Marine Directorate

Areas of Research Interest: Marine & Freshwater

August 2025

Scottish Government
Riaghaltas na h-Alba

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Prof. Mark Inall

Scottish Government,

Chief Scientific Adviser, Marine

Foreword

As Chief Scientific Adviser for Marine, it is my pleasure to present the Scottish Government's Areas of Research Interest (ARI) for our marine and freshwater environments. Scotland's seas and waters are vital national assets, covering over 462,000 km^2 and almost six times the size of the territorial area of Scotland. It supports our economy, communities, and natural heritage. Our stewardship of these resources must be founded on robust scientific evidence that enables us to balance protection, conservation, and sustainable use.

This document articulates the research questions that will be crucial for delivering our Blue Economy Vision and addressing the twin crises of climate change and biodiversity loss. It reflects a commitment to evidence-based policy making and our recognition that collaboration with the research community—across academia, industry, public bodies, and civil society—is essential to developing the knowledge and innovations needed for Scotland's marine future.

The research areas identified here will inform our priorities for, collaboration, and knowledge exchange. By clearly stating our evidence needs, we aim to stimulate research that will directly inform policy development and implementation, while building a shared understanding of Scotland's marine and freshwater priorities among our research partners.

I look forward to working together to advance these research interests and build the evidence base that will enable Scotland to be a global leader in sustainable marine and freshwater management.

Prof. Mark Inall
Scottish Government, Chief Scientific Adviser, Marine
May 2025

Introduction

Scotland's Blue Economy Vision encapsulates our increasing awareness of the importance of the marine and inter-linked freshwater and coastal environments. This document builds on that importance and the potential for marine and freshwater (henceforth, we use 'marine' to include freshwater habitats of anadromous fishes, e.g. salmon) resources to support sustainable prosperity by gathering those ideas into coherent **Areas of Research Interest (ARIs)**.

ARIs are statements of which areas of research are most important to government for policy making and aims to improve the evidence base for policymaking by fostering dialogue between policymakers and academia. ARIs are designed to encourage academia to contribute to addressing key policy questions. They are generally owned by Chief Scientific Advisers. ARIs are not government commitments to undertake or fund research, rather they are statements of research need.

Scotland's Marine and Freshwater Context

Scotland's marine area is vast, covering over 462,000 km², and includes some of the most productive and diverse marine ecosystems in Europe. Our coastal waters, territorial seas, and Exclusive Economic Zone contain a wealth of habitats and species, support vital economic activities, and play a significant role in Scotland's cultural identity and heritage.

Scotland's marine economy includes activities dependent on the marine environment. They provide an important source of income and employment across Scotland. Some key points are:

- In 2022, the marine economy generated £4.9 billion in approximate Gross Value Added (aGVA), 3% of the overall Scottish economy.
- In 2022, the marine economy employed 71,000 people (headcount), 2.7% of the total Scottish employment.
- Between 2021 and 2022, the marine economy's aGVA increased by 7%.

Scotland's freshwater systems include some 125,000 km of rivers and streams, and over 31,000 freshwater lochs. These freshwater environments support biodiversity, generate renewable energy, and offer recreational opportunities that enhance wellbeing and support tourism.

Together, these environments face significant challenges from climate change, biodiversity loss, competing demands for space and resources, and historic environmental degradation.

They also present substantial opportunities for sustainable economic development, community regeneration, and ecosystem restoration.

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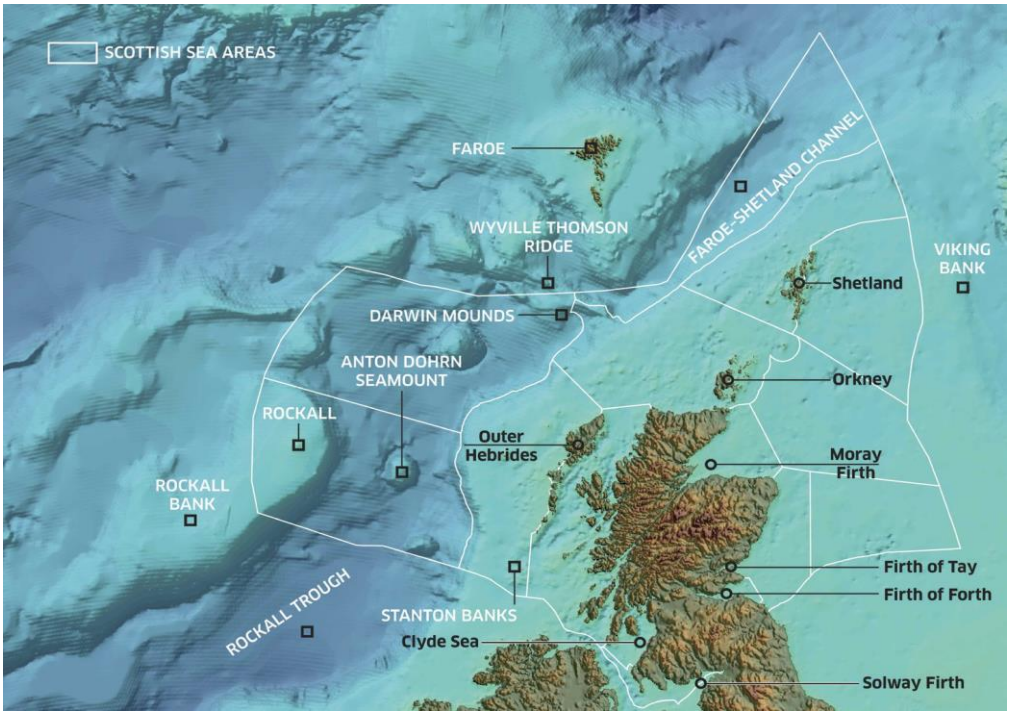

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Figure 1. Bathymetry and selected features of the seas around Scotland

Purpose of this document

This ARI document sets out the key research questions that will help the Scottish Government deliver its Blue Economy Vision and develop evidence-based policies for the sustainable management of Scotland's marine and freshwater environments. It aims to:

- Articulate the Scottish Government's medium to long-term evidence needs for marine and freshwater policy development and decision-making.
- Promote collaboration, partnerships, and engagement with relevant academic and industry experts.
- Encourage research that addresses critical knowledge gaps and informs policy development, whilst recognising the trade-offs inherent in balancing protection, sustainable use and economic development

ARIs are a mechanism for government to communicate its research interests to the academic community, research funders, industry, commerce and other stakeholders. This document will be used to guide research commissioning, inform strategic research partnerships, and encourage external researchers to engage with policy-relevant questions.

Land-sea interactions

Whilst our focus is on the aquatic, the health of marine and freshwater environments is intimately connected to activities on land. Research is needed to understand these connections and develop integrated approaches to management across the land-sea interface.

