CENTRE OF EXPERTISE FOR WATERS

Review of monitoring approaches to deliver healthy ecosystems for Scotland's protected fresh waters and wetlands

Richard Gosling, Neil Coles, Sarah Halliday, Sayali Pawar, Andrew Black, John Rowan

United Nations Educational, Scientific and Cultural Organization
University of Dundee
Centre for Water Law, Policy and Science under the auspices of UNESCO

Scottish Government
gov.scot

CENTRE OF EXPERTISE FOR WATERS

Review of monitoring approaches to deliver healthy ecosystems for Scotland's protected fresh waters and wetlands

Richard Gosling, Neil Coles, Sarah Halliday, Sayali Pawar, Andrew Black, John Rowan

United Nations Educational, Scientific and Cultural Organization

University of Dundee

Centre for Water Law, Policy and Science under the auspices of UNESCO

Scottish Government
gov.scot

Published by CREW – Scotland's Centre of Expertise for Waters. CREW connects research and policy, delivering objective and robust research and expert opinion to support the development and implementation of water policy in Scotland. CREW is a partnership between the James Hutton Institute and all Scottish Higher Education Institutes. The Centre is funded by the Scottish Government.

This document was produced by:
Richard Gosling, Neil Coles, Sarah Halliday, Sayali Pawar, Andrew Black, John Rowan

University of Dundee, Nethergate, Dundee, DD1 4HN, Scotland, UK

CREW Project Manager: Maureen Whalen

Please reference this report as follows:
Gosling, R., Coles, N., Halliday, S.J., Pawar, S., Black, A., and Rowan, J.S. (2025). *Review of monitoring approaches to deliver healthy ecosystems for Scotland's protected fresh waters and wetlands CRW2023_15*. Centre of Expertise for Waters (CREW).

Available online at: crew.ac.uk/publications

ISBN: 978-1-911706-34-2

Dissemination status: Unrestricted

Acknowledgements: Project Steering Group: Sue Marrs, Sean Dugan, and Lisa Davidson (NatureScot), Claire Campbell (SEPA), and Brian Eardley (Scottish Government).

Thanks also to David Genney, Julia McCarthy and Adam Fraser for their valuable insights and Maureen Whalen for her support throughout the project.

Cover photographs courtesy of: Sarah Halliday.

Contents

List of figures

List of figures in Appendices

List of tables

List of tables in Appendices

List of boxes

Glossary/Acronyms

AI Artificial Intelligence

AWIC Acid Waters Indicator Community

CBD Convention on Biological Diversity

CEFAS Centre for Environment, Fisheries and Aquaculture Science

CEH UK Centre for Ecology and Hydrology

CNPA Cairngorms National Park Authority

COP Conference of the Parties

CSMG Common Standards Monitoring Guidance

DaRT Data Reporting Tool for MEAs

DPSIR Drivers, pressures, state, impact, and response model of intervention

eDNA Environmental DNA

EU European Union

FMS Fisheries Management Scotland

Forth ERA Forth Environmental Resilience Array

GBF Global Biodiversity Framework

GPP Gross Primary Productivity

HD Habitats Directive

InSAR Interferometric Synthetic Aperture Radar

IPBES Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

JNCC Joint Nature Conservation Committee

LMNI Lake Macrophyte Nutrient Index

MoRPh Modular River Physical Survey

NBMF National Biodiversity Monitoring Framework

NBSAP National Biodiversity Strategies and Action Plans

NCAI Natural Capital Asset Index

NEPS National Electrofishing Programme for Scotland

NPA National Parks Authority

OECMs Other Effective area-based Conservation Measures

PCA Protected Conservation Area

PSG Project Steering Group

PSI Proportion of Sediment-sensitive Invertebrates

RIVPACS River Invertebrate Prediction and Classification System

RSPB The Royal Society for the Protection of Birds

SAC Special Area of Conservation

SCM Site Condition Monitoring

SEPA Scottish Environment Protection Agency

UNEP United Nations Environment Programme

WFD Water Framework Directive

Executive Summary

Purpose of Research

The aim of this project is to review and make recommendations on a monitoring framework that will support transition from feature-based assessments towards informing the effective delivery of healthy ecosystems for Scotland's protected fresh waters and wetlands. The key research questions to be addressed were:

1. What are the key issues that need to be acted on to deliver healthy ecosystems?
2. What is 'ecosystem health' in the specific context of Scotland's freshwater and wetland protected areas?
3. For lakes, rivers and wetlands what are the thresholds for "good" health, "bad" health, and the stages in between?
4. Which indicators should be used in assessing ecosystem health?
5. What datasets exist to support analysis of ecosystem health and what gaps need to be filled for an effective approach?
6. How can monitoring results and assessments be developed to better inform site management and tackle the pressures that currently account for biodiversity loss?

