Coastal and Marine Restoration and Repair White Paper

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Abstract (289 / 250)

Australian coastal and marine ecosystems are foundational to the nation's social, cultural and economic values, yet are negatively impacted by climate change and other anthropogenic stressors. Conventional management approaches have not been able to slow, halt and reverse biodiversity loss resulting in calls to include increasingly active interventions in the ecosystem management toolkit. Australia is a world leader in restoration research and development (R&D) pioneering fundamental knowledge, applied restoration tools and climate-proofing strategies, and many approaches are at the cusp of large-scale implementation. Spanning most marine ecosystems and regions our contributing experts identified common challenges and solutions for R&D.

1. **Large-scale and long-term restoration hubs/test beds** across ecosystems with equitable, transparent, and fit-for-purpose governance and finance structures. This will enable key R&D questions around efficacy, value and impact to be answered in realistic field settings and time frames.
2. **Rate-changing R&D for scaling up and climate resilience**. Prioritising innovative approaches across disciplines (engineering, AI, multi-omics) including genetic approaches to boost heat tolerance and climate adaptation.
3. **Evidence-based decision support tools** to integrate information platforms for improved prioritisation, prediction and evaluation of restoration outcomes.
4. **Solutions to societal barriers and skillset shortages** to create enabling conditions (social license, permitting, and funding) and a skilled workforce to implement restoration at scale. Supporting co-design and leadership from First Nations and local communities enhances quadruple bottom line benefits.

Investment in these four priority areas will ensure a coordinated and efficient approach to meet Australia's restoration knowledge needs into the future. Together, they maximise down-stream ecological, societal, economic and cultural benefits of restoration and repair activities for our valuable coastal marine ecosystems and communities.

Relevance - Societal Benefits

Why does Australia need to pursue this endeavour?

Healthy and productive coastal marine ecosystems are foundational to Australia's social, cultural and economic values with marine industries contributing $203B pa to the national economy in FY2023 (AIMS Index of Marine Industry: 2025). Over 45% of coastal marine habitats in Australia have been degraded or significantly altered, leading to declines in biodiversity, fisheries productivity, and natural coastal protection (Babcock et al. 2019). Critically, climate change projections suggest accelerating decline of many marine ecosystems unless rapid action to reduce emissions and additional management actions are taken to boost resilience of populations, species and ecosystems. This reinforces the urgent need for evidence-based, scalable interventions that are relevant at the scales where

degradation is evident and where it can be used to step or reversed (Sustainable Oceans Plan). Coastal and marine ecological restoration and repair (hereafter, restoration) research and development (R&D) is the science that is focussed on addressing these challenges at increasing spatial, temporal and socioeconomic scales with the aim to ensure the long-term health, resilience and values of our unique coastal and marine environments.

Classical ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (Gann et al., 2019). Methods include reducing stressors, introducing biological material, reconstructing physical substrates, and reinstating hydrological regimes. However, as human impacts and climate change progress, the return to historical baseline or reference state conditions will become increasingly infeasibly, necessitating a flexible conceptualisation of restoration (sensu Saunders et al. 2024) to be inclusive of novel, hybrid, or 'climate adjusted' states. Here, we use the term 'restoration' to represent concepts of 'classical' ecological restoration as well as restoration-like approaches from the field of Nature-based Solutions (NbS, e.g. living shorelines, living seawalls). NbS aim to meet societal objectives and ecological functions simultaneously. Our flexible interpretation of the goals and realities of restoration in complex coastal zones subjected to multiple stressors and increasing climate change emphasises that effective and realistic restoration will need to increasingly innovate and learn to develop and employ proactive and interventionalist approaches that aim to restore functions and boost climate resilience.

Rapid and transformational restoration R&D is necessary for Australia to reach international commitments under the Global Biodiversity Framework (GBF) and United Nations Framework Convention on Climate Change. This includes upscaling restoration activities to meet commitments such as Target 2 of the GBF to restore 30% of degraded ecosystems. Nationally, large scale restoration is central to delivering on priority plans and strategies including Australia's Sustainable Ocean Plan, Australia's Strategy for Nature (Australia's National Biodiversity Strategy Action Plan under the GBF) and the Nature Positive Plan. Restoration programs should support the inclusion of Indigenous knowledge and create and maintain economic opportunities to support quadruple bottom line benefits (Planet, People, Purpose, Profit) for Australia. Strengthened national and international partnerships across restoration sectors are also key for knowledge sharing, translating and operationalising restoration R&D to achieve and offer new equitable long-term benefits for Australia's valuable marine ecosystems.

This white paper focuses on restoration R&D, and how it aims to develop knowledge and tools to enable restoration now and under intensifying climate change. This knowledge has intrinsic value and can inform conventional and resilience-based management approaches. Importantly, the full impact of R&D is realised once it is applied and supports restoration implementation at ecologically and socioeconomically relevant scales. Restoration R&D becomes operationalised to restoration implementation by adoption and uptake of knowledge into policy, through education aimed at increasing social license, by supporting private and public infrastructure and through training and capacity building of the restoration workforce. The approach will improve decision making for environmental markets and

restoration programs and connect into national reporting frameworks such as Environmental Economic Accounts, the State of the Environment Report, and Australia's Strategy for Nature.

The Beneficiaries of Restoration R&D Activities are diverse

Scientists gain valuable knowledge, expertise and job opportunities. Restoration practitioners gain access to improved techniques and methodologies. Environmental agencies and NGOs benefit from enhanced knowledge, collaboration and funding opportunities. Managers and policy makers receive essential data and tools to inform policy, decision making and accountability such as Australia's Strategy for Nature commitments towards the Global Biodiversity Framework. The private sector benefits from increased certainty on the outcomes and risks of restoration enabling more scalable, cost-effective, and sustainable practices. When R&D leads to large scale programs of restoration, the broader community benefits from enhanced ecosystem services and other social and economic values. Traditional Owners can benefit from training opportunities, employment, and enhanced connection to Country. Local communities benefit from improved ocean literacy and environmental awareness, new skills, and sense of community. Together these can form a feedback loop where local communities perceive benefits of restoration and then are more supportive of future restoration efforts, leading to more successful outcomes

How would you know that these benefits have been delivered?

Demonstrating ecological success from restoration R&D relies heavily on setting *a priori* goals and objectives and identifying suitable baselines or targets along with appropriate indicators to evaluate outcomes. To track ecological outcomes, restoration trials or experiments will ideally monitor change in extent or coverage as well as indicators of biodiversity, and ecosystem function and services relative to control or baseline locations. A variety of metrics can be used depending on the restoration objectives, for example, indicators of structural complexity, carbon sequestration, water quality, connectivity, diversity, adaptation or resilience. Common to most is the requirement of long-term monitoring which is typically resource intensive and not always prioritised in shorter and constrained funding cycles.

The economic and social advantages of restoration, for example to Indigenous groups, local communities, or tourism operators, can be identified through existing socio-economic indicator analyses. Metrics include job creation, investment from commercial entities, community participation, enrolments in educational programs, ocean literacy and stewardship, visitation rates and consumer surpluses for ecosystem services provided by restored sites, including non-market values associated with improved community wellbeing. Fit-for-purpose socioeconomic evaluation approaches are required to track these outcomes.

The impacts of restoration R&D to partners and end users can be measured by a change in management or policies, uptake of new technologies or techniques, as well as increases in

scientific standing and educational and training outcomes. Ultimately, the full value of restoration R&D will be realised when large scale restoration is valued by mainstream society as a primary conservation intervention conducted proactively and strategically with other activities such as protection and pollution control, and when restoration is adopted by influential industries (e.g. energy, fisheries, transport) as a means of mitigating negative influences on nature in line with initiatives such as the Taskforce on Nature-related Financial Disclosures and Taskforce on Climate-related Financial Disclosures. As with any R&D activity, not all research is expected to lead to implementation, but R&D is essential to moving forward.

How can Indigenous perspectives, science, and knowledge and participation be included and enhanced?

Indigenous co-designed and led restoration R&D is required to implement and scale up restoration nationally and internationally. Indigenous perspectives and knowledge should be included through well planned, co-designed or Indigenous-led projects and activities (Saunders et al. 2024, Waltham et al. 2025). Respectful cultural conduct, relationship building, and partnerships are foundational to the success of these endeavours (Waltham et al. 2025). For practitioners and researchers, learning and adopting principles of respect and reciprocity as well as recognising and valuing Indigenous knowledge systems and world views will be central to developing effective partnerships. The current level of Indigenous inclusion in restoration R&D varies across ecosystems and geographies and reflects varied rights, interests, capacity and obligations amongst Indigenous peoples. For all geographies, R&D programs with inbuilt training and capacity-building initiatives will be crucial for enhancing Indigenous participation and leadership in restoration. Dedicated funding and resources for Indigenous-led initiatives, along with cultural protocols respecting intellectual property rights, are necessary. Empowerment of Indigenous communities to lead restoration R&D and implementation contributes to employment opportunities and connection to Country in alignment with broader visions for Indigenous leadership in sustainable ocean culture (E.g. [1]).

