projects). In terms of physical variables, monitoring of temperature may be useful to highlight stress or to indicate when recruitment is expected to peak, however this information is already known for many oyster growing estuaries. Measurement of pH, salinity, temperature, and turbidity is relatively straightforward, but consideration needs to be given to the frequency of monitoring of these physical parameters. Socio-economic variables were acknowledged to be important and the degree to which these variables are monitored within restoration projects varies. Variables relevant to shellfish reefs were: restoration costs; economic value of ecosystem services, e.g., dollar values that can be compared across projects from all ecosystems; creation of jobs (including number of volunteers, number of full-time employees or local contractors); change in public perception over time; use of area by the public; Indigenous/cultural knowledge.

4.4 Workshop on draft guidelines

The second day of the workshop produced draft guidelines for monitoring restoration projects. The guidelines for a universal approach to marine and coastal restoration monitoring should be prefaced with the clear rationale for measuring ecological, physical, socio-economic “success” of restoration through monitoring. Importantly, the overall success of having a monitoring plan requires a clear vision which leads to defined objectives and goals (with clear language). Goals (identified in the survey and clarified with discussions in the workshop) include: Restoration of lost habitat/ recovery after adverse event; Improvement of biodiversity; Increased fisheries; Water quality improvement; Improved cultural/ social amenity; Shoreline stabilisation/ coastal hazard reduction; Recovery of threatened species/ return totem species. The time taken to define the objectives and goals for a restoration project may take a considerable amount of time prior to deciding on the approach required for monitoring or even if restoration is the appropriate management action. If the restoration researchers and practitioners have a clear vision, have agreed upon objectives and goals, a series of physical, ecological, and socio-economic variables are suggested for an effective restoration monitoring project.

Variables that are relevant to all restoration projects, regardless of the ecosystem type and goals include physical, ecological, and socio-economic variables (Table 6). Additional variables are recommended but the relevance varies depending on the defined objectives and goals (Table 7). The recommended temporal scales (frequency and duration) for monitoring each of the variables need to carefully considered prior to commencing a monitoring project. Furthermore, the budget required to do such monitoring also need to be considered to correctly determine the progress and success of a restoration project. This information will also be necessary for future planning of resources. At the end of a monitoring project, there is a strong recommendation that data be made publicly available.

Table 6. Variables recommended to all projects - broadly applicable across habitat types (seagrass, kelp, coastal wetlands, mangroves, saltmarsh, Melaleucas, shellfish and coral).

Variable	Units	Details
Physical		
Total project area	m^2	Includes bare areas between patch reefs, for example
Restored area footprint	m^2	Includes only the physical area subject to restoration attempts (e.g., patches within a broader area)
Ecological		
Survival/recruitment	Standard units for ecosystem type	Particularly for initial stages but less important once established
Socio-economic		
Costs of restoration (if ongoing)/ monitoring/ maintenance	$ (local currency) per annum	Cost as percentage of overall build cost
Community participation (subcategories: including specific indigenous participation, volunteers)	# of people, FTE, hours per activity, # of community events, # of other organisations	Data is generally easily available; social benefits of volunteerism are based on numbers of people rather than FTE
Job provision (e.g. contractors) – project maintenance	FTE	Data is generally easily available, jobs are rarely full time

Table 7. Additional recommended variables – relevance varies depending on primary goals.