Background

NatureScot is prioritising the reversal of the declining trend in freshwater biodiversity by protecting and improving the health of ecosystems as part of Scotland's commitment to protect 30% of land and sea by 2030. A refocusing of activities toward delivering healthy ecosystems requires a review of existing monitoring to achieve a wider landscape approach to understanding the state of freshwater and wetland ecosystems.

To assist in transitioning to an alternate system, NatureScot recognises the need to utilise existing tools and new collaborative approaches in smart, deliberate and creative ways.

A combination of literature review and stakeholder engagement was used to agree a common understanding of 'healthy ecosystems' and review current practices, gaps and opportunities for NatureScot to improve its current monitoring programme. From this it was agreed that:

"Ecosystem health is a measure of the capacity of an ecosystem to maintain its structure and function over time in the face of external stress. In the context of freshwater and wetland protected area restoration in Scotland, healthy ecosystems are defined as having reached the least degraded and most ecologically dynamic state possible."

Using this definition, views were gained from stakeholders via an online workshop on how NatureScot should use existing and new monitoring data and techniques to develop an assessment framework that could support the delivery of healthy ecosystems.

Key findings

- Monitoring to inform the delivery of healthy ecosystems should recognise that freshwater and wetland ecosystems are open and unstable systems that are rarely free of pressures.
- The review of the current Site Condition Monitoring (SCM) method for freshwater and wetlands demonstrated that there are existing tools and techniques, and examples of frameworks to utilise them, that NatureScot could use to assist in transitioning towards developing a healthy ecosystem approach to monitoring.
- Pressure indicators are valuable as they generate stakeholder-relevant evidence to inform decision-making on the management of protected areas.
- A structured framework can be used to create an integrative process to inform the delivery of healthy freshwater and wetland ecosystems.
- To be able to effectively utilise wider ecosystem evidence, monitoring data integration and interpretation platforms should be developed.

Opportunities

- A hierarchy of monitoring scales, in combination with rapid and more detailed assessments, could deliver a comprehensive and scalable approach to delivering healthy ecosystems.
- By strengthening existing and developing new partnerships to deliver collaborative monitoring and data sharing, and by harnessing new technologies (e.g. eDNA or LiDAR mapping), there was the potential to increase data richness, reduce redundancies and optimise resource use.

- Better use of spatial data frameworks would allow assessments of protected freshwater sites to be contextualised within the wider catchment.
- Adoption of common spatial data frameworks, (e.g. digital watercourse networks utilised by SEPA and Marine Directorate) help enable data sharing and statistical modelling insight.
- Incorporating greater automation and citizen science provide the potential to expand monitoring capacity and, at the same time, enhance a sense of stakeholder ownership.
- Data sharing can provide access to monitoring that captures long-term trends and risks that could help improve an understanding of ecosystem dynamics and discriminate between local and global threats at different levels of severity.
- Focused long-term monitoring post-intervention, even if just at sentinel sites, could ensure adaptive management feedback loops are based upon sound evidence.

Challenges

- While some ecosystem indicators are well established and can be adopted with little additional development, there are others that will require more work to implement.
- Changes in methodologies could lead to the risk of fragmented or incompatible datasets unless a period of parallel monitoring is undertaken.
- Data sharing and collaboration has been identified as a way of optimising resource use, although prudence should be exercised in understanding the ease with which this integration/optimisation can occur.
- Different monitoring locations, data formats, frequencies, protocols and the requirement for data sharing agreements must be considered as part of a cost-benefit and prioritisation analysis to create an inclusive monitoring framework.
- Stakeholders raised concerns that transitioning to an ecosystem approach could lead to a neglect of site-specific needs, local stakeholder engagement or species-specific conservation goals.