Current state of the science or R&D

R&D activities currently undertaken in Australia

There is much restoration R&D and practice currently undertaken in Australia's marine and coastal waters (Fig. 1a) with projects spanning most significant ecosystems, states and institutions. Most projects are collaborative but focus on specific ecosystems or species (e.g. coral reefs, kelp forests, seagrass meadows). Many embed one of more R&D objectives to fast-track knowledge and to scale-up and transition from R&D to implementation at

[1] Hunter et al. In Press Flipping the Tide: A First National vision for Indigenous leadership in sustainable ocean culture. NMSC Black Paper

relevant scales. Examples of focal R&D activities and ecosystem including generalities and specificities are summarised below.

Ecosystem baselines– present and past habitat extent and condition

Baseline knowledge of ecosystem distribution, condition, threats and trajectories of change, are required to identify locations requiring restoration across Australian ecosystems. These data are created using a suite of data sources and R&D tools including remote sensing, *in situ* empirical observations, modelling and historical archives (Fig 1a). For coastal wetlands, maps of ecosystem extent and sometimes condition are available from state governments, however there are gaps in the consistency of these data across state borders. Nationally consistent maps of mangroves, saltmarsh and mudflats have been created including some estimates of historical distributions. Habitat maps derived from satellite remote sensing and modelling, as well as long-term *in-situ* datasets on environmental parameters, key species, and communities, are available for shallow coral reef. For shellfish, broad information on historical distributions have been produced from historical archives. High resolution maps of seagrass and seaweed habitat are available at local-regional scales, but at present there are major gaps in coverage at national scale and beyond 20m depth. Data on ecosystem extent and condition are being used to populate Australia's Environmental Economic Accounts (EEA) and if done effectively at appropriate scales, will allow us to track change to natural assets resulting from restoration at local, national and international scale.

Research to increase the effectiveness of methods

Research aimed at developing and testing effectiveness of methods for on ground active restoration techniques works is a substantive and growing focus. Restoration techniques are varied and span a continuum of interventions (*sensu* Gann et al. 2019). These techniques include:

- Removing or mitigating stressors (e.g. crown of thorns starfish and algae in coral reefs, sea urchins in kelp beds, feral ungulates in wetlands, improving water and sediment quality)
- Reinstating hydrological flows (e.g. in wetlands)
- Adding and/or improving suitable substrates and structures (e.g. eco-engineering human-built structures, hessian mats for seagrass, hard substrate for biota such as artificial reefs)
- The addition of desirable biota—through transplantation, propagation, and dispersal of propagules such as seagrass and mangrove seeds and seedlings, as well as oyster and coral larvae, spat, and fragments—is a direct restoration intervention to repopulate degraded areas.
- Novel techniques for climate proofing of added biota (e.g. Assisted evolution and climate-adjusted provenance)

Rate changing R&D that is aimed at developing effective techniques that can be efficiently scaled up and achieved cost-effectively is needed as is improved and nationally consistent

reporting of results and outcomes from methodological studies. Examples could include AI assisted visual analysis, robotics, miniaturisation, high throughput multi-omic analysis for coral fitness and adaptation, as outlined in several White Papers in this collection.

Developing and testing monitoring and evaluation tools and frameworks

The use of new technologies such as eDNA, omics, remote sensing, underwater drones, acoustic monitoring, and photogrammetry (the use of imagery to build 3D models that capture high resolution information of habitat builders size and spatial configurations, as well as structural complexity of the area), as well as more traditional biodiversity surveys and citizen science monitoring initiatives are being extensively developed and tested in Australia. There is a need for integrating and translating these techniques into consistent and repeatable frameworks for restoration monitoring and evaluation. Standardised field and genetic monitoring protocols across levels of biological organisation help to build consistency in data collection, and standardises monitoring frameworks, data-repositories, and user interfaces are needed to ensure consistency, comparability, and ease of use for R&D and decision making.

Measuring benefits and outcomes of restoration

Over the past decade there has been concerted effort to gain qualitative and quantitative understanding of the ecosystem services which (could) accrue through restoration. This has included identifying and standardising methods to measure how restoration projects contribute to ecosystem condition and value, climate regulation via carbon sequestration and emissions reduction; water purification resulting from managing nutrient flows; coastal protection from mitigation of erosion and inundation; reduced pest invasion from improved habitat resilience; and increased fisheries biomass resulting from habitat provision. Cultural services have also been recognised, including delivery of recreational opportunities, values associated with existence of biodiversity, and First Nations values.

Guidance has been developed on how to translate biophysical measures of ecosystem services into monetary metrics, enabling the potential for many benefits to be formalised through inclusion in Environmental Ecosystem Accounts (EEA), which demonstrate co-benefits of a restoration project over time, or in welfare analyses (e.g. benefit-cost analysis), which measure the net contributions of projects to inform investment decisions. Limited applications exist at the restoration project level demonstrating implementation of measurement methods and guidelines and resources are rarely available to measure benefits adequately or at scale. Guidance on First Nations values has appropriately focussed on providing advice to implement co-designed processes to identify values case-by-case, rather than on identifying the values themselves.

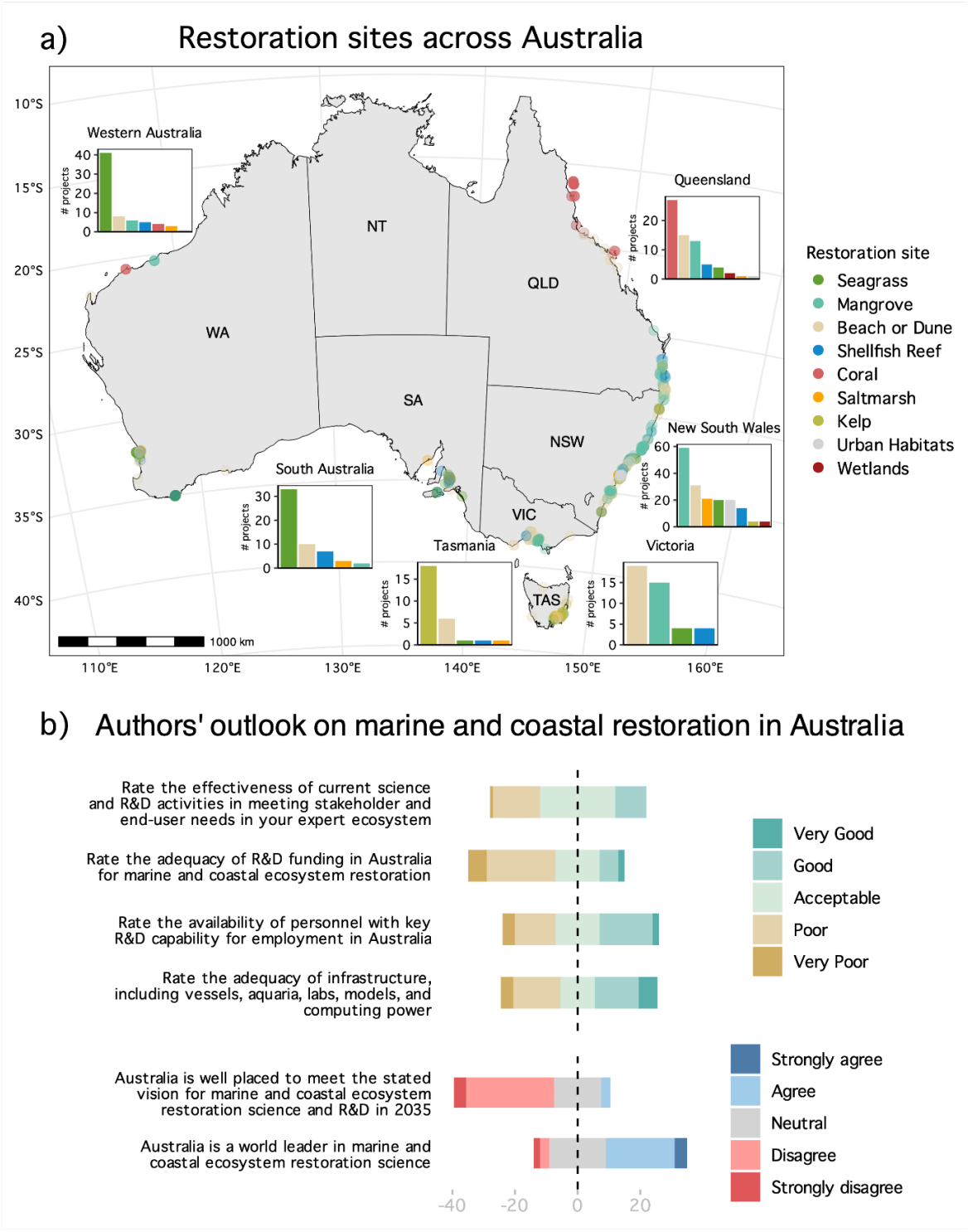

Figure 1. Current state of restoration in Australia. a) Locations of restoration projects from the Australasian Coastal Restoration Network database (https://www.acrn.org.au/), Living Shorelines database (https://livingshorelines.com.au), and Living Seawalls database (https://www.livingseawalls.com.au) as of April 2025. Inset bar plots highlight the variability in restoration types across states (no restoration data for the Northern Territory). **b)** Author ratings of the current state of R&D within Australia (gold-green bars) and agreement with two statements regarding restoration activity in Australia (red-blue bars; n = 50 each).