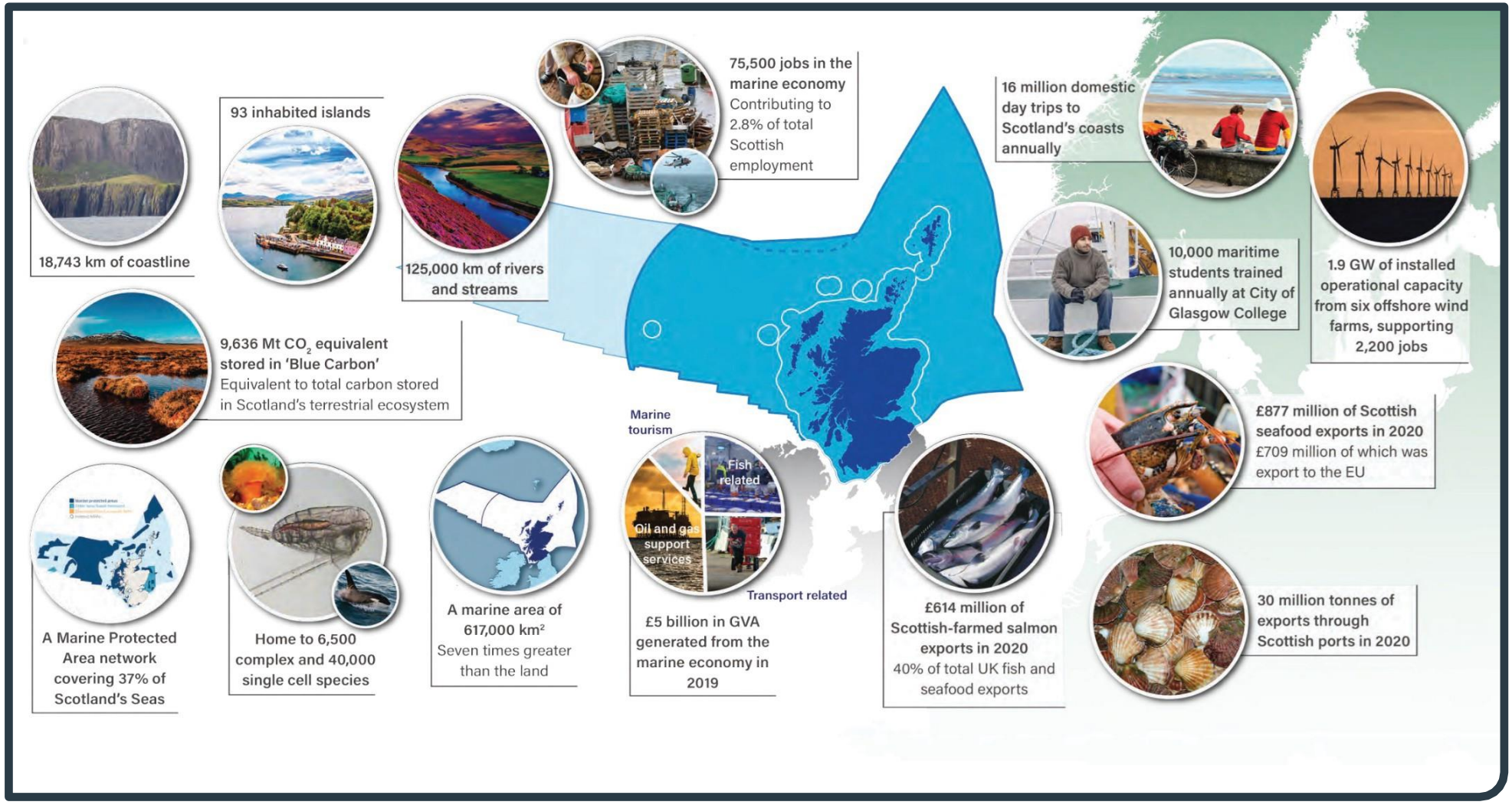

Figure 2. The Importance of Scotland's Marine and Freshwater Systems

Blue Economy Vision	ARI	CEFAS	ICES
Resilience to Climate Change	Climate Change & Biodiversity	Climate Change	Marine Ecosystems Science
Healthy Marine Ecosystems	Clean Seas and Restoration	Ecosystem Resilience Water Quality	Conservation & Restoration Science
Innovative & Competitive Marine Sectors Leadership in Sustainable Blue Foods	Renewable Energy Sustainable Fisheries Aquaculture	Energy Transition Aquatic Food Supply	Impacts of Human Activities Food From the Sea
Equal Access to Ocean Benefits	Marine Governance & Community	One Health	Sea & Society
Ocean Literacy and Awareness	Intelligent Observation	System Monitoring	Observation & Exploration of the Seas & Oceans Emerging Techniques & Technologies

Figure 3: Relationship between Blue Economy Vision, ARI, CEFAS and ICES themes categorisation of marine (and freshwater) areas.

Structuring of ARIs

There are many ways to categorise ARIs, none of which is perfect in the sense that a single research area may service many needs, and a single need may require evidence from many areas. A number of existing structural entities serve as a guide: The Scottish Government's Blue Economy Vision sets out six Outcomes, which are consistent with the UK Marine Policy on "*a marine environment, which is clean, healthy, safe, productive and biologically diverse, managed to meet the long-term needs of nature and people*"; The **UK Marine Strategy** has eleven Good Environmental Status (GES) qualitive descriptors, reported on through four DEFRA working groups; **MCCIP (Marine Climate Change Impacts Partnership)** , focusing on climate change, identifies three impact areas; CEFAS has seven **Science Themes** , as does the **science plan of the International Council for the Exploration for the Seas (ICES)** . All these approaches have commonalities; here we have identified seven ARI themes and we demonstrate how they relate to the Blue Economy Vision outcomes and to CEFAS and ICES Science Themes (Figure 3). Figure 4 sets our seven identified ARI themes in the context of legislated government commitments, which are elaborated on in Appendix A.