Variable	Units	Details
Physical		
Water quality	pH, salinity, turbidity, dissolved oxygen, temperature, nutrients	The variables depend on those required for the health of the restoration target e.g., oxygen and light for seagrasses Relatively easy to take snap-shot measurements Determine availability (and relevance) of large- scale data e.g., BoM
Hydrology/ hydroperiod	mm or m	Expected change for intertidal projects
Bank stabilisation	Slope, rugosity	Sediment deposition /erosion (vertical height)
Ecological		
Growth or productivity	Standard units for ecosystem type	Measure of size or estimate of biomass suitable for each habitat e.g. shell height
Health/condition of restored ecosystem	Per ecosystem type	e.g., condition index (oysters), epiphyte loads (seagrass)
Biodiversity	Species richness	Overall, or fish, invertebrate, microbe specific
Socio-economic		
Indigenous engagement	Attitudes (positivity /negativity towards restoration) Involvement in project development/planning Culturally important species (presence/ increase in number)	Benefits: Cultural, food and medicine provision, materials (e.g., wood and seeds), social and community, learning on country (intergenerational knowledge sharing), working on country (long term - ecotourism, rangers managing site etc.), working on country (short term)
Use of restoration area	Users/day, willingness to pay	Use of restoration area: recreational boating, fishing, enjoying scenery, birdwatching visitation, dog walking, locals exercising, family outing, picnics, swimming Visitation by locals, by within state/ out of state / international
Education and learning	Number of events, number of participants	Self-guided walks, school trips, citizen scientists, survey of knowledge
Change in opinion of quality	Ranking on scale	Over time
Costed ecosystem services	$ in local currency	Based on economic costings of ecosystem services

4.5 Discussion

Over the workshop, monitoring practices and priorities were investigated in greater detail than was gained from the survey. All groups identified that the purpose of restoration will dictate variables to be measured. Importantly, the workshop reached consensus of variables that can be standardly used across restoration projects to facilitate broad comparisons and benchmarking. There was also a clear promise of significant gain from adoption of new technology. The discussion of open data highlighted the need for data from monitoring to be available. It was agreed that a specific database for restoration monitoring would only be used if it were well designed, well-maintained, and easy to use, and that the use of existing data-sharing platforms should serve the needs of the restoration community.

As a result of the international literature review of restoration monitoring, the stakeholder survey, and the workshop for researchers and practitioners actively involved in restoration in Australia, we have identified a range of variables that are commonly measured in monitoring programs regardless of the focus ecosystem, and others that are habitat-specific. The final guidelines document: "Guidelines for a universal approach to marine and coastal restoration monitoring in Australia" (Cole et al. 2022; Appendix B), brought together key commonalities between these guidelines for application to restoration monitoring across different types of biogenic habitats, specifically: 1) seagrass and kelp; 2) coastal wetlands, mangroves, saltmarsh and Melaleucas; and 3) shellfish and coral. It was recommended in the document that when designing a monitoring program, this project report is read in conjunction with outputs from other NESP projects that focus on restoration (particularly 1.5, 1.6, 1.8, 1.10).

5. Conclusions

The combined results of the literature review and survey show alignment of current Australian practice with monitoring of restoration projects globally. There is a strong focus on monitoring of variables associated with ecosystem composition and function, which reflects that the overarching goals and objectives of most restoration projects are similar (generally, to restore biodiversity). Monitoring of social, economic and/or cultural parameters lags behind that of ecological variables. Both the literature review and survey indicated uptake of advanced technologies, pointing towards an increase in the capabilities of restoration practitioners and efficiencies in monitoring effort. One contrast found between the survey and report is the level of involvement of citizen scientists in monitoring programs; just under half of the Australian restoration projects reported in the survey involved citizen scientists, whereas only four of the studies found in the literature review indicated involvement. This may reflect a very recent adoption of citizen science, a bias in reporting, or a geographical difference.

The primary objective of our project was to use the knowledge gained from the survey, literature review, and workshop, to generate a standardised set of monitoring variables for facilitation of benchmarking and comparison between marine and coastal restoration projects. A summary of the most common variables highlighted by each activity is given in Table 8. Variables identified during the workshop cover a much broader range of categories (e.g., physical and socio-economic). This is because workshop participants were made aware that underrepresentation of variables within these categories was identified by the literature review and survey and were specifically asked to consider these in their assessments. Given the diversity of objectives, habitats, stakeholders, budgets and geopolitical landscapes inherent within these projects standardisation is challenging, but possible if the overall objective of the project is reflected in a decision tree. To further facilitate comparison an emphasis should be placed on the use of standardised definitions and units. The guidelines document generated here is by no means the final solution, but we hope that it is a first, and immediately implementable, step towards the overall objective.