Emerging work is focussed on delivering evaluation frameworks that allow for transparent interpretation of the uncertainty that accompanies data porosity, in the absence of resources to establish more informative databases of ecosystem service values derived from restoration. The focus on establishing Australia's Nature Repair Market has emphasised the need for these frameworks and more robust value databases to enable a market that is well-informed about the potential supply of biodiversity credits from restoration. Developing standardised frameworks and online portals to track restoration efforts, harmonise monitoring data and evaluate outcomes data will be critical to learning from past efforts and evaluating progress towards targets.

Resource allocation and prioritisation

This research area examines how we allocate resources effectively to maximise outcomes relative to conservation and restoration objectives. Drawing from the fields of ecological modelling, resource management, decision theory and economics, restoration prioritisation approaches aim to identify actions and locations for which restoration is predicted to meet, or maximize, particular objectives. Many quantitative approaches are used, including systematic conservation planning, cost-benefit analysis, cost-effectiveness analysis, multi-criteria decision analysis, and structured decision making. Qualitative approaches, such as the Resist-Accept-Direct (RAD) Framework developed by the US Geological Survey and adopted by Parks Victoria to inform coastal parks planning under climate change, are useful where quantitative data are limited. Habitat or restoration suitability models underpin many of these approaches. They enable prediction of site suitability for restoration in the present. They also generate insights for ecological reference states in the absence of historical data, and future prediction in the context of increasing climate change. Incorporating social values into analytical tools to estimate the feasibility of achieving outcomes and the potential beneficiaries is an active and growing area of research. Recent R&D employing spatial prioritisation tools for restoration planning has occurred for coral reefs, coastal wetlands, and shellfish reefs but in many instances, this has not yet translated into management, given that on-ground restoration decisions are typically more driven by social, governance, permitting and political opportunities. As restoration is scaled up, and climate change impacts worsen, prioritisation tools will help decision makers to develop more cost-effective and equitable programs of investment. These technical tools must also be aligned with participatory methods for priority-setting and location selection that include community, stakeholder and First nations perspectives. Importantly, decision support models will be needed to inform restoration planning in the context of other management strategies such as protected areas, pollution control, and fisheries management, as well as in relation to policy and management objectives related to the developing Blue Economy.

Structural and societal barriers

This research focusses on identifying structural societal barriers to the implementation of restoration and providing recommendations on how to overcome them (Saunders et al. 2024, Waltham et al. 2024). Such research is fundamental to enabling restoration at scale

and draws from experts in multiple disciplines and sectors. Prominent barriers which are being addressed include:

- Legal and governance issues, such as permitting, land tenure and uses, and liability
- Insufficient funding for the full life cycle of restoration and ongoing maintenance
- Social factors preventing local communities and Indigenous groups from effectively supporting, participating in, co-designing, leading or benefiting from restoration
- Disciplinary divides preventing the engineering sector in implementing NbS for coastal hazard protection due to lack of ecological knowledge, standards, or codes of practice.

Development of tools and techniques to future-proof restoration

Research is increasingly focussed on how to make restoration projects more resilient to climate change and using restoration as a proactive adaptation tool. Current areas of focus include:

- Assisted evolution interventions which involve selecting and/or moving individuals (e.g. coral, kelp) that can withstand higher temperatures to enhance rates of natural adaptation. This includes phenotyping and selective breeding, climate provenance, assisted gene flow, and hybridization approaches.
- Microbial treatments are being investigated to boost organisms' health and resistance to stressors (e.g. coral, kelp, seagrass). This involves manipulating microbiota or symbionts to improve survival rates and performance.
- Shading and cooling approaches aim to reduce stress on coral reefs. Cloud brightening and local fogging are emerging atmospheric techniques being trialled to mitigate the direct effects of warming on corals by reducing light stress.
- Spatial modelling of predicted climate impacts identifies restoration locations suited to future conditions (e.g. www.reefadapt.org). For example, modelling to predict natural refugia from warming, sources of stock, or locations where landward migration of vegetation with sea level rise can occur.

Main ecosystems and flagship programs being implemented and associated R&D

Wetland restoration in Australia targets mangrove, saltmarsh, and coastal floodplain habitats, primarily by restoring natural hydrology and sediment supply. This approach reduces the need for intensive planting or engineering, making it cost-effective and ecologically sustainable. As sea levels rises, identifying and prioritising habitat migration pathways will become increasingly important. Large-scale projects exemplify this strategy: the Blue Heart Wetlands on Queensland's Sunshine Coast aim to create climate-resilient blue carbon habitats while mitigating flood risks; Big Swamp, Hexham Swamp and Yarrahapinni restoration projects in NSW have restored over 2300 hectares of degraded land into functioning wetlands; and the Lower Murray Wetlands in South Australia focus on enhancing breeding habitats for waterbirds and other threatened species. Research at these and other degraded wetlands is being undertaken to improve understanding of approaches

to reinstate catchment and tidal flows to support biodiversity, climate resilience and community protection.

Shellfish reef restoration is occurring across Australia and a national shellfish restoration project has been established with at scale projects in most states (McAfee et al. 2022). Notably, The Nature Conservancy's Reef Builder program has restored 40.5 ha of lost shellfish reefs to date around Australia. Key R&D activities include documenting remnant populations and using historical information to estimate extent of loss; valuation of ecosystem service benefits to build business cases for restoration; developing modelling and decision support tools to decide where to build new reefs; ascertaining the optimal substrates and configuration for restoration; developing knowledge around key limiting factors to recovery and how to mitigate these; and working with aquaculture to seed new reefs.

Kelp forest and macroalgal restoration is a focus of the Great Southern Reef (Fig. 1a; Layton et al. 2020) where these valuable ecosystems have experienced significant declines due to warming waters and other environmental stressors. Restoration activities are occurring across all southern states and involve replanting kelp and managing sea urchin populations to support the recovery of these critical habitats as well as identifying warm tolerant strains for futureproofing. Key projects include Operation Crayweed (*Phyllospora comosa* restoration) in NSW, *Macrocystis pyrifera* restoration off Tasmania and *Ecklonia radiata* restoration off WA and Victoria. R&D activities focus on determining the most effective restoration techniques, identification of appropriate genotypes and source populations and how to manage key stressors limiting recovery.

Seagrass restoration is underway across all Australian coastal states, with projects growing in scale, sophistication, and community involvement. Recent efforts have shifted from small trials to large, collaborative initiatives involving Traditional Custodians. Common methods include transplanting shoots, seeds, or seedlings, improving water quality, and replacing damaging boat moorings with eco-friendly alternatives. Key projects include Seeds for Snapper in WA and SA, Operation Posidonia in NSW, and large-scale efforts in the tropics. Volunteers, including recreational fishers, help collect seagrass fragments and seeds. Seagrass nurseries, some of which are developed with Traditional Owners, produce seeds to support scaling efforts. In WA, robotic seed injection trials are underway to enhance efficiency. R&D focuses on improving cultivation facilities, boosting survival and resilience of restored meadows, reducing costs, and developing genetic tools to identify suitable genotypes. These efforts aim to restore vital habitats, support biodiversity, and strengthen coastal ecosystems.

The Reef Restoration and Adaptation Program (RRAP) is a large R&D effort that supplements on the ground projects to develop innovative restoration techniques for **tropical coral reefs** to be applied nationally and globally (McLeod et al. 2022). This large program is focussed on the Great Barrier Reef and currently involves two coral restocking tools – coral restoration through larval capture and release, and aquaculture breeding and deployment of corals on seeding devices. Other R&D in the program focuses on ecological, social, traditional, and

governance knowledge systems, as well as improvement of technologies (including cryopreservation) and logistics for large scale operations (Bay et al 2023). RRAP is a partnership among seven primary Australian organisations, with further collaboration with >25 national and international institutions. It is funded by the Australian Government, program partners and third-party donations via the Great Barrier Reef Foundation.