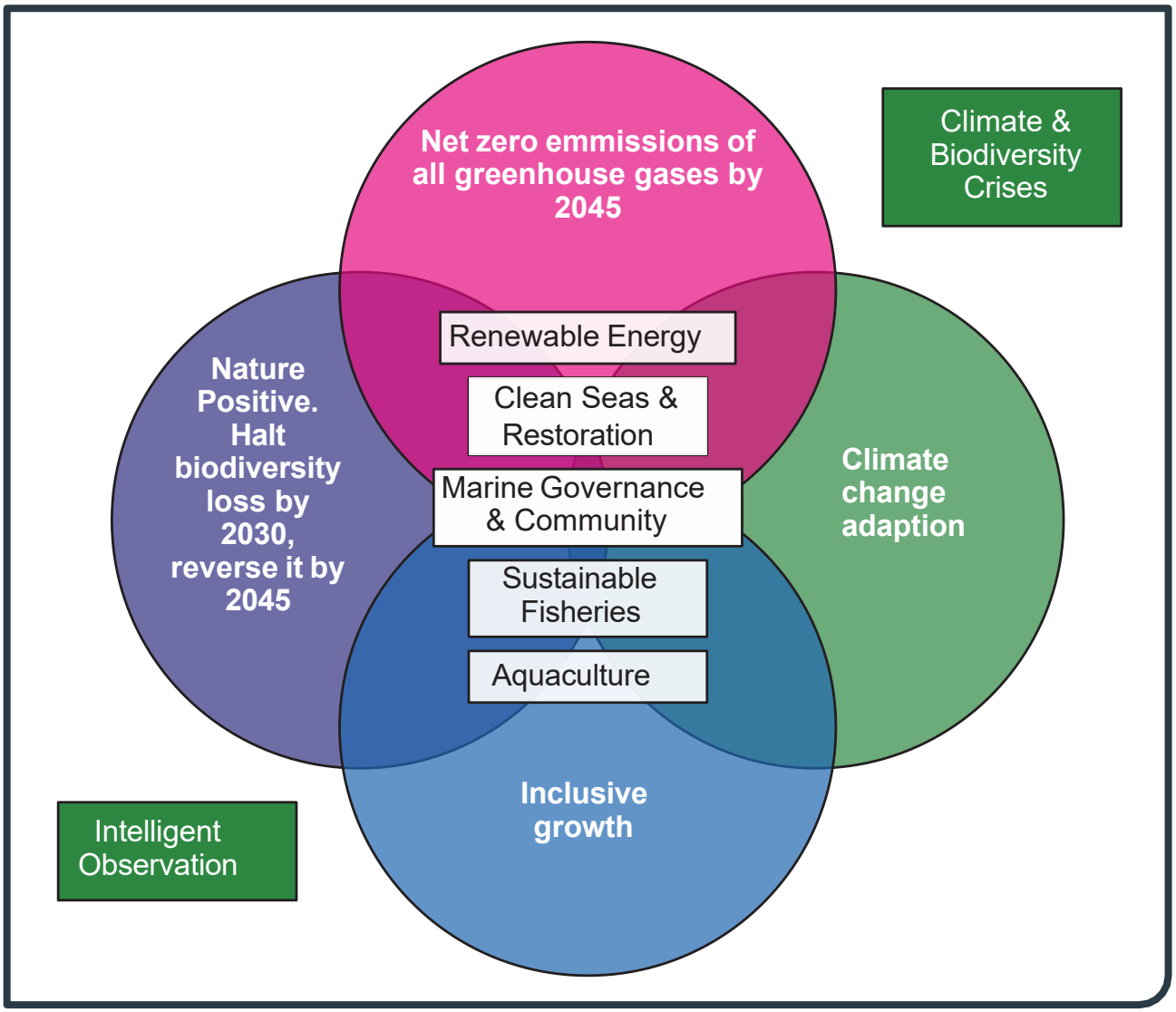

Figure 4: ARIs in the context of Primary Legislation

Cross cutting themes

Three of the ARI themes cut across four specific research area themes; Figure 5 illustrates the interconnected structure of Scotland's seven marine and freshwater ARI themes, providing an integrating framework. We now introduce the cross-cutting themes and specific research area themes, before fully expanding the science questions raised within each.

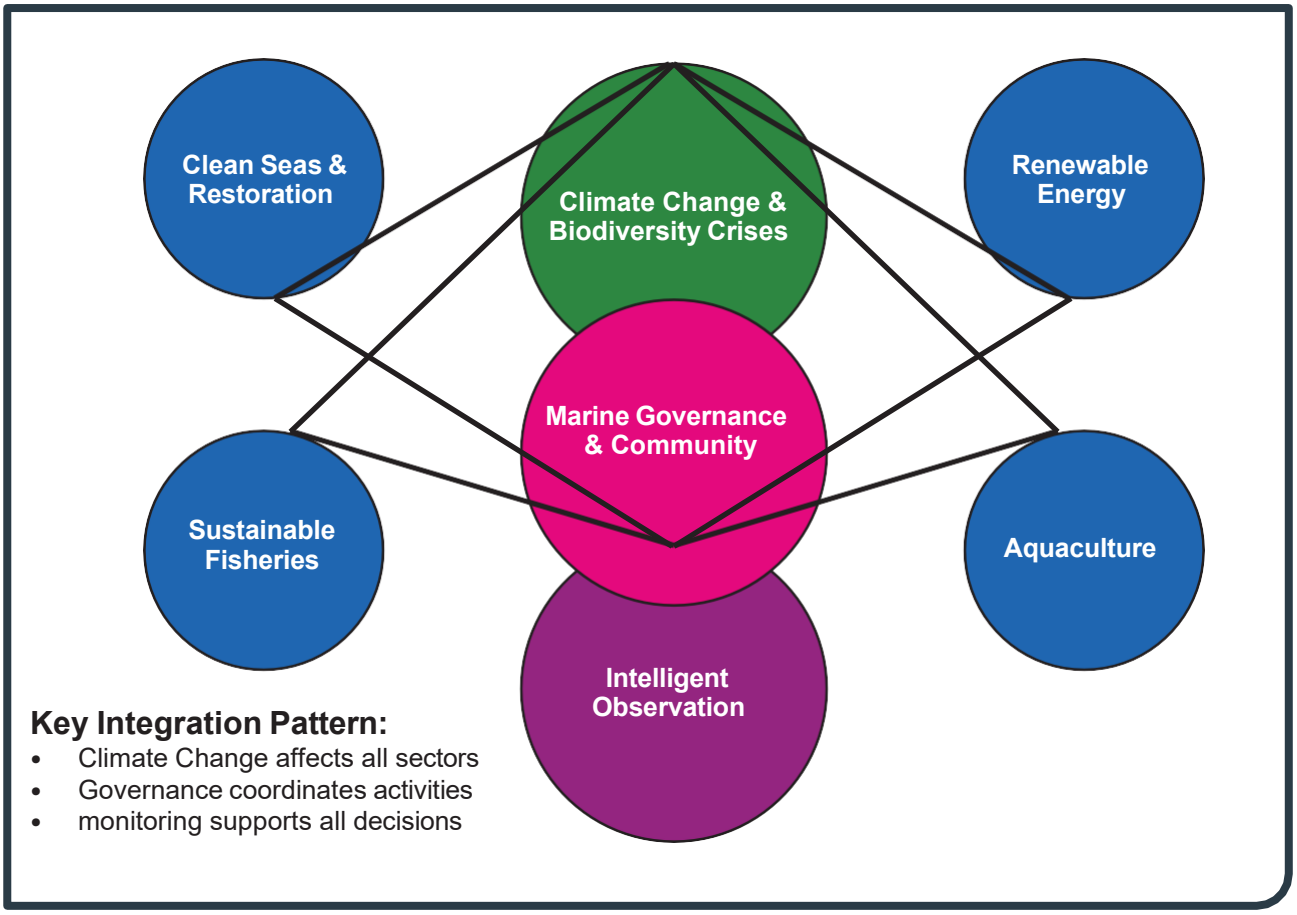

Figure 5. Diagrammatic illustration of the interconnectivity between themes.

Climate and biodiversity crises

Scotland is facing the interlinked crises of climate change and biodiversity loss, which are central to the Scottish Government's priority of addressing the climate emergency and provide an overarching context for our ARIs. **Scotland's Marine Assessment 2020** (SMA2020) highlights significant climate-related impacts on marine and freshwater environments, including:

- Ocean warming, sea level rise, and acidification
- Shifts in biodiversity and species distribution
- Changes in plankton communities, with cascading effects on marine food webs (e.g., marine mammals, seabirds, and commercial fish species)

Coastal habitats—such as beaches, dunes, saltmarshes, and machair—are under increasing pressure from rising sea levels and more frequent storm surges, leading to erosion and habitat fragmentation. These habitats are vital for coastal resilience and support resident and migratory waterbirds.

The intensification of human activities in marine and freshwater environments is increasing competition for space and resources. Key pressures include:

- Seabed disturbance from bottom-contact towed fishing gear, particularly affecting subtidal biogenic habitats
- Cumulative impacts from multiple activities (see figure 6)

Research is needed to support marine spatial planning, assess cumulative impacts, and develop strategies for the co-existence of diverse marine uses.