Finally, our literature review indicated that there is evidence of uptake of open data practices globally, but that adoption is slow, and that data is not currently centralised. There was consensus among workshop participants that any centralised database needs to be well-resourced, well-designed, easy to use, and sustainable. Until this can be achieved we advocate for the upload of raw monitoring data to any easily accessible database (e.g., Dryad, Open Science Framework), or for its provision as supplementary material associated with open-access publications.

Table 8. Comparison of commonly monitored variables identified in the survey, literature review, and workshop.

Category	Variable	Survey	Literature review	Workshop
General	Total restored area			Yes
Ecosystem/ habitat function	Survival/mortality	Yes	Yes	Yes
	Species composition/biodiversity	Yes	Yes	
	Percent cover	Yes	Yes	
	Growth/productivity	Yes	Yes	
	Recruitment	Yes	Yes	Yes
	Size	Yes	Yes	
	Density		Yes	
	Health			
Physical	Salinity		Yes	
Socio-economic	Costs			Yes
	Community participation			Yes
	Job creation			Yes

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Appendix A

Survey information

Please complete questions for a single restoration project. If you have been involved in multiple projects, please complete the survey for your largest project. If you have the time, we would appreciate you completing an additional survey for other projects that you have been involved in (the survey will allow multiple attempts).

Q2. Please provide a title and brief description of your restoration project. The sole purpose of this question is to identify when multiple survey responses have been received for the same restoration project. The information provided in response to this question will not be published or analysed further.

Project title _____________ Brief description

____

OR prefer not to say

Q3. Which of the following best describes your organisation?

- Consultancy
- Private business
- University
- Non-university research organisation
- Non-government organisation
- Local, state or federal government organisation
- Natural Resource Management group
- Aboriginal or Torres Strait Islander organisation
- Native title body
- Community group
- Individual
- Other (please specify) ___________

Q4. Did your organisation have primary responsibility for the planning and implementation of the restoration project?

Y/N/Unsure

Q5. What types of marine and coastal habitat is targeted in your project? Select all that apply.

Wetlands
Shellfish/oyster reef
Seagrass

Saltmarsh
Mangrove
Kelp
Coral
Single species restoration (e.g., seahorse hotels)
Other (please specify) _____________

Q6. What is the spatial scale of your project? Please give your best estimate.

Less than 10 hectares
10-50 hectares
50-100 hectares
100-1000 hectares
1000-5000 hectares
Greater than 5000 hectares
Unsure

Q7. What are the primary goals of the restoration project? Select all that apply.

Restoration of lost habitat
Increased fisheries production
Water quality improvement
Carbon sequestration
Shoreline stabilisation
Coastal hazard reduction
Improvement of biodiversity
Nutrient cycling
Sediment trapping
Improvement cultural/social amenity
Recovery after adverse event
Recovery of threatened species
Unsure
Other (please specify) _____________

Q8. Is monitoring and evaluation a part of your restoration project?

Y/N/unsure

If Y – go to Q11
If N go to Q9
If unsure – exit

Q9. In your opinion, did the project have adequate access to resources (equipment and funding) to facilitate monitoring?

Y/Partly/N/unsure

If Y or unsure – exit
If Partly or N– got to Q10

Q10. What monitoring activities would you have delivered with additional resources? Please specify _______________ Go to exit

Q11. Who is responsible for delivering the monitoring program? Select all that apply.

Consultancy
Private business
University

Non-university research organisation
Non-government organisation

Local, state or federal government organisation
Natural Resource Management group
Aboriginal or Torres Strait Islander organisation
Native title body

Community group
Citizen scientists
Individual

Unsure

Other (please specify) ___________

Q12. Is the organisation responsible for the monitoring the same as the organisation responsible for overall implementation of the restoration project?

Y/N/unsure

Q13. What parameters/variables are monitored? (Broad categories only, feel free to provide specifics in the 'Notes' section). Please select all that apply.