Living shorelines use restored coastal habitats, sometimes supported by structural components (hybrid approaches), to improve resilience to erosion and flooding. While beaches and dunes have long been managed for coastal protection purposes in Australia, interest has grown in restoring other habitats like mangroves and shellfish reefs for coastal protection. Hybrid approaches are increasingly used in challenging areas, such as NSW estuaries, where bank-parallel rock fillets have supported mangrove establishment since 2000. R&D efforts aim to balance ecological and engineering outcomes by optimising structural components to support habitat recovery and persistence. Additionally, research is quantifying the benefits and co-benefits of living shorelines to inform cost-benefit analyses comparing such approaches with traditional infrastructure.

Living Seawalls employ modular high relief panel systems to increase the ecological functions of concrete shoreline structures. Living seawalls started in Sydney Harbour in 2018 and has expanded to 32 sites across four states and 10 countries. Initially focused on biodiversity enhancement, R&D now explores functional benefits like water filtration, productivity, and wave dissipation, alongside methods to quantify these outcomes. Recent research includes addition of sensory cues for the panels (visual, sound) and low-carbon materials. Understanding social licence for these interventions has become a major R&D focus aimed at scaling up.

Multi-habitat seascape restoration involves moving beyond habitat-by-habitat restoration towards implementing multi-species and multi-habitat restoration (Vozzo et al. 2023). Recent advances include developing decision and modelling tools to support site selection for seascape restoration projects and/or rehabilitation of habitats within connected seascapes. Developing monitoring and evaluation programs for seascape restoration projects are also a focus. For example, how do we best evaluate increased cross-habitat connectivity and resilience. Project Restore in Sydney Harbour, NSW is among the first seascape restoration projects, and includes restoration of connected seagrass, kelp, and shellfish habitats. The Reef Trust initiative to incentive riparian restoration with the aim of mitigating downstream delivery of sediment pollutants to the GBR lagoon is an example of large-scale investment that specifically targets connections among ecosystems.

Current support for restoration research and development (R&D)

Benchmarking the current and required support for restoration R&D requires articulating a vision for where we want to be in the future. The authors envision a future where

restoration R&D will provide the environmental, social, technical and economic knowledge to enable delivery of effective and successful restoration at relevant scales. Here, scale depends on context and necessarily starts smaller with a plan to grow to the scales where impacts are experienced. Ultimately, we envision large regional to national scale coordinated R&D is undertaken to achieve larger large scales and portfolios of objectives. The conceptualisation of scale is not just output and extent but includes longer timescales and greater socioeconomic benefits. Here we report on expert opinions from the authorship on Australia's ability to meet this vision for marine and coastal ecosystem in 2035 under current investment, resourcing and capability levels

There are diverse perspectives on the effectiveness of current restoration R&D activities in the authorship team where a majority (68%) feel that the effectiveness is acceptable or good. However, none thought it was 'very good', suggesting there is significant room for improvement. These findings underscore the need for updated and enhanced R&D strategies to deliver essential knowledge tools and methods effectively and at the pace where they are needed (Fig. 1b). When asked "Is Australia well placed to meet the stated vision for marine and coastal ecosystem restoration science and R&D in 2035?" the overwhelming majority (64%) of authors disagreed or strongly disagreed with the statement. Only 6% of authors agreed with the statement, and no authors strongly agreed (Fig. 1b).

Perception of the adequacy of current support for restoration by the authors varies across four key areas: R&D funding, R&D personnel availability and R&D infrastructure (Fig 1b). Significant concern regarding the adequacy of current funding for restoration R&D exists by experts specialising in all ecosystem types and rated as poor or very poor by most authors (56%). Only 28% thought funding was adequate and only a small number of respondents (16%) rating funding as good or very good (Fig. 1b). Authors generally thought there was a substantial shortfall in the amount and duration of funding for restoration R&D projects and methods for their long-term monitoring, evaluation and further improvement. Resources also need to be allocated effectively and equitably across ecosystems and projects to optimise the benefits for Australia. This requires a comprehensive understanding of benefits across four dimensions (Planet, People, Profit, Purpose) and filling this gap is critical to support decision making and operationalisation of ongoing and future initiatives.

Ongoing restoration site stewardship and management requires community capacity, a skilled workforce and a new industry to deliver on the ground benefits for Australia. There is a clear need for increased investment in education and training programs to develop a skilled workforce capable of supporting restoration projects. The outlook for the availability of personnel with key R&D capabilities for employment in Australia by the authors was mixed. While 38% of respondents thought that the availability of personnel for restoration R&D was good or very good, 34% thought it was poor or very poor (Fig. 1b). This range of responses likely reflects substantial difference in personnel availability both within and

across systems and highlights that strategic cross sector improvements are necessary to ensure sufficient and skilled personnel by 2035.

Similarly, author agreement regarding the adequacy of current infrastructure for restoration R&D were largely split between good or very good (40%) and poor or very poor (38%), highlighting the varied perspectives within and across systems regarding the availability of infrastructure for restoration (Fig. 1b). Authors felt that existing infrastructure, such as vessels, aquaria, labs, models, and computing power, requires upgrading and expansion to support cutting-edge R&D activities.

Here we identify and discuss key high-level challenges to meet the vision for 2035 to enhance Australia's positioning and ensure the successful implementation of restoration initiatives. Commonalities across ecosystem types highlight the widespread nature of these concerns and the solutions emphasise inter and trans-disciplinary collaboration.

Australia's international standing in the fields required to progress marine and coastal ecological restoration

Australian universities are highly ranked (top 50 globally) for their standings in scientific fields central to restoration R&D including biological, environmental and marine sciences, ecology, oceanography and engineering and author perspectives reinforced this view. Given the statement: "Australia is a world leader in marine and coastal ecosystem restoration science", approximately half of respondents (53%) agreed or strongly agreed, while 37% remained neutral (Fig. 1a), and only 10% disagreed or strongly disagreed. A small group (8%) strongly agreed with the above statement.

Australia is recognised for its strong international leadership in certain areas of marine and coastal ecosystem restoration, and the country has made significant strides in knowledge when significant investments underpinned mission driven R&D programs such as RRAP. This model program has positioned Australia at the forefront of coral restoration science, with advanced research on enhancing thermal tolerance, scaling restoration footprints in coral reefs, and moving from R&D to deployment operations thinking. This program provides a blueprint for large scale restoration test beds for less well-funded habitats. Projects such as Operation Crayweed and Seeds for Snapper provide world leading examples of engaging citizen scientists and the community in restoration. Australian researchers and on ground projects such as Project Restore in Sydney Harbour have pioneered conceptual thinking about seascape restoration which enhances connectivity across multiple habitats. Cross-disciplinary research funded by the National Environmental Science Program (NESP) Marine and Coastal Hub has focussed on how to overcome societal barriers to scaling restoration. Further, Australian researchers have developed world first tools to operationalise and make accessible genetic data in restoration projects (www.reefadapt.org) and developed new restoration techniques (www.greengravel.org and Reef Builder). Future investment should

capitalise on the successes and innovation of these specific programs to apply to other systems.