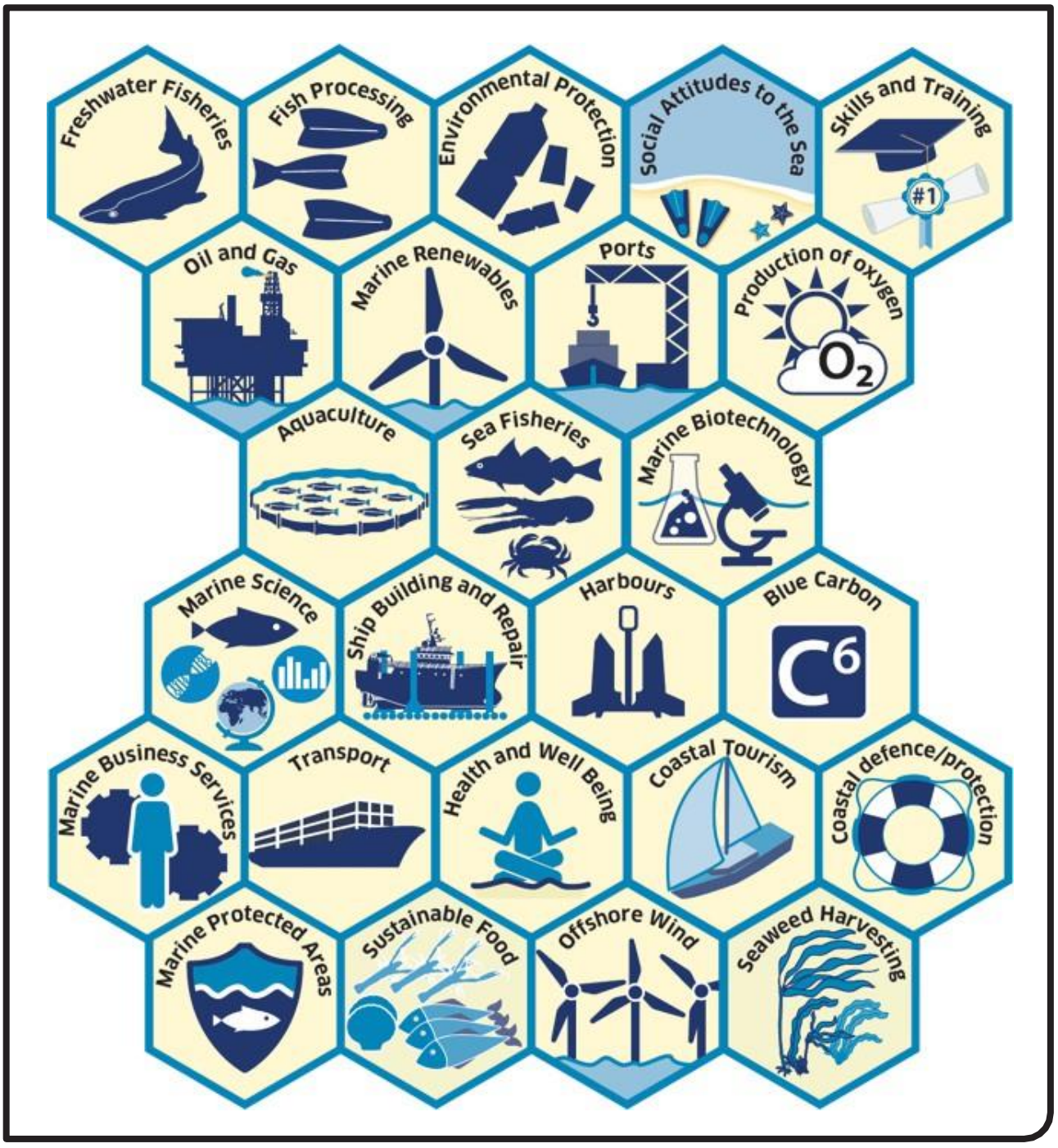

Figure 6. Range of Marine Users

Marine governance and community engagement

At the centre of Scotland's marine and freshwater ARI framework is the need for effective governance (Figure 4). Marine Governance & Community provides a coordination mechanism. This includes:

- Translating climate and biodiversity imperatives into actionable policies
- Engaging stakeholders in decision-making
- Supporting evidence-based governance aligned with Scotland's Blue Economy vision

Understanding the social and economic dimensions of marine and freshwater management is essential for developing policies that are fair, equitable, and effective. Research is needed to assess the distribution of benefits and costs, understand behavioural drivers, and develop approaches that support just transitions.

Specific research areas

Four sector-specific research themes (Figures 3 and 4) represent the primary domains where research questions and findings can be applied to real-world challenges.

- Renewable Energy
- Clean Seas & Restoration
- Sustainable Fisheries
- Aquaculture

Each area addresses specific challenges while contributing to broader environmental, economic, and social goals.

Intelligent observation and data systems

Supporting the entire ARI structure is Intelligent Observation. Effective marine and freshwater management requires robust data and evidence. Research is needed to develop integrated monitoring systems, harness new technologies, and ensure that data is accessible, interoperable, and useful for decision-making. Research priorities include:

- Developing interoperable and accessible data systems
- Harnessing new technologies for real-time observation
- Building a strong evidence base for adaptive management

The connecting lines in Figure 5 emphasise that while each theme has distinct research questions, they operate as an integrated system where advances in one area informs and strengthen others. This reflects the underlying principles of Scotland's Blue Economy Vision with regards to marine stewardship, where environmental management, economic development, and social considerations are balanced through evidence-based governance, underpinned by monitoring systems and guided by the urgent need to address climate change and restore biodiversity.

Translating research in to policy

ARIs create a mechanism lying between knowledge creation and practical application, enabling research outputs to align with policy and industry decision-making processes. ARIs provide an articulation of government evidence requirements, providing researchers with strategic direction for their work, where that is desired. This approach provides a platform for knowledge exchange by creating common language and priorities between researchers and policy makers, making research findings more accessible and applicable to those who implement policies or make business decisions. When combined with collaborative governance frameworks, ARIs establish feedback mechanisms where research has a route in to policy implementation. The transparency provided by ARIs also helps funders wishing to target investments toward policy-impact research areas, while giving researchers confidence that their work addresses societal needs, ultimately accelerating the translation of scientific insights into tangible environmental, economic, and social benefits for marine and freshwater environments.

Relationship to legislative and strategic frameworks

Relevant UK and Scottish legislation and Scottish, UK and international strategic frameworks (explained in Appendix A) create a comprehensive, if complex, approach to marine and freshwater governance that addresses three key priorities: driving sustainable economic growth, enhancing environmental protection, and building resilience and strengthening capacity in marine, freshwater and coastal management.

A note on nature-based solutions and natural capital

Nature-based solutions (NbS) are approaches that work with and enhance natural ecosystems to address societal challenges — especially climate change and biodiversity loss—while providing benefits for people and nature. Nature-based approaches are often considered to be better than purely engineered solutions in many contexts—not because they replace engineering entirely, but because they offer multiple co-benefits, greater sustainability, and long-term resilience.

The transformation toward nature-positive management, seeking to halt and reverse nature loss by 2030 and restore and regenerate by 2045 requires the adoption at scale of NbS. This means going beyond protecting what remains to actively restoring marine ecosystems at scale, enhancing their capacity to address societal challenges while delivering net gains for biodiversity. The aim is systemic change that rebuilds marine ecosystem function and resilience. This requires developing beyond small-scale initiatives to wide-scale interventions that can meaningfully enhance ecosystem service provision and biodiversity at a sea-basin level.