Ecosystem/Habitat function
Growth or productivity

Survivorship or mortality of species
Reproduction (including recruitment)
Nutrient cycling

Coastal protection (including wave attenuation or indirect measures)
Sediment trapping (mean phi, particle size distribution)

Chlorophyll A concentration/photosynthesis
Species composition/biodiversity

Biomass
Percentage cover
Disease/stress
Predation

Physical variables

Flow rate
Turbidity
Salinity
Temperature
pH
Dissolved oxygen
Structural diversity/topography
Sedimentation rate
Turbulence
Nutrients
Depth
Irradiance
Contaminants
Rainfall
Disturbance events

Socio-Economic

Restoration costs
Community capacity building
Community engagement/awareness
Employment/jobs
Fisheries harvest size/value
Unsure

Q14. Are citizen scientists or volunteers involved in delivering the monitoring?

Y/N/unsure If N or unsure – go to Q16

If Y – go to Q15

Q15. What variables are citizen scientists involved in monitoring?

- Options as above

Q16. Is there Aboriginal or Torres Strait Islander involvement in delivering the monitoring?

Y/N/unsure If N or unsure – go to Q18

If Y – go to Q17

Q17. What variables are Aboriginal or Torres Strait Islander participants or groups involved in monitoring?

- Options as above

Q18. Which of the following traditional methods are/were used in the monitoring program?

Visual census
Quadrats/transects?
Cores

BRUVs/RUVs

Nets
Mapping

Others (please specify) ___________

Unsure

Q19. Are any of the following non-traditional methods utilised in the monitoring program?
automation

artificial intelligence/machine learning/deep learning
eDNA techniques

drones (including RTK)
multispectral cameras
hydroacoustics

other, please provide further detail _____________

Unsure

Q20. Are there plans to utilise new methods in the project?

- Yes (please specify which methods) ______________
- No
- Unsure

Q21. What is the duration of the monitoring?

1-3 months

3-6 months

6-9 months

9-12 months

1-2 years

2-5 years

5-10 years
Ongoing
Unsure

Q22. Is the monitoring data publicly available?

Y/Partly/N/unsure

If N or unsure – go to Q24

If Y or partly – go to Q23

Q23. How is the monitoring data available?

Upon request

Project specific website/database

Institutional, government or company website/database
Public repository (e.g., dryad)

- Other (please specify) _______________
- Unsure Go to Q25

Q24. If a free, easy access platform was available, would you consider adding your monitoring data?

Y/N/unsure

Q25. Are project reports publicly available?
Y/Partly/N/unsure

Q26. In your opinion, did the project have adequate access to resources (equipment and funding) to facilitate monitoring?

Y/Partly/N/unsure If Y or unsure – go to Q28

If N or partly – go to Q27

Q27. What monitoring activities would you have delivered with additional resources? Please specify __________________ Go to Q28

Q28. What was the total cost of the project's monitoring effort (if ongoing, what is the total cost to date)? Please provide your best estimate ($AUD).

Under $1,000

$1,000 - $5, 000

$5,000 - $10,000

$10,000 - $50,000

$50,000 - $100,000

$100,000 - $500,000

Over $500,000
Unsure

Q29. Were any constraints or challenges experienced in the delivery of the monitoring project?

Yes (please describe) ____________

No

Appendix B

Guidelines document

Guidelines for a universal approach to marine and coastal restoration monitoring in Australia

An output from NESP Marine and Coastal project 1.7: Towards a consolidated and open-science framework for restoration monitoring

Dr. Victoria Cole, Dr. Carmel McDougall, Prof. Rod Connolly

The purpose of these guidelines is to provide a universal approach to marine and coastal restoration monitoring in Australia, including outlining the important considerations for designing and implementing a monitoring program, and recommending universal variables for monitoring that will allow broader measures of success of restoration. These guidelines focus on the restoration of biogenic habitats specifically.