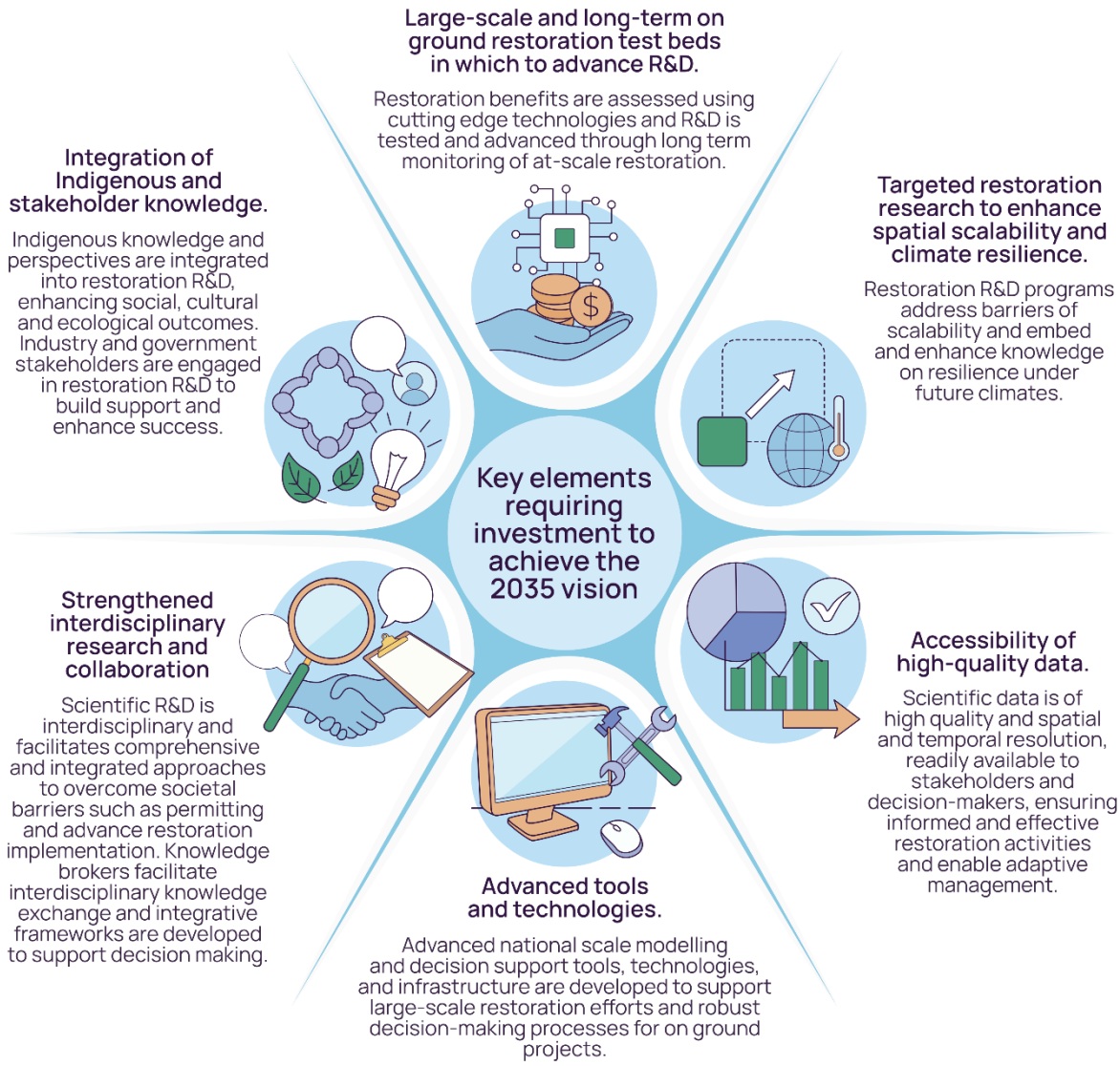

Figure 2. Key elements requiring investment to achieve a vision where restoration R&D will provide the environmental, social, technical and economic knowledge to enable delivery of effective and successful restoration at scale by 2035.

Australia's leadership is also evident in its adoption of innovative technologies and research methodologies. The use of advanced monitoring tools, genetic research, and biotechnology has enhanced the effectiveness of restoration projects. For example, genetic research on corals, kelp forests and seagrass meadows has provided valuable insights into the potential for improving the resilience of these ecosystems to accelerating climate change. We are also leaders in development and adoption of eco-engineering with Living Seawalls projects being adopted in 9 countries. Investment in testing these technologies at scale is the next step in

realising the long-term benefits of this world-leading R&D. However, challenges such as funding limitations, policy barriers, and the need for better coordination among stakeholders limit adequate tests of this R&D capability at appropriately large scales. Addressing these challenges through continued collaboration, integration of traditional knowledge, and investment in capacity building, Australia can enhance its leadership in restoration. These efforts will ensure that Australia remains at the forefront of marine and coastal ecosystem restoration, contributing to global conservation goals and the resilience of its unique ecosystems.

Knowledge and disciplinary requirements (1937 / 2000wds)

Key Knowledge Gaps

We identified many key scientific knowledge gaps that will be critical to fill for achieving multidimensional beneficial restoration in coastal and marine ecosystems by 2035. By focusing on ecological, social, economic, and technological dimensions, we can develop comprehensive and effective strategies for restoring and enhancing these vital ecosystems. The integration of robust scientific research, community engagement, and innovative technologies will be essential to meet the ambitious goals of restoration. These knowledge gaps were almost always identified by authors across more than one ecosystem, highlighting the general need for this work to enhance restoration in Australia.

Ecological Questions:

Baseline Knowledge and Monitoring: What are the past and current states of habitat degradation, predicted future trajectories of ecosystems, and the aspirational target states for various ecosystems? How to combine traditional and new data for robust baseline data and long-term monitoring for restoration benefits, outcomes and value?

Restoration Techniques and Effectiveness: Can we develop cost-effective restoration methods that enhance resilience to large scale disturbances such as climate change and other stressors? What restoration techniques are most effective for different environmental contexts and how can they be scaled up? What risks are there to achieving desired and unwanted outcomes on the target species and broader system, and how does risk change as projects are scaled up?

Species-Specific and Ecosystem-Level Interventions: What are the key species and habitats or combinations thereof that should be prioritised for restoration to achieve desired outcomes? How do we ensure that restoration efforts consider the complexity and interactions within ecosystems, including ecological succession, genetic diversity, species interactions and multigenerational effects and eco geomorphic changes?

Climate Change Adaptation: How can restoration activities be designed to enhance the resilience of ecosystems to climate change impacts, such as warming temperatures, sea-

level rise, habitat migration and increased storm intensity? What are the potential trade-offs and risks associated with different genetic management and adaptation strategies?

Social and Economic Questions:

Socio-Economic Benefits and Trade-Offs: What are the socio-economic benefits of restoration activities, and how can they be quantified and communicated to stakeholders? How do we balance the ecological goals of restoration with the social, environmental and economic needs and values of both local and broader communities?

Community and Indigenous Engagement and Participation: How can we effectively engage local communities, including Indigenous groups and land managers, in the planning, implementation and ongoing management of restoration projects as they change? What are the best practices for co-designing restoration projects with community stakeholders to ensure their needs and knowledge are incorporated? How can cultural objectives and traditional knowledge be better incorporated into restoration planning? How can we improve ocean literacy and communication of scientists, practitioners and the broader community to clarify and improve social license for restoration activities?

Law, Policy and Governance: What policy and regulatory frameworks are needed to support large-scale restoration efforts including those that seek to enhance resilience under future climates, and those occurring on private land? How can we advance land use planning approval and permitting processes to move restoration beyond R&D scales and reduce regulatory barriers to facilitate timely and effective restoration activities at scale? Are there approaches used internationally which can be adopted in Australia?

Funding and Resource Allocation: What sustainable funding mechanisms can be developed to support long-term restoration projects? How can funding be allocated efficiently and cost-effectively to maximise the ecological and socio-economic benefits?

Technological and Methodological Questions:

Innovative Tools and Technologies: What advanced tools and technologies can be developed to improve the efficiency and effectiveness of restoration efforts? E.g., artificial intelligence for image analysis and classification. How can we leverage remote sensing, modelling, and data analytics to prioritise and enhance restoration R&D, planning and monitoring?

Trans and Interdisciplinary Approaches: How can interdisciplinary approaches, integrating ecology, social science, land use and climate adaption planning, economics, and engineering, be applied to address complex restoration challenges? What are the key knowledge gaps that need to be filled through trans/ interdisciplinary research to support successful restoration outcomes?

Barriers to R&D required at the required pace and scale

Funding and Financial Constraints

The largest barrier to effective restoration is the lack of consistent and adequate funding to allow study at the relevant scales for their enquiry (Saunders et al. 2024). Restoration is a long-term endeavour, yet projects often rely on short-term funding cycles, which are insufficient for cross life stage and generation monitoring and evaluation. This also includes social and cultural outcomes associated with the direct restoration activity and associated stakeholders, communities and policy settings. The scarcity and uncertainty of financial resources limit the ability to scale up restoration efforts and hinders the development of innovative techniques and effective long-term collaborations. There is imbalance in the way that funding is allocated, for instance, ecosystems on the Great Barrier Reef receive much more funding than other regions and ecosystems which limits our capacity to undertake the required R&D in those other systems.

Policy and Regulatory Barriers

Policy and regulatory frameworks are generally a large barrier to increasing the number and scale of restoration projects across ecosystems. There is also a need for greater national and cross jurisdictional cohesion and oversight in policy as we move into an era of increasing interventions under climate change. The permitting process for restoration activities in Australia is complex, varies among ecosystems and places, time-consuming, and not tailored to the specific activities being undertaken (Saunders et al. 2024, Waltham et al. 2024). Issues with obtaining permits can be caused by not having the required data and can prevent or delay on-ground trials and large-scale implementation or reduce their scale or outcomes. Moreover, policy and subsequent permitting processes to enable climate adaptation interventions is lacking for many regulatory agencies and incomplete understanding of risk associated with these proposed interventions can hinder restoration. There is a need for a properly resourced, modern, rigorous, fit-for-purpose permitting processes and flexible policies that can adapt to the evolving needs of restoration science and the complexities of the highly contested coastal zone. Several options to remediate this issue are available, ranging from preparing guides to navigating the permitting systems, the development of self-assessable codes which allow projects to proceed on the basis that they comply with the code requirements, to large-scale law reform to develop fit-for-purpose permitting regimes (Bell-James et al. 2025).