Understanding and valuing Scotland's marine natural capital is fundamental to this transformation. Sophisticated frameworks are needed that capture the economic value of our seas including ecosystem services, especially climate regulating services, and their contribution to climate resilience, food security, coastal protection and cultural identity. To do this an evidence base is needed which links the ecosystem state to service provision, understanding connectivity and cumulative impacts, and quantifying both the costs of degradation and the benefits of recovery. By understanding these relationships, it will enable informed decisions about marine use that optimises outcomes across environmental, social and economic dimensions while ensuring genuine nature recovery.

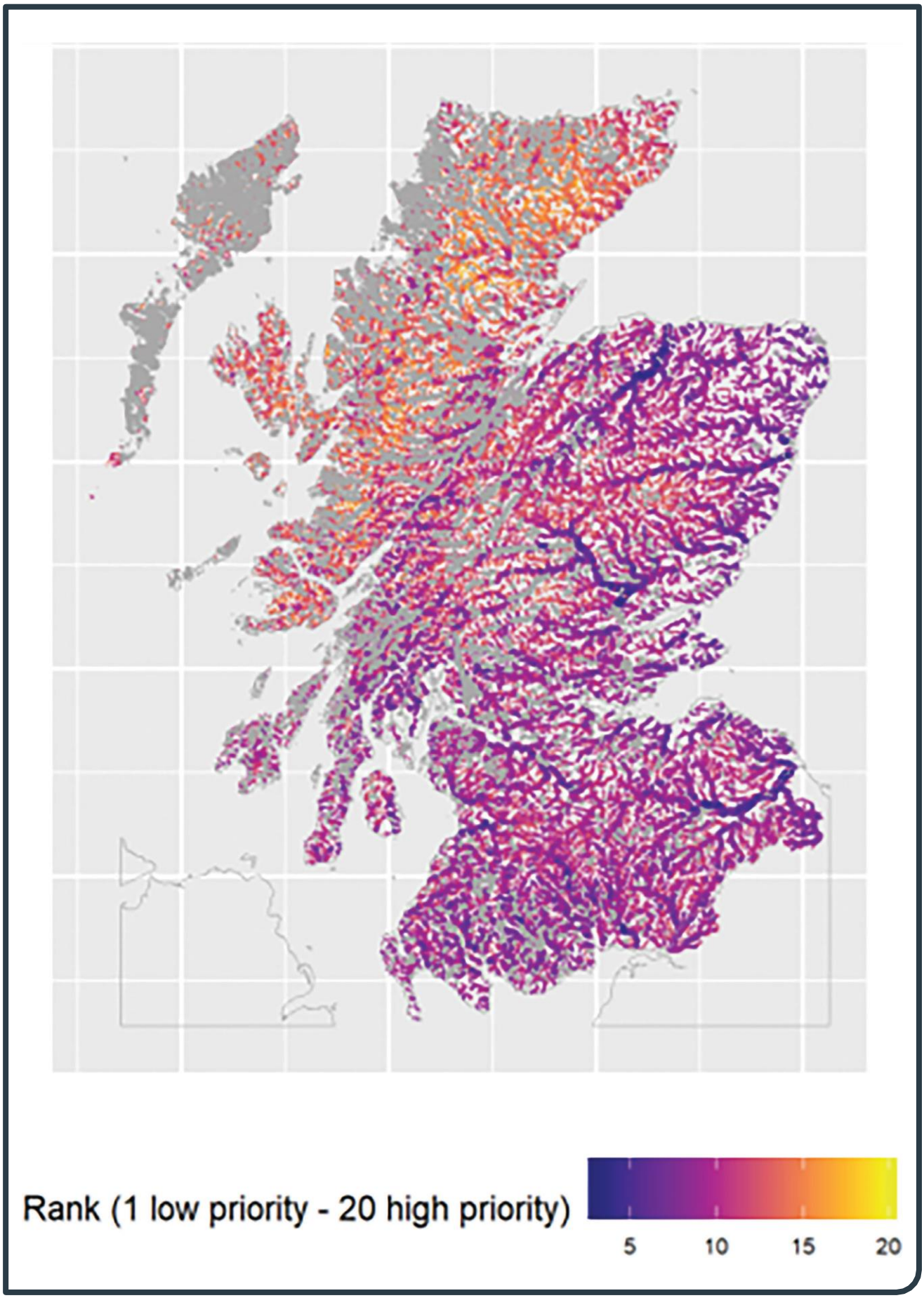

Figure 7. An example of a nature-based solution. National riparian woodland prioritisation scores assuming trees are planted on both banks.

Areas of Research Interest

1. Climate Change & Biodiversity Crises

Context and policy relevance

Climate change and biodiversity loss represent two interlinked crises affecting Scotland's marine and freshwater environments. Understanding the impacts of climate change, developing effective adaptation strategies, and enhancing the resilience of marine and freshwater ecosystems are essential for delivering the Blue Economy Vision and meeting Scotland's climate and biodiversity commitments.

Key research questions:

I. Ocean Change

- How do multiple climate change stressors (acidification, warming, deoxygenation) impact Scottish marine and freshwater ecosystems across different spatial and temporal scales, including effects of changing geomorphology?
- How do changing ocean circulation patterns affect Scottish marine ecosystems?
- How can we improve access to and integration of existing data while enhancing monitoring of future climate change impacts in offshore regions?
- What are the potential impacts of sea level rise on Scotland's marine ecosystems and sectors?

II. Carbon Sequestration

- How can we improve carbon sequestration through protection and restoration of blue carbon habitats, including planning of new blue carbon areas in coastal zones?
- What are the most effective approaches for blue carbon projects at a local, regional, and national scale?
- How can we better integrate blue carbon into climate policy?

III. Ecosystem Resilience

- What are the impacts of marine and freshwater heatwaves and other climate-related perturbations (e.g., salinity and nutrient fluctuations) on marine and freshwater species and ecosystem function at different spatial and temporal scales?
- What defines climate resilience in marine and freshwater habitats and what are their multiple-stressors?
- How can we build ecological and social resilience to climate change impacts, considering geomorphological characteristics and the land-sea interface?
- How will climate change affect disease dynamics and pathogen distribution in marine and freshwater ecosystems?
- What novel indicators could be developed for assessing Good Environmental Status that are robust to climate change and other shifting environmental conditions?
- What are the socio-economic impacts of marine and freshwater climate change?
- How can we assess and manage invasive species risks?

IV. Nature-based solutions and Ecosystem Scale Change

- How can we scale up blue carbon restoration to contribute to net zero targets while ensuring broader ecosystem recovery, and what are the economic mechanisms to finance this scaling?
- What would a climate-resilient Scottish marine and freshwater ecosystem look like, considering shifting species distributions and ecosystem functions, and how do we transition toward it?
- How do we measure progress toward transformational ecosystem-scale change?
- How can nature-based solutions be implemented in urban coastal environments to enhance resilience to climate change while delivering multiple benefits?
- How can freshwater carbon sequestration through peatland restoration and riparian management contribute to climate change mitigation and support biodiversity?

Relationship to Blue Economy outcomes

This research area directly supports the Blue Economy outcome: "Scotland's blue economy is resilient to climate change, contributing to climate mitigation and adaptation, with marine sectors decarbonised, resource efficient and supporting Scotland's Net Zero and Nature Positive commitments."

2. Clean Seas & Ecosystem Restoration

Context and policy relevance

Clean, healthy, and biologically diverse seas and freshwater environments are fundamental to delivering Scotland's Blue Economy Vision. This research area focuses on understanding and addressing the impacts of human activities on marine and freshwater ecosystems, developing approaches to reduce pollution and degradation, and promoting active restoration to enhance ecosystem health and function.