Key points

- A universal approach to marine and coastal restoration monitoring in Australia combines approaches for monitoring restoration of key habitats (seagrass, kelp, coastal wetlands, mangroves, saltmarsh, *Melaleucas*, shellfish and coral).
- Each restoration project is location and activity specific, but all restoration projects require clear identification of the project objectives and determination of the most informative variables to monitor.
- A set of minimum universal variables was compiled for marine and coastal restoration monitoring projects, examples of habitat-specific and goal-based variables are also provided.
- All variables (even universal) require specific expert advice and further refinement of monitoring methodology through ecosystem-specific working groups.

Introduction

Ecological restoration is defined as the activity of restoring degraded sites, which encompasses multiple forms of intervention (Ableson et al. 2016). Some restoration activities entail amelioration of the physical and chemical characteristics of the substratum which will enable a return of vegetation cover, the improvement of the productive capacity of degraded lands by fixing acid sulphate soils, or the enhancement of conservation values by removing invasive species or grazers (Hobbs & Norton 1996), whereas others focus on on-ground activities to assist recovery (for example, transplanting seagrass rhizomes). As the method of restoration defines the restoration goals and subsequent monitoring, it is important to define that these guidelines refer to "active restoration" of on-ground activities that focus on biogenic habitat-forming elements (e.g. seagrass, kelp, coastal wetlands, mangroves, saltmarsh, *Melaleucas*, shellfish and coral).

There is currently a surge of interest in marine and coastal restoration within Australia, with a significant number of projects underway and many more in the planning phase. The Coastal Restoration Database developed by the Australian Coastal Restoration Network lists over 230 individual projects between 1978 and 2020 focused on restoration of biogenic habitat-forming elements i.e., coral, seagrass, kelp, mangroves, saltmarsh, shellfish reefs, or entire estuaries or wetlands (Purandare, 2021). These projects are undertaken by a range of non-government organisations, government agencies, universities, and community groups, and vary in scale, objectives, and resourcing.

The need for a standardised framework for coastal and marine restoration monitoring and reporting has been clearly documented in previous projects and studies (Goergen et al., 2020; Lindenmayer 2020; Mack et al., 2020; Eger et al., 2022). The benefits of implementing standardised reporting include 1) facilitation of comparisons between restoration projects/sites (Goergen et al., 2020), 2) ensuring that future restoration projects can evaluate the effectiveness of previous approaches, improving efficiency and maximising outcomes (Eger et al., 2022), 3) enabling promotion of the collective benefit of habitat restoration (and incentivisation of future projects) (Eger et al., 2022), 4) ensuring that variables beyond the ecological and physical realms (e.g., socio-economic benefits) are considered (Eger et al., 2022), 5) to reduce reporting bias (Eger al., 2022), 6) facilitation of effective co-operation between stakeholders involved in restoration within the same geographic and/or legislative area (Mack et al., 2020), and 7) ensuring key and cost-effective variables are measured to help determine success of a restoration project.

There are a range of comprehensive guidelines for monitoring restoration, most of which are habitat-specific (e.g., Paling et al. 2009, Baggett et al. 2015, Fitzsimons et al. 2019, Eger et al. 2022), or habitat and location-specific (e.g., Fonseca 1998, Van Katwijk et al. 2009, NSW Department of Primary Industries 2021, zu Ermgassen et al. 2021). Eger et al. (2022) called on practitioners to develop a restoration reporting framework that includes a standardised set of variables that can be recorded for all marine restoration projects, and presented a roadmap for the development of this framework. An initial step of the roadmap is the co-production of a draft restoration reporting framework by a focal group for one or two ecosystems within one jurisdiction. This initial step aligns with the aim of this project, which is to develop a guidelines document for co-ordinated monitoring of restoration initiatives.

As a result of an international literature review of restoration monitoring, a stakeholder survey, and a workshop for researchers and practitioners actively involved in restoration in Australia, we have identified a range of variables that are commonly measured in monitoring programs regardless of the focus ecosystem, and others that are habitat-specific (see

McDougall et al., 2022). Here, key commonalities between these guidelines are brought together for application to restoration monitoring across different types of biogenic habitats, specifically: 1) seagrass and kelp; 2) coastal wetlands, mangroves, saltmarsh and *Melaleucas*; and 3) shellfish and coral.