Climate Change and Environmental Degradation

Climate change poses an enormous threat to marine and coastal ecosystems and complicates restoration efforts. Symptoms of climate change, including increasing frequency and intensity of marine heatwaves, rising sea levels, displacement of suitable habitat, increasing storm intensity and biosecurity risks, and changing precipitation patterns create moving targets for restoration design and cause project setbacks or failure. Restoring to past conditions may no longer be feasible and alternative ecosystem states may need to be considered. Diversity, provenance and climate resilience must be considered when seeding organisms to structures or remnant habitat. The uncertainty of future environmental

conditions and ecosystem states necessitates adaptive management strategies focused on ecosystem function and climate resilience to ensure long-term success of restoration activities.

Social and Cultural Barriers

Ineffective engagement and lack of support for restoration activities by local communities or Indigenous groups can be a major barrier to restoration outcomes. While many communities are supportive, there are challenges in achieving meaningful participation and co-design of projects. Indigenous knowledge, priorities, and perspectives must be integrated from the outset, and capacity-building programs are needed to empower local communities. Use of private land and access to sea Country, recognition of existing or potential uses, social license and public awareness are also critical factors that influence the acceptance and support of restoration initiatives; these factors extend beyond local communities, recognising that the wider public have values and preferences for marine environments and their management. Addressing these barriers requires a coordinated and strategic approach that includes adequate funding, supportive policies, genuine and authentic engagement, education and awareness building programs, and effective coordination.

Integrating Land-Sea Connectivity and Management

Poor water and sediment quality is a common driver of coastal ecosystem degradation and if not rectified impedes ecological recovery. The success of coastal marine ecosystem restoration is closely tied to the condition of adjacent catchments, where poor land management can drive altered hydrodynamic regimes, sedimentation, nutrient and chemical influx. Moreover, land-sea connectivity and management are important for managing upslope migration of coastal wetlands into terrestrial areas under climate change. Effective restoration therefore requires integrated land-sea management with strong coordination across terrestrial and marine systems. Building human capacity and collaboration across these systems is essential for successful restoration outcomes at scale.

Coordination and Collaboration

Fragmentation and lack of coordination and vision among key agencies and stakeholders impede the exchange of knowledge and best practices and the ability to conduct on-ground works. Effective restoration requires a multidisciplinary approach, integrating ecological, social, and economic perspectives. However, the current lack of coordination limits the ability to achieve economies of scale and maximize outcomes (Saunders et al. 2024). National and international organisations aimed at coordinating across sectors and geographies, such as the Australasian Coastal Restoration Network and the Society for Ecological Restoration, are essential in driving scientific success and progress. Aligning vision and goals across multiple government agencies with varying legislative mandates is also essential for progressing restoration at scale.

Other disciplines required to address the challenge

Achieving the vision for R&D over the coming decade requires a multidisciplinary approach. Integrating various disciplines will enhance the effectiveness and scalability of restoration efforts and provide innovative solutions to challenges. By fostering trans and interdisciplinary collaboration and leveraging expertise from various fields (indicative list below), Australia can drive scientific progress and enhance its capacity to restore marine and coastal ecosystems.

Natural Sciences

Natural sciences, including ecology, biology, genetics and oceanography, form the foundation of restoration science. These disciplines provide the necessary knowledge of past and present ecosystem functions, species interactions, and environmental processes. Integrating natural sciences ensures that restoration techniques are ecologically sound and based on scientific evidence. Additionally, genetics and biotechnology offer innovative solutions for enhancing the resilience of restored ecosystems.

Engineering and Technology

Engineering and technology are critical for developing innovative restoration techniques and infrastructure and for scaling up. Coastal engineering plays a vital role in designing and implementing restoration projects that can withstand environmental stressors. Advanced technologies, such as remote sensing, artificial intelligence (AI), and machine learning, are essential for assisting in monitoring and predicting restoration outcomes. These tools enable precise mapping, data analysis, and real-time monitoring, which are crucial for adaptive management. Hydrological studies are essential for estimating estuary entrance conditions and SLR and floodplain inundation.

Social Sciences & Humanities

Social sciences, including sociology, anthropology, geography, psychology, behavioural economics, philosophy (including ethics), and urban planning are essential for understanding the human dimensions of restoration. Engaging local communities and Indigenous groups requires insights into social behaviour, cultural values, and community dynamics. Social sciences also contribute to developing effective communication strategies, fostering public awareness, and understanding the requirements for social license for restoration projects. Integrating social sciences ensures that restoration efforts are socially inclusive and culturally sensitive.

Economics and Finance

Economic and financial disciplines are crucial for developing sustainable funding mechanisms and business models for restoration. Environmental economics helps to design market-based instruments, quantify the socio-economic benefits of restoration, such as ecosystem services and blue carbon or biodiversity credits, and integrate diverse information to prioritise competing decision outcomes. Financial expertise is needed to design innovative investment strategies, including public-private partnerships and

philanthropic contributions. These approaches ensure long-term financial sustainability for restoration projects.

Policy and Law

Policy and legal disciplines are vital for analysing and making recommendations on regulatory frameworks and governance structures. Environmental law provides the legal basis for restoration activities, while policy studies help design effective regulations and incentives. Integrating policy and law ensures that restoration efforts are aligned with national and international environmental goals, such as the GBF, the Sustainable Development Goals (SDGs) and the Paris Agreement.

Infrastructure and capability need

There is an urgent need to build capacity and infrastructure to meet the vision for restoration to be enabled by 2035. Below we highlight the main gaps in capability and infrastructure if existing infrastructure and capacity is be maintained.

Research Facilities

To support cutting-edge research and large-scale restoration projects, several key research facilities need to be upgraded and expanded:

- **Aquaria and Mesocosms:** State-or-the-art aquaria and mesocosm systems are required that have capabilities and automation for simulating various environmental conditions, such as temperature, salinity, and light. For example, Sea Sim (AIMS) is an excellent example of the type of facilities needed for other priority systems.
- **Computing and Data Analysis Facilities**: National scale integrated data repositories, high-resolution mapping, and integrated environmental modelling suites that are managed and appropriately funded long-term are needed. These can be used to develop simulations (e.g. digital twins) to guide effective monitoring efforts, to generate counterfactuals, and to predict outcomes of management strategies.
- **Advanced monitoring and field equipment:** Restoration R&D would be improved with advances in automated Sensors and Data Loggers for continuous, real-time monitoring of environmental parameters at restoration sites, such as e-DNA, ground surface elevation, hydroperiod, temperature, salinity, pH, and dissolved oxygen. The sensor data would improve adaptive management and could be tied into remote sensing pipelines.

People and Capability Requirements for Marine and Coastal Restoration

To achieve successful marine and coastal restoration, Australia needs to address several key capability gaps in people skills and expertise and ensure that skilled people have the funding for ongoing employment to ensure skills are retained. Restoration is a complex endeavour and requires interdisciplinary knowledge both in R&D and implementation phases.

Connections among diverse disciplines can be facilitated by knowledge and partnership brokers and mediators who are individuals skilled in communicating, translating and sharing knowledge, reducing conflict and unifying visions for restoration R&D across disciplines and among researchers and stakeholders.

- **Input of technical expertise**: Collaboration with professionals skilled in deploying and maintaining advanced monitoring tools, remote sensing technologies, and automated systems will enhance our ability to plan and evaluating restoration interventions. Collaboration with engineers enhances the accuracy and efficiency of restoration efforts. Collaboration with modellers is essential to understand oceanographic processes such as tidal inundation and coastal protection by NbS and the impacts of climate change.
- **Interdisciplinary collaboration with social, legal and economic researchers**: Scaling up restoration requires understanding the socio-ecological system in which restoration takes place. Professionals with knowledge of environmental laws and policies, regulatory frameworks, and governance play a vital role in integrating scientific findings into policy decisions and ensuring compliance with regulations. Working with Indigenous Knowledge Holders is essential for incorporating traditional knowledge and practices into restoration efforts, informing ecosystem management, and contributing to culturally appropriate restoration practices. As we move towards more interventionalist restoration approaches, there is a pressing need for experts in the field of ethics to provide insight into the implications of these new approaches.
- **Skilled workforce of restoration scientists and practitioners**: Trained professionals with expertise in science and practice of restoration will be required to meet the 2035 vision including Indigenous Ranger programs. Expertise in marine ecology, restoration techniques, project management, engineering, and ecological monitoring are essential for implementing and managing restoration projects on the ground. Building up this capacity will require tailored tertiary programs to train, support and enable a skilled workforce. Programs specifically designed to build capacity in Indigenous groups will be required to cater to the unique contexts and needs of those communities. Investment in supporting interdisciplinary early-career researchers will generate expertise required for advancing understanding ecosystem dynamics, developing adaptive restoration techniques, and conducting cutting-edge research.

National and International Partnerships and Resourcing for Scientific Success and National Progress

To drive scientific success and national progress in restoration, a multifaceted approach involving robust national and international partnerships, along with strategic resourcing, is essential.