Key research questions

I. Marine Use Impacts

- How can we assess and manage cumulative environmental impacts on marine and freshwater ecosystems from all sources, including industries, communities, and other users?
- What are the most effective mitigation measures for different offshore impact types?
- How can we improve and develop standardised approaches to impact assessment monitoring?

II. Cumulative Stressors

- What are the impacts of emerging contaminants (e.g., PFAS) on marine and freshwater ecosystems?
- How do multiple stressors interact to affect ecosystem function?
- How can we improve prediction of cumulative effects, which capture uncertainty for decision-making?

III. Marine Pollution

- How can we evolve contaminant monitoring to address emerging priorities while maintaining surveillance of historical contaminants?
- What are the most effective indicators for environmental status?
- How can we integrate and improve environmental quality data across the land-sea interface from all monitoring programmes?
- What are the pathways and risks of contaminants from terrestrial run-off, historical contaminants from reclaimed land and coastal infrastructure entering the marine and freshwater environments currently, and as coastlines change?

IV. Enhancement and Transformation

- How can we move beyond pollution reduction to actively enhance marine and freshwater ecosystem function for improved water quality?
- What transformational changes in industries affecting marine and freshwater environments would contribute to ecological improvement?
- What metrics demonstrate ecosystem improvement rather than just impact reduction?

Relationship to Blue Economy outcomes

This research area directly supports the Blue Economy outcome: "Scotland's marine ecosystems are healthy and functioning, with nature protected and activities managed using an ecosystem-based approach to ensure negative impacts on marine ecosystems are minimised and, where possible, reversed."

3. Renewable Energy

Context and policy relevance

Scotland has significant marine renewable energy resources and capacity potential, including offshore wind, wave, and tidal energy. The responsible development of these resources is essential for meeting Scotland's climate targets, supporting economic growth, and delivering the Blue Economy Vision. Research is needed to support the sustainable growth of marine renewable energy while minimising environmental impacts and maximising benefits for Scotland's communities and economy.

Key research questions

I. Assessing and Managing Impacts

- How might approaches to site or regional characterisation more efficiently inform offshore renewables planning, consenting and monitoring.
- How could the potential impacts of offshore renewables on protected habitats and species be better assessed?
- How could the assessment of cumulative impacts of protected habitats and species from offshore renewables developments be improved, and integrated with an ecosystem-based approach?
- What new mitigations for the ecological or environmental impacts of offshore renewables can be developed?
- What approaches could be taken to reduce uncertainty when assessing environmental impacts of offshore renewables, given variability in the marine environment?
- How should the environmental impacts of offshore renewables be assessed?
- What opportunities exist for designing plan- or project-level compensatory measures for offshore renewable energy infrastructure and how would success be determined?
- What measures are needed for decommissioning, life extension, or repowering of offshore renewable energy infrastructure that balance environmental and economic considerations?

II. Environmental Monitoring

- How can baseline information on environmental conditions (animal abundance, distribution and vital rates) and influence of wider environmental drivers of change be effectively and efficiently gathered with meaningful purpose yet broad application and be kept up to date?
- How can we optimise monitoring requirements of offshore renewables projects or plans to effectively measure environmental effects while being proportionate to inherent uncertainty?
- How do offshore renewables impact protected species, habitats or the wider environment?

- What are the impacts of wind energy extraction on marine mixing, stratification, and resulting ecological effects?
- What new technologies could improve quantification of effects on marine environments to inform impact assessments?

III. Industry Integration

- How can we optimise array layouts to maximise energy generation while minimising environmental impacts, including effects on hydrographic conditions?
- What are the opportunities for co-location with other marine activities?
- How can we ensure fair co-existence between renewables and other marine users, recognising the distinction between co-existence and co-location?
- Within the context of climate change, how can we understand the cumulative impacts of the changing use of Scotland's seas on other sectors in the marine environment?
- What approaches best support stakeholder engagement on issues of co-existence and co-location?
- What are the socio-economic impacts of offshore renewable developments on coastal communities, and how can benefits be distributed equitably?
- What are the challenges and opportunities for expansion of marine renewable energy beyond current programmes, and how should these be integrated into long-term planning and monitoring?
- What are the cumulative impacts of land-based renewable energy infrastructure and activity on freshwater and ecosystems?

IV. Environmental Enhancement

- How can we use offshore renewable energy infrastructure to enhance marine ecosystems, and their monitoring?
- What novel technologies and approaches could enable marine renewable developments to deliver nature positive approaches?
- What integrated monitoring frameworks would verify enhancement claims?

Relationship to Blue Economy outcomes:

This research area supports the Blue Economy outcomes related to climate resilience and mitigation, as well as the development of innovative, productive, and internationally competitive marine sectors.

4. Sustainable Fisheries

Context and policy relevance

Fisheries are a vital part of Scotland's marine economy and cultural heritage, particularly in coastal communities, and those beside the river network. Sustainable management of both marine and freshwater fisheries is essential for ensuring long-term ecological, economic, and social sustainability. This research area focuses on developing the evidence base needed to support sustainable fisheries management including viable fish stocks, ecosystem integrity, socio-economic sustainability of fishing communities in a changing environment.

Key research questions

I. Marine Fisheries

- How can we enhance data collection and assessment methodologies for priority data-limited stocks?
- How can new technological, behavioural, and management approaches be developed and evaluated to reduce bycatch and discard issues in mixed fisheries while maintaining economic viability?
- How can we better understand and model multi-species interactions, natural mortality, and environmental influences on recruitment to improve stock assessments?
- How can we understand and predict shifts resulting from climate change in species distribution and migration patterns for key commercial species such as mackerel, blue whiting, and bluefin tuna to inform future management decisions and international quota agreements?
- How can genetic and other methods be applied to understand sub-stock structure of key commercial species and incorporate this knowledge into management?

II. Freshwater Fisheries

- How can we better protect and restore populations of priority species (salmon, trout, eels)?
- What are the specific impacts of climate change on freshwater systems and migratory species?
- What factors limit productivity of diadromous fish in marine and freshwater environments?

III. Socio-economic and Interaction Management

- What is the contribution of fisheries to the resilience of coastal communities, and how might this change under future scenarios?
- What strategies can support industry adaptation to changing climatic conditions?
- How can we enhance the value and domestic consumption of nationally landed fish to improve food security and reduce dependency on imports?

Relationship to Blue Economy outcomes:

This research area supports the Blue Economy outcomes related to sustainable food production, thriving coastal communities, and healthy marine ecosystems.

5. Aquaculture

Context and policy relevance

Aquaculture is a significant part of Scotland's marine and freshwater economy, with the potential to contribute to food security, economic growth, and rural development. Sustainable development of the Scotland's finfish, shellfish and seaweed industries following the Scottish Government's Vision for the sector by 2045, managing environmental interactions, and maximising benefits are essential for delivering the Blue Economy Vision. Research is needed to support innovation, sustainability, and responsible growth in the sector.

Key research questions

I. Environmental Monitoring

- How can we better monitor and assess cumulative aquaculture impacts in the marine environment?
- What are the key environmental limits and carrying capacities for different types of sustainable aquaculture within varying locations?