These guidelines have been produced through the National Environmental Science Program Science Program Marine and Coastal Project 1.7 "Towards a consolidated and open-science framework for restoration monitoring" as the results of the literature review of restoration monitoring, the stakeholder survey, and the workshop for researchers and practitioners actively involved in restoration in Australia (McDougall et al., 2022). It is recommended that when designing a monitoring program, the project report (McDougall et al., 2022) is read in conjunction with outputs from other NESP projects that focus on restoration (particularly 1.5, 1.6, 1.8, 1.10).

Restoration objectives and project monitoring stages

The context (degree of human impact, ecosystem type, habitat), geographical location, scale, and method of each restoration project varies (Fraschetti et al. 2021), and will influence the primary restoration goals. All restoration projects require clear identification of goals and objectives as the first step; this will enable identification of the most appropriate variables to monitor, regardless of the habitat. Early-stage monitoring, referred to as "implementation monitoring", is often performed to evaluate early on-ground work, for example, milestones for the kilograms of seeded gravel deployed by contractors (Layton et al. 2022). Despite the importance of implementation monitoring, the monitoring of restoration performance requires greater consideration from a scientific perspective. "Performance monitoring" evaluates the trajectory of restoration project and whether the restoration activity is achieving its desired objective(s) (Layton et al. 2022). A flow chart describing important steps for the design of monitoring programs for marine and coastal ecosystems is presented in Figure 1.

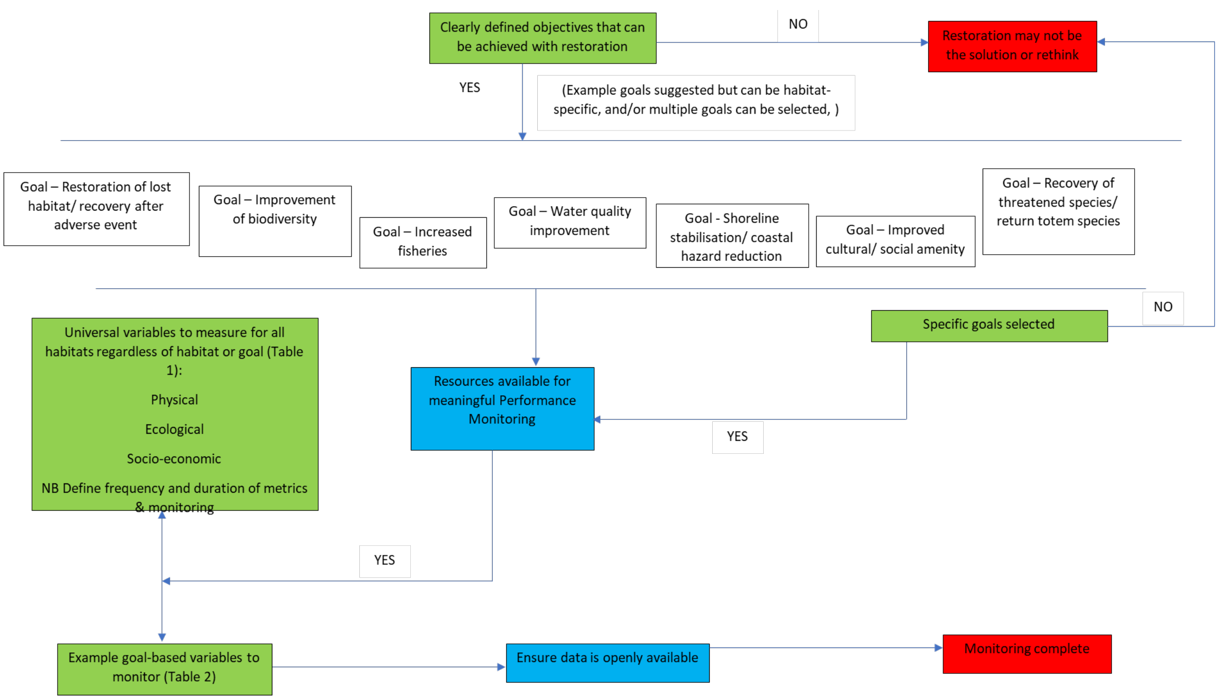

Figure 1: Flowchart for the development of monitoring programs for marine and coastal restoration projects