Resources are required across four areas:

1. **Large-scale and long-term restoration hubs/test beds** across ecosystems with equitable and open governance and finance structures. This will enable key R&D questions around efficacy, value and impact to be answered in realistic field settings and time frames.
2. **Rate-changing R&D for up-scaling and climate resilience**. Prioritisation of innovative approaches across disciplines (engineering, AI, multi-omics) including genetic approaches to boost heat tolerance and climate adaptation.
3. **Evidence Based Decision Support Tools** to integrate information platforms for improving prioritisation, prediction and evaluation of outcomes of management including restoration.
4. **Addressing societal barriers and skillset shortages** to create enabling conditions (social license, permitting, and funding) and a skilled workforce to implement restoration at scale. Supporting co-design and leadership from First Nations and local communities enhances quadruple bottom line benefits.

To enable success of the above initiatives, national partnerships across state, federal and local government agencies, research institutions, non-governmental organizations (NGOs), Natural Resource Management (NRM) groups, and local community and Indigenous groups are crucial. These collaborations can facilitate the sharing of knowledge, resources, and expertise, thereby enhancing the effectiveness and efficiency of restoration efforts. They also play pivotal roles in providing regulatory support and on-ground implementation. Engaging with the private sector (e.g. industry partners focussing on tourism, fisheries, engineering and coastal development) can provide additional funding and resources for restoration. For example, the emerging Nature Repair Market aims to incentivise private sector investment into nature repair. Proponents of developments that have offset requirements will also need to resource restoration efforts and in doing so can help to grow the restoration sector, providing funds to increase capacity and expertise to subsequently support conservation goals.

Such collaboration could be facilitated and embedded in actions through new R&D partnerships like RRAP, Centres of Excellence or Cooperative Research Centres for integrated marine restoration, or by building off existing architectures, such the Australasian Coastal Restoration Network. Establishment of a National Aboriginal and Torres Strait Islander Marine Science Institute would enable Traditional Owner led research and development. Schemes such as the Australian Research Council Industry fellowships should embed academic researchers in government organisations and vice versa to develop a depth of understanding and overcome barriers in the regulatory, policy and implementation space.

Strengthening international partnerships are also key. Initiatives like the United Nations Decade on Ecosystem Restoration, the Ocean Decade Vision 2030 and Coral Research & Development Accelerator Platform (CORDAP) facilitate international cooperation and provide frameworks for large-scale restoration efforts. These programs can help standardize practices, share successful methodologies, and mobilize resources across borders. Global partnerships with international research programs and institutions, such as the Global

Restoration Initiative, the Society for Ecological Restoration (SER), Kelp Forest Alliance, Coral Restoration Consortium (USA) and the International Union for Conservation of Nature (IUCN), can enhance knowledge exchange and provide access to global expertise and funding opportunities. Establishing bilateral agreements with countries that have advanced restoration programs can foster mutual learning and capacity building.

Progress/Impact Measurement (651 / 500wds)

Utilisation and Impact of Restoration Data and Knowledge

State, national, and international initiatives currently leverage data and knowledge from various Australian restoration initiatives and experts to drive policy, conservation, and restoration efforts. At the state and national levels, initiatives such as the State of the Environment (SoE) reports and local and state government policies utilize knowledge and data to inform environmental management and regulatory decisions. Nationally, programs like Australia's National Science and Research Priorities, the National Climate Resilience and Adaptation Strategy, the SoE and the Reef 2050 Plan integrate ecosystem knowledge to shape strategic planning and funding allocations. Internationally, initiatives such as the United Nations Sustainable Development Goals (SDGs), the Ocean Decade Vision 2030, and the International Union for Conservation of Nature (IUCN) reports rely on ecosystem and restoration data to guide global conservation efforts and track progress towards biodiversity targets.

Great efficiencies could be obtained if data from all restoration projects were available, however, this is often not the case, especially for projects that failed. When it is, assessments often follow approaches developed by projects or individual institutions rather than standardised and cohesive approaches. To ensure that data between projects becomes comparable and can be utilised in national and international data systems, approaches compatible with ecosystem accounts should be employed. For example, the Australian Government has published guidelines for measuring and accounting for the benefits of restoring coastal blue carbon ecosystems [2]. Expansion to other ecosystems and broad implementation of such guidelines will enable the uptake of data from these projects into decision making and policy. Ideally mechanisms to upload data into standardised reporting frameworks in real time will become available, for instance, through an expansion to the ACRN database capability.

Research Translation, Knowledge Transfer, and Impact Measurement

Current State of Research Translation and Knowledge Transfer

[2] https://www.dcceew.gov.au/sites/default/files/documents/eea-guide-accounting-benefits-coastal-restoration_1

Research translation and knowledge transfer to stakeholders are currently achieved through multiple channels, including scientific publications, technical reports, standard operating procedures, workshops, symposia, and public engagement activities. Digital platforms and databases also play a crucial role in disseminating research findings. For example, the Australasian Coastal Restoration Network (ACRN) shares knowledge across >650 stakeholders via newsletters, social media, and annual symposia. Additionally, initiatives like the Kelp Forest Alliance and RRAP provide databases, SOPs and guidebooks to support restoration efforts. Online tools such as Reef Adapt translate complex scientific information into tools for restoration practitioners to improve restoration decisions. Operational roll outs such as the RRAP pilot deployment program also provide opportunities for community participation, training and capacity building via knowledge sharing and implementation and forming the base for further scaling up.

Opportunities for Improvement

Despite these efforts, there is room for improvement in the translation and transfer of research. Enhancing accessibility and standardization of data across platforms can facilitate broader use and integration of ecosystem knowledge. Establishing centralized databases where data can be easily accessed, shared, and analysed as well as syntheses of data into recommendations for practitioners will support informed decision-making. Fostering stronger collaborations between researchers, policymakers, and practitioners through regular workshops, symposia, collaborative projects and workplace exchange programs can bridge the gap between science, policy and practice. Increasing public awareness and engagement through targeted communication campaigns and educational programs are needed to enhance societal support for conservation initiatives.

Impact Measurement

The impact of restoration R&D on society can be measured through various metric and mechanisms including:

- Uptake of research findings by policymakers resulting in changes to laws and policies
- Increased funding available
- Progress towards meeting national and international targets, and (value of) of improved evidence-based practices
- Improvement of ecosystem health and services including enhanced resilience to disasters
- Social indicators, such as enhanced environmental engagement and awareness, access to green/blue spaces, community cohesion and engagement, Mental and physical health improvements, cultural heritage preservation, and stakeholder satisfaction
- Economic indicators, such as job creation, volunteer participation, eco-tourism revenue, changes in property value, improvements in fisheries, or local business growth

Approaches to measuring impact include

- Application of the Society for Ecological Restoration Ecological Recovery Wheel (ERW) and Social Benefits Wheel (SBW)
- Surveys of community members and practitioners, for instance Healthy Country survey tools.
- Quantifying number of visits to online resources
- Quantification of citations of scientific research in policy documents
- Quantification of citations to scientific papers indicating impact in the scientific community
- Monitoring and evaluation frameworks for ecological outcomes, such as biodiversity enhancement and ecosystem function restoration (further discussed in monitoring and evaluation section).

Dependencies and Priorities (810 / 750wds)

When do critical achievements need to be underway or completed and why?

The Australian government has set a target to restore at least 30% of priority degraded land and water ecosystems by 2030 (Australia's Strategy for Nature). Progress towards this target requires significantly increased knowledge, tools, investment and implementation to meet for all coastal and marine ecosystems. Several R&D priority areas were commonly identified across ecosystems to accelerate an upscaled progress:

Establishment of **large scale and long-term restoration test beds** where we learn by applying various methods at scales that are relevant to answer questions around their benefits, efficacy, cost and risks. Restoration hubs need to be underpinned by fit-for-purpose governance, adequate funding, vision and mission to support research, development and implementation simultaneously. Knowledge generation is accelerated via a coordinated and standardised approach and with a focussed R&D prioritisation in place-based focus areas (like the Blue Carbon Ecosystem Restoration Grants and the RRAP program for the Great Barrier Reef). Hubs include a learning by doing component that is focussed on training and capacity building and local participation including Indigenous Rangers. The on-the-ground activities include:

- **Quadruple bottom line evaluation of the best practice restoration at defined and impact relevant.** This includes the measurement of ecological and evolutionary benefits of management options.
- **Testing and application of advanced monitoring tools**: Development and deployment of advanced monitoring tools, such as remote sensing technologies, drones, automated sensors and photogrammetry to develop (simpler tools for) real-time monitoring of restoration to an individual organismal level to understand drivers of ecological changes and the effectiveness of restoration.