II. Aquaculture Production, Including Fish Health and Welfare

- What climate-related health impacts face aquaculture species and how can they be managed through improved health and welfare practices?
- How can we improve understanding and management of harmful algal blooms, jelly fish blooms and gill health?
- What are the most effective preventative approaches for improving health, welfare, and reducing mortality in salmon farming throughout the production cycle?
- What are appropriate welfare indicators for farmed fish and how can these best be incorporated through the production cycle?
- What are the opportunities and risks of facilitating new ways of farming, including but not limited to production in new environments and/or using novel technologies?
- How do we Identify routes of transmission of infection to and between farms and how to quantify their roles in pathogen spread, with practicable controls?

III. Industry-Environment Interactions

- What are the interactions between farmed species and the environment and are they effectively managed?
- How can technological innovation improve/reduce environmental impacts and be deployed and monitored effectively?
- What new species could offer viable sustainable aquaculture potential in Scotland?

IV. Ecosystem and Community Enhancement

- How can aquaculture systems be designed to contribute to marine ecosystem recovery, including but not limited to, multi-species aquaculture?
- What metrics would demonstrate ecosystem improvement from aquaculture practices?
- How can we best understand and measure social attitudes to aquaculture and the social and economic impacts arising from the sector's activity?

Relationship to Blue Economy outcomes

This research area supports the Blue Economy outcome: "Scotland is a global leader in healthy, quality, sustainably harvested and farmed Blue Foods, for our own population and beyond."

6. Marine Governance and Community

Context and policy relevance

Effective marine planning and governance are essential for balancing the multiple uses of Scotland's marine and freshwater environments, protecting and enhancing ecosystems, and delivering the Blue Economy Vision. Evidence gaps to enable effective spatial management need to be filled and further research needed to develop evidence-based approaches to marine spatial planning, protected area management, stakeholder engagement, and policy design and implementation.

Key research questions

I. Marine Protected Areas

- Are MPAs effective in achieving their stated conservation objectives in a changing environment?
- What are the connectivity requirements for MPA networks under changing conditions?
- How can we improve monitoring of MPAs to assess their effectiveness and contribution to wider ecosystem recovery?
- Are MPAs effective in supporting wider ecosystem recovery, including spillover, carbon sequestration, and productivity enhancement?

II. Stakeholder Integration

- How can we improve ocean literacy and stakeholder understanding of marine planning within coastal communities?
- What approaches best integrate different marine users and coastal communities in both planning and decision-making to ensure equitable consideration?
- How can we ensure equitable access to planning processes, data, and decision-making for all stakeholders, including coastal communities?
- How can we effectively communicate environmental monitoring results and marine planning decisions to the public to increase transparency and engagement?

III. Policy Design and Implementation

- How can ecosystem service assessments inform marine planning and decision-making?
- How can marine plans effectively adapt to short and long-term change?
- What evidence gaps need to be addressed to enable effective spatial management?

IV. Systemic Change

- How do we move from protecting individual features to enhancing whole-ecosystem function?
- What would successful ecosystem-scale recovery look like and how do we measure progress given shifting environmental baselines?
- How can we better capture cumulative benefits across multiple interventions?

Relationship to Blue Economy outcomes

This research area supports multiple Blue Economy outcomes, particularly those related to ecosystem health, social inclusion, and economic prosperity through effective governance and shared stewardship.

7. Intelligent Observation

Context and policy relevance

Effective management of Scotland's marine and freshwater environments requires robust, timely, and accessible data and evidence. This research area focuses on developing and implementing new approaches for monitoring, data collection, analysis, and curation and sharing to support evidence-based decision-making and adaptive management.

Key research questions

I. New Technologies

- How can we better integrate emerging technologies (eDNA, remote sensing, AI, automation) with existing monitoring programmes to enhance environmental monitoring effectiveness and efficiency?
- How can numerical modelling be incorporated within the intelligent observations framework to support future predictions and scenario testing?
- How can ecosystem modelling capabilities be developed and integrated with monitoring data to better interpret ecosystem dynamics and support decision-making?

II. Enduring Data Integration

- How can we improve data integration and sharing across different monitoring programmes and sectors to provide training material for machine learning?
- What approaches best support data accessibility and comparability while allowing for innovation in data collection methodologies?
- How can we address infrastructure needs for storing, processing, and sharing increasing volumes of environmental data?
- How can data generated through research and monitoring activities be collated and made available for wider use?
- How can we maintain and maximise the value of long-term monitoring datasets while ensuring their integration and consistency with new technologies and approaches?

III. Transformation Monitoring

- What novel technologies and approaches could transform our understanding of ecosystem recovery and nature-positive change?
- How can we develop integrated monitoring frameworks that capture progress toward nature-positive goals across multiple scales?
- What are the key early warning indicators of systemic change versus incremental improvement that can inform adaptive management?
- What long-term funding frameworks could sustain the monitoring infrastructure needed to detect ecosystem-scale changes over decadal timeframes?

Relationship to Blue Economy outcomes

This research area supports all six Blue Economy outcomes by providing the data, evidence, and information systems needed for effective decision-making, adaptive management, and evaluation of progress.

Working With Us

The Scottish Government is committed to working collaboratively with the research community to apply the discoveries arising from research and monitoring outlined in the ARI questions identified in this document. Such interactions informed these ARI questions, developed through exchanges and discussions with members of the MASTS community, Fisheries Management Scotland, Scottish Freshwater Group, JNCC, SEPA and NatureScot. We recognise that effective partnerships between government, academia, industry, and civil society are essential for developing the evidence base needed to inform policy and practice.

Using similar engagement with the Scottish marine science communities, this ARI document will be reviewed periodically and updated as necessary to reflect changes to context, focus or delivery. Updates will consider:

- Emerging policy priorities
- New research findings and evidence gaps
- Stakeholder feedback

We will continue to explore the optimal ways to review and refresh this ARI with our stakeholders and research communities.

Figure 8. Attendees at the MASTS ARIs Workshop in March 2025

Further engagement opportunities

Scottish Government's Marine Science Innovation strategy (2024) laid great emphasis on collaboration. Collaborative opportunities are proposed in the strategy's Implementation Plan to be published during 2025.

Glossary of Terms

Adaptation: The process of adjustment to actual or expected climate change and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In natural systems, human intervention may facilitate adjustment to expected climate and its effects.

Aquaculture: The farming of aquatic organisms, including fish, molluscs, crustaceans, and aquatic plants, typically for food production.

Areas of Research Interest (ARIs): Statements by government departments about evidence gaps and research questions that would support policy development and implementation.

Biodiversity: The variability among living organisms from all sources including terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems.

Biodiversity net gain: An approach to development and/or land management that aims to leave the natural environment in a measurably better state than it was beforehand.

Blue carbon: The carbon captured and stored by coastal and marine ecosystems, including saltmarshes, seagrass beds, and kelp forests.

Blue Economy: An approach that recognises the interconnections between economic, societal, and environmental challenges in a holistic way, focusing on sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of marine ecosystems.

Bycatch: The unwanted fish and other marine species caught during commercial fishing

Carbon sequestration: The process of capturing and storing atmospheric carbon dioxide to mitigate climate change.

Climate change: A change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer.

Co-existence: Multiple marine activities or sectors operating in the same area or sharing the same resource in a managed way that minimises conflicts and maximises synergies.

Co-location: The deliberate placement of multiple marine activities in the same spatial area, as distinct from co-existence which may be less intentionally planned.

Cumulative impacts: The combined effect of multiple pressures on the environment, which may be greater than the sum of individual effects.