Variables for restoration projects

Performance monitoring includes the combination of measurements of: (a) universal variables (i.e., variables that can be compared across projects and habitat types), (b) habitat-specific variables, and (c) restoration goal-based variables. For example, there are a number of habitat-specific variables and goal-based variables for shellfish reef restoration projects, e.g., increased biodiversity, habitat enhancement for fish and crabs, or removal of excess nitrogen. It is unrealistic that all projects can monitor an extensive number of performance variables that often require extensive experience and expertise (DeAngelis & Geselbracht 2019), and may be costly. Clear identification of the objectives for a restoration project ensures that resources are not wasted on monitoring of variables that are unlikely to be informative.

Minimum universal variables

Despite each restoration project being habitat-specific and aiming to achieve specific goals, there are a small number of variables that are commonly monitored across projects. Their uptake across a large number of projects indicates that they are simple to implement and cost-effective, therefore they are ideal candidates for inclusion in a universal monitoring scheme to facilitate cross-project comparisons and benchmarking. Here we identify a small set of physical, ecological, and socio-economic variables that can be used for this purpose (Table 1). These variables have been deliberately selected for their relative ease of generation and low cost, ensuring that they will be able to be reported for most marine and coastal restoration projects. As the most commonly reported variables are focused on monitoring ecological function, we suggest additional variables within the physical and socio-economic realms to ensure that outcomes in these areas are also captured.

We note that the recommended temporal scales (frequency and duration) for monitoring each of the variables (if appropriate), and the required budget, need to be carefully considered prior to commencing a monitoring project (Figure 1). This information will also be necessary for future planning of resources, enabling adaptive maintenance, and determining required maintenance.

We also note that although many of these variables are commonly measured across projects, that the precise way in which they are measured and reported varies significantly (for example, the reporting of ‘biodiversity’ variables. We propose standardised units for most variables here, but acknowledge that consistent methodology will need to be developed by future working parties.

Table 1: Minimum universal variables for marine and coastal restoration monitoring across habitat types (seagrass, kelp, coastal wetlands, mangroves, saltmarsh, *Melaleucas*, shellfish and coral).

Variable	Units	Details
Physical		
Total project area	m^2	Includes bare areas between patch reefs, for example
Restored area footprint	m^2	Includes only the physical area subject to restoration attempts (e.g., patches within a broader area)
Ecological		
Survival	% survival	Particularly for initial stages but less important once established – e.g., successful survival of transplants
Recruitment	Individuals/m^2/year	Natural recruitment over time
Socio-economic		
Costs of restoration (if ongoing)/ monitoring/ maintenance	$ (local currency) per annum	Cost as percentage of overall build cost
Community participation (subcategories: including specific indigenous participation, volunteers)	# of people, FTE, hours per activity, # of community events, # of other organisations	Data is generally easily available; social benefits of volunteerism are based on numbers of people rather than FTE
Job provision (e.g. contractors) – project maintenance	FTE	Data is generally easily available, jobs are rarely full time

Restoration goal-based variables

The primary motivation, or goal, of most marine restoration projects (that are not experimental) is to enhance biodiversity (Bayraktarov et al., 2020). Therefore, evaluation of the success or failure of restoration works is often measured relative to the improvement and functioning of the restored habitat.

Marine and coastal restoration monitoring requires a clear rationale for measuring ecological, physical, socio-economic "success" of restoration. Importantly, the overall success of having a monitoring program requires a clear vision which leads to defined objectives and goals (Figure 1). Examples of broad goals include: restoration of lost habitat/ recovery after adverse event; improvement of biodiversity; increased fisheries; water quality improvement; improved cultural/ social amenity; shoreline stabilisation/ coastal hazard reduction; recovery of threatened species/ return of totem species.