2. Prioritisation of rate-changing R&D for scale and climate resilience.

- **Testing of strategies for enhancing climate resilience**: Genetic management via natural diversity, selective breeding, assisted gene flow and symbiont or microbial manipulations to enhance the resilience of restored populations measured in real world settings and over appropriate temporal scales. Innovations in genetic and genomic research can support the development of resilient and adaptive restoration techniques
- **R&D is needed to underpin a step change to overcome bottlenecks** for the delivery of restoration impact at scale. This will be specific to the system and species but can be supported by advanced engineering, AI and genomic resources such as annotated genomes.
- **Mechanisation and Automation to** increase the scale and efficiency of restoration efforts. This includes automated planting machines, robotic systems, and mechanised seeding techniques can facilitate large-scale restoration of kelp forests, seagrass meadows, mangroves, and other ecosystems.

3. **Evidence-Based Decision Support Tools** delivered as integrated information platforms to:

- **Track progress:** Develop a national scale monitoring and reporting system to evaluate outcomes and track progress towards national targets, with capability for users to input data on project activities and outcomes.
- **Predict outcomes:** National scale integrated data analytics and predictive modelling platforms capable of handling large ecological datasets to support analysis of ecological trends and predictive modelling of future restoration outcomes, for example for the Nature Repair Market.
- **Inform management and policy:** Integrate data and models into decision-making frameworks to optimize restoration strategies and guide evidence-based policy and management actions for restoration and in the context of other management tools such as protection and mitigation of stressors.
- **Connect the community:** Utilise collaborative digital platforms and tools that facilitate real-time communication, coordination, and knowledge exchange among stakeholders to ensure restoration efforts are well-integrated and aligned with best practices.
- **Harness technologies:** Advance and apply Artificial Intelligence, big data, multi-omics and remote sensing technologies. This will enable identification of patterns and trends in genetic, physiological and ecological data, enhance monitoring, inform parameterisation of models, and improve forecasting accuracy.

4. **Solutions to societal barriers and skillset shortages** to create enabling conditions (social license, permitting, and funding) and a skilled workforce to implement restoration at scale. Supporting co-design and leadership from First Nations and local communities enhances quadruple bottom line benefits.
    - Support Indigenous led initiatives and directions including the establishment of a **National Aboriginal and Torres Strait Islander Marine Science Institute** (or similar) to enable Traditional Owner led and co-designed research and development, including Indigenous Ranger programs.

- Develop **education and training programs** to support 1) an ecologically literate society, 2) engineers with skills in implementation of restoration and NbS, 3) a technically skilled workforce with the capacity and agency to conduct restoration at scale; and 4) tertiary education programs in restoration; 5) landholders to engage in restoration now and as sea levels rise.
- Develop **alternative funding mechanisms** for restoration to enable larger scale and longer-term restoration projects, encompassing planning, action, monitoring, adaptive management and evaluation.
- **Review, and ideally reform, current legislative frameworks** to develop fit-for-purpose policy and permitting pathways, particularly for climate-adaptation interventions.

How can connectivity and communication be improved across Australia and sectors?

Effective communication amongst project partners including researchers, Traditional Owners and Indigenous groups, restoration practitioners, local community partners, natural resource managers, the private sector and decision makers will be essential to meeting the 2035 vision. Communication will need to occur via tailored mechanisms adapted for the participants and the engagement events. Specialists from related fields can add great value and will be engaged in the design and execution of R&D. Knowledge sharing and communication already occur via workshops, special sessions at conferences, showcases, webinars and newsletters based on existing networks such as the Australasian Coastal Restoration Network. It is proposed that existing networks could be supported to increase capacity to meet the 2035 vision. Design and execution of multi-ecosystem R&D hubs will enhance cross-ecosystem collaboration and knowledge sharing.

Developing standardised reporting databases will be required to maximise transparency, accessibility, comparability and communication of outcomes and lessons learned. For example, enhancing, harmonising, and improving existing databases such as ACRN, Living Shorelines, and Living Seawalls, by creating standardisation across systems, user data entry functionality and underlying spatial environmental data. Databases should be openly accessible and with national coverage.

Enhanced engagement with the private sector and with community groups will be needed to rapidly scale up restoration. Rapid communication with these groups will need to be accomplished through existing peak-bodies and groups, using synthesised information which is understandable and relatable to those groups. For example, case studies of successful restoration approaches and potential risks for landholders and community led restoration groups; of nature-based methods for coastal defence to engineers; or environmentally friendly moorings to moorings contractors.

Conclusions

Safeguarding Australia's coastal and marine ecosystems is central to the nation's ecological, social, cultural, and economic wellbeing and a national and international priority. However, doing so requires a rethink from traditional conservation management centred on protection and mitigation of stressors, to one that includes active mitigation, restoration and adaptation tools. But it does not stop there – we cannot replace like for like and learning to implement restoration in a step-by step manner is too slow and too expensive. While Australia leads globally in restoration science, translating this knowledge into large-scale impacts on the ground is still lacking and constraining the full value of this excellent work for Australia's ecosystem and our people. This white paper recommends investment in four key areas to accelerate knowledge generation and on the ground impact by 2035 and are common across Australia's marine and coastal ecosystems. A quadruple bottom line return on research investments can be optimised by focussing on place based, multi-ecosystem (where possible) test beds where longer and larger R&D and deployment hubs are secured through traditional and alternative long term funding mechanisms. Through appropriate governance R&D should be mission driven and focus on rate changing and future focussed technologies. Science-based decision support tools will bridge the gap between R&D and management and allow for the most strategic, evidence-based, and cost-effective allocation of limited resources to benefit Australia. At scale restoration and quadruple bottom line benefits will be achieved by addressing key societal barriers including social license, permitting, funding, and capability, through interdisciplinary research and training programs. Co-designed and leadership from First Nations and local communities will central to translating R&D into on ground action. Strengthening national and international partnerships will be essential to share knowledge, operationalise research, and ensure equitable, enduring benefits for Australia's valuable marine ecosystems.

References

Australian Institute of Marine Science & Deloitte Access Economics. 2025. AIMS Index of Marine Industry: 2025.

Babcock, R. C., R. H. Bustamante, E. A. Fulton, D. J. Fulton, M. D. Haywood, A. J. Hobday, R. Kenyon, R. Matear, É. E. Plagányi, A. J. Richardson, and M. A. Vanderklift. 2019. Severe continental-scale impacts of climate change are happening now: extreme climate events impact marine habitat forming communities along 45% of Australia's coast. Frontiers in Marine Science 6:411.

Bay LK, LK, J Gilmour, B Muir, PE Hardisty. 2023. Management approaches to conserve Australia's marine ecosystem under climate change. Science 381 (6658), 631-636

Bell-James J, Shumway N, Villarreal-Rosas J, Andradi-Brown DA, Brown CJ, Fitzsimons JA, Foster R, Hamman E, Lovelock CE, Saunders MI, Waltham NJ (2025) Upscaling marine and coastal restoration through legal and governance solutions: Lessons from global bright spots. Environmental Science & Policy 163:103962

Gann, G.D., McDonald, T., Walder, B., Aronson, J., Nelson, C.R., Jonson, J., Hallett, J.G., Eisenberg, C., Guariguata, M.R., Liu, J., Hua, F., Echeverría, C., Gonzales, E., Shaw, N., Decleer, K. and Dixon, K.W. (2019), International principles and standards for the practice of ecological restoration. Second edition. Restor Ecol, 27: S1-S46. https://doi.org/10.1111/rec.13035

Layton, C., Coleman, M.A., Marzinelli, E.M., Steinberg, P.D., Swearer, S.E., Vergés, A., Wernberg, T. and Johnson, C.R., 2020. Kelp forest restoration in Australia. Frontiers in Marine Science, *7*, p.74.

Vozzo, M.L., Doropoulos, C., Silliman, B.R., Steven, A., Reeves, S.E., Ter Hofstede, R., Van Koningsveld, M., Van De Koppel, J., McPherson, T., Ronan, M. and Saunders, M.I., 2023. To restore coastal marine areas, we need to work across multiple habitats simultaneously. Proceedings of the National Academy of Sciences, 120(26), p.e2300546120.

McAfee, D., Larkin, C. and Connell, S.D., 2021. Multi-species restoration accelerates recovery of extinguished oyster reefs. Journal of Applied Ecology, 58(2), pp.286-294.

McLeod, Ian M., et al. Coral restoration and adaptation in Australia: The first five years. Plos one 17.11 (2022): e0273325.

Saunders et al. 2024, A roadmap to coastal and marine ecological restoration in Australia. Environmental Science and Policy 159, 103808.

Nathan Waltham, Megan I Saunders, Rebecca Morris et al. 2024. Identifying and overcoming barriers to marine and coastal habitat restoration and nature-based solutions in Australia. Final report to the National Environmental Science Program (NESP) Marine and Coastal Hub. The University of Tasmania.