Diadromous fish: Fish species that migrate between freshwater and saltwater environments during their life cycle, such as salmon and sea trout.

Ecosystem: A dynamic complex of plant, animal, and microorganism communities and the non-living environment, interacting as a functional unit.

Ecosystem-based approach: An integrated approach to management that considers the entire ecosystem, with the goal of maintaining healthy, productive, and resilient ecosystems. Ecosystem restoration: The process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed.

Ecosystem services: The benefits people obtain from ecosystems, including provisioning services (e.g., food, water), regulating services (e.g., climate regulation, flood regulation), cultural services (e.g., recreational benefits), and supporting services (e.g., nutrient cycling).

Environmental DNA (eDNA): Genetic material obtained directly from environmental samples (soil, sediment, water) without any obvious signs of the biological source material.

Exclusive Economic Zone (EEZ): The sea zone prescribed by the United Nations Convention on the Law of the Sea over which a state has special rights regarding the exploration and use of marine resources, extending two hundred nautical miles from the coast.

Good Environmental Status (GES): The environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive within their intrinsic conditions, and the use of the marine environment is at a level that is sustainable.

Harmful algal blooms: Proliferations of algae that can produce toxins harmful to humans or marine life, or that can harm the environment through excessive growth, habitat alteration, or oxygen depletion.

Hydrographic conditions: The physical conditions of oceans, seas, and coastal areas including currents, waves, and tides.

Intelligent monitoring: Advanced monitoring approaches that utilise new technologies, automated systems, artificial intelligence, and integrated data systems to collect, process, and analyse environmental data.

Just transition: A framework that encompasses a range of social interventions needed to secure workers' rights and livelihoods as economies shift to sustainable production, particularly regarding climate change and environmental policies.

Marine heatwave: A prolonged period of anomalously warm water in a particular location.

Marine Protected Area (MPA): A clearly defined geographical space, recognised, dedicated, and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values.

Marine spatial planning: A public process of analysing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic, and social objectives.

Natural capital: The stock of natural resources, which includes geology, soils, air, water, and all living organisms. Natural capital provides a wide range of services, often called ecosystem services, which make human life possible.

Nature-based solutions: Actions to protect, sustainably manage, and restore natural or modified ecosystems, which address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits.

Nature-positive: An approach that halts and reverses the loss of nature and biodiversity, resulting in the natural world being in a better state than it was previously.

Net zero: Achieving a balance between greenhouse gas emissions produced and greenhouse gas emissions taken out of the atmosphere.

Ocean acidification: The ongoing decrease in the pH of the Earth's oceans, caused by the uptake of carbon dioxide from the atmosphere.

Ocean deoxygenation: The decrease in oxygen content of the oceans due to climate change and nutrient pollution.

Ocean literacy: Understanding of the ocean's influence on humans and human influence on the ocean.

OSPAR Convention: The mechanism by which 15 Governments and the EU cooperate to protect the marine environment of the North-East Atlantic.

PFAS (Per- and polyfluoroalkyl substances): A group of synthetic chemicals that are persistent in the environment and in the human body, with potential adverse environmental and health effects.

Regenerative practices: Approaches that go beyond sustainability to actively improve and restore ecosystems and their functions.

Resilience: The ability of a system to absorb disturbances and reorganise while undergoing change to retain essentially the same function, structure, identity, and feedback.

Social license: The level of acceptance or approval by local communities and stakeholders

for organisations and their operations.

Stakeholder: Any person, group, or organisation with an interest or concern in something, such as marine management or policy development.

Sustainability: Meeting the needs of the present without compromising the ability of future generations to meet their own needs.

Sustainable development: Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Transformational change: Fundamental, systemic change that disrupts established patterns and leads to a significantly different state or condition.

UK Marine Strategy: A framework for achieving or maintaining Good Environmental Status in UK waters, established under the Marine Strategy Regulations 2010.

Wellbeing economy: An economic system that prioritises human and ecological wellbeing, rather than focusing primarily on economic growth or GDP.

Appendices

Appendix A: Legislative and Policy Framework

The UK's **Marine Strategy Regulations 2010 (MS2010)** govern statutory monitoring of UK EEZ. Good Environmental Status indicators (GES) are contained within MS2010 and the Secretary of State for Scotland and Scottish Government Ministers must comply with MS2010, insofar as it applies to Scotland's seas. GES emphasises the use of an "ecosystems approach."

OSPAR is the mechanism by which fifteen Governments and the European Union cooperate to protect the marine environment of the North-East Atlantic; it is an instrument of international law and appears in MS2010.

Government legislation governing marine and freshwater environments includes:

- **Climate Change (Scotland) 2009, amended 2019** : sets out climate change plans to meet the target of net zero by 2045 using a carbon budget-based approach.
- **Marine (Scotland) Act 2010** : provides a framework to balance competing demands on Scotland's seas, including a duty to protect and enhance the marine environment and boost economic investment and growth.
- **Aquaculture and Fisheries (Scotland) Act 2013** : ensures that farmed and wild fisheries - and their interactions with each other are managed effectively, supporting economic growth with due regard to the wider marine environment.
- **Fisheries Act 2020** : Set out provisions in relation to fisheries, fishing, aquaculture and marine conservation. It established a post-EU Withdrawal legal framework for the regulation of fisheries in the UK and empowered the governments to make detailed secondary legislation for the same purpose.
- **Salmon and Freshwater Fisheries Act 1975** : provides fundamental legislation for managing salmon and freshwater fisheries, contributing to ecosystem resilience.
- **Nature Conservation (Scotland) Act 2004** : establishes the legal framework for conserving natural habitats and species, supporting biodiversity protection through sustainable practices.
- **Marine and Coastal Access Act (MACAA) 2009** : provides comprehensive legislation for marine planning, conservation, and coastal access.
- **Natural Environment Bill** : Proposed legislation including requirements for biodiversity improvement targets.

Key Scottish strategic frameworks include:

- **Blue Economy Vision for Scotland**: establishes the foundation for balancing economic development with marine stewardship, supporting sustainable growth in Scotland's marine and coastal areas.
- **Biodiversity Delivery Plan 2024 to 2030** : outlines specific actionable steps for biodiversity protection and sets measurable targets for conservation efforts.
- **Artificial Intelligence Strategy** : promotes innovation in marine management and sustainable economic activities through the integration of AI technologies.
- **Scottish Biodiversity Strategy to 2045** : provides long-term strategic direction for

biodiversity conservation and enhancement in Scotland's marine and terrestrial environments.

- **Marine science and innovation strategy** : enhances capacity through research and innovation in marine science and management.
- **Scottish National Adaptation Plan** : sets out the actions that the Scottish Government and partners will take to respond to the impacts of climate change. This Adaptation Plan sets out actions from 2024 to 2029.

Key UK and International frameworks include:

- **UK Third National Adaptation Programme (NAP3)** : sets out the strategy for building resilience to climate change impacts in marine and coastal environments.
- **EU Marine Strategy Framework Directive** : establishes European standards for marine environmental protection that continue to influence UK policy.
- **UK Marine Strategy**: provides an assessment of UK seas and sets objectives, targets and indicators for achieving Good Environmental Status.

Post-Brexit policy framework

EU Exit has changed policy making in Scotland, especially for marine management, which was directed by EU legislation. The Scottish Government has new powers, obligations, opportunities, and responsibilities, placing increasing importance on governance, accountability, and open government principles.

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