If the restoration researchers and practitioners have a clear vision and have agreed upon the objectives and goals (Figure 1), physical, ecological, and socio-economic goal-based variables should be measured to evaluate the progress, success, or failure of restoration works (Table 3). For example, if a restoration project aims to increase biodiversity through improvement of oyster reef habitat, measurement of ecological goal-based variables is required (Box 1). All monitoring programs should consider suitable methods and determine the relevant spatial and temporal scales in consultation with experts, for example, there are many variables and methods to measure biodiversity. Frequency of sampling is also an important consideration (e.g., continual water quality monitoring versus single measurements from a water quality probe). We recommend the establishment of additional working parties to propose best-practice for monitoring methodologies (with consideration of new and emerging technologies), and standardisation of variables.

Box 1. Summary of an example restoration monitoring program.

Habitat:

Intertidal oyster reef

Goals:

1) Return lost habitat
2) Increase local biodiversity (fish and invertebrates)

Universal variables:

All physical, ecological and socio-economic variables, but the method of restoration relies on seeding with oyster spat (not natural recruitment), therefore only survival will be measured.

Goal-based variables

1) Return lost habitat: Reef areal dimension, Project footprint (m^2), Reef area (m^2), Reef height (m), oyster density (individuals/ m^2), Size-frequency distribution (mm).
2) Increase local biodiversity (fish and invertebrates): abundance (Fish: MaxN, number of individual per core) and diversity

Ideal goal-based monitoring includes monitoring of not just at the restoration site, but also reference and control sites, before and after on-ground works (Chapman et al. 1999, DeAngelis and Geselbracht 2019, NSW DPI 2019). It requires the use of systematic and standardised monitoring protocols before and after the on-ground restoration work, and reference ecosystems where project outcomes can be evaluated against expectations and objectives (DeAngelis and Geselbracht 2019, NSW Department of Primary Industries 2021), i.e., experimentally testing the interaction between spatial and temporal components of variation against a variable background (Chapman et al. 1999).

Table 2: Examples of restoration goal-based variables

Variable	Units	Details
Physical		
Water quality	pH, salinity, turbidity, dissolved oxygen, temperature, nutrients	The variables depend on those required for the health of the restoration target e.g., oxygen and light for seagrasses Relatively easy to take snap-shot measurements but need to consider its 46relevance Determine availability (and relevance) of large-scale data e.g., BoM
Hydrology/ hydroperiod	mm or m	Expected change for intertidal projects
Bank stabilisation	Slope, rugosity, or change in shoreline position (m yr-1) or sediment volume (vertical change	Sediment deposition /erosion (vertical height), Wave attenuation, Wave transmission coefficient
Ecological		
Growth or productivity	Standard units for ecosystem type	Measure of size or estimate of biomass suitable for each habitat e.g. shell height
Health/condition of restored ecosystem	Per ecosystem type	e.g., condition index (oysters), epiphyte loads (seagrass)
Biodiversity	Species richness, diversity	Overall, or fish, invertebrate, microbe specific
Socio-economic		
Indigenous engagement	Attitudes (positivity/negativity towards restoration) Involvement in project development/planning Culturally important species (presence/ increase in number)	Benefits: Cultural, food and medicine provision, materials (e.g., wood and seeds), social and community, learning on country (intergenerational knowledge sharing), working on country (long term – ecotourism, rangers managing site etc.), working on country (short term)
Use of restoration area	Users/day, willingness to pay Number of events, number of participants	Use of restoration area: recreational boating, fishing, enjoying scenery, birdwatching visitation, dog walking, locals exercising, family outing, picnics, swimming Visitation by locals, by within state/ out of state / internationals Frequency
Education and learning		Self-guided walks, school trips, citizen scientists, survey of knowledge
Change in opinion of quality	Costed ecosystem services	

Data availability

To facilitate comparison and analysis these data should be made fully and easily available, ideally as raw data in a format that can be easily parsed electronically. We encourage practitioners to make monitoring data available throughout the project, rather than at its conclusion.

Acknowledgements

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National Environmental Science Program

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