Recommendations

It is this project's recommendation that a multi-index framework is developed based upon the Drivers-Pressures-State-Impact-Response model.

This framework would incorporate biological and physicochemical indicators; identify what is wrong with the health of an ecosystem; and use pressure indicators to point to why it is wrong. Utilising this type of framing can enable decision-makers to determine the level of monitoring resources, data sources and inter-organisational collaborations, required to generate landowner and stakeholder-relevant recommendations to inform the delivery of healthy ecosystems.

For NatureScot to transition from feature-based monitoring to a broader landscape or catchment-scale programme, it will require a consideration of the resources, policy and legislative implications anticipated during and after the transition period. Key steps required in the short term are:

- Understand the indicator data availability, type, format, granularity, temporal variability and access.
- Develop the skills to interpret and collate data.
- Ensure the availability of expertise to conceptualise protected area ecosystems, develop modelling frameworks, interpret data and ensure confidence levels in data and outputs are well understood.
- Make resources available for the purchase of datasets, digital spatial frameworks, integration software, in-field exploration, and for ground-truthing new monitoring techniques.

Medium-long term key steps are:

- Data sharing agreements and data source and differentiation issues need to be resolved.
- Automate data input, cataloguing and integration from third parties.
- Retain specialist input to interpret indicators.
- Continue research into linking pressure indicators to ecosystem health.
- Operationalise new technologies and techniques as they are identified and adopted.

1 Introduction

At COP15, it was agreed in the Convention on Biological Diversity (CBD) to set a global target to protect 30% of the planet for nature by 2030 (known as '30 x 30'). The United Kingdom was a signatory to this with the Scottish Government making a clear commitment to this target in its Statement of Intent on Biodiversity (Scottish Government, 2020). The draft Biodiversity Strategy for Scotland reflects this through the stated ambition to halt nature loss and begin regenerating biodiversity by 2030 (Scottish Government, 2023). There is an expectation that by 2030 NatureScot will be able to (NatureScot, 2024a):

- Monitor protected areas more consistently and see the bigger picture across the land/seascape;
- Better understand and document what is already happening on each site;
- Establish a clear connection between monitoring and managing sites;
- Look wider than monitoring only specific features;
- Incorporate evidence from trusted data sources and make use of the latest technology where appropriate; and
- Efficiently and effectively manage sites for nature recovery.

Currently around 18% of land in Scotland is designated as areas protected for nature (Davidson *et al.,* 2024). NatureScot, as Scotland's statutory agency for nature with responsibilities for enhancing the natural environment, is taking a key role in the development of monitoring and assessment approaches to enable this commitment to be realised. As part of this NatureScot has signalled an intention to reform its monitoring to better deliver healthy ecosystems within Scotland's protected areas. The current approach to monitoring protected areas undertaken through the Site Condition Monitoring (SCM) programme assesses a range of attributes of features using common standards set out by Joint Nature Conservation Committee (JNCC). This guidance is used to determine whether each feature is in favourable condition or not, within protected areas. There are over 5,500 natural features (approximately 580 relating to freshwaters and wetlands) that have a unique set of attributes of special interest across nearly 2000 designated sites. As such there is the potential for conflicting targets between different features at site level.

With so many features, and attributes to assess, NatureScot has recently introduced a three-tiered risk-based approach to monitoring. This approach includes a basic 'site-check' for low-risk features and two levels where full SCM is carried out, either by NatureScot staff or national contractors. Despite this approach, **44% of features have not been fully assessed in the last 10 years** (NatureScot, 2024a). Evaluation of SCM data and related remedial management for the previous 20 years has also **indicated that ~25% of Scotland's features are thought to be in unfavourable condition** with landscape-scale pressures among the most prevalent (NatureScot, 2024b). However, this approach does not facilitate a clear link between monitoring and management action, particularly for catchment-wide pressures such as diffuse pollution and invasive species. Additionally, climate change effects and the need to monitor increasingly dynamic habitats and species adds to the problem. Consequently, there is a need for a pragmatic, scalable methodology capable of delivering the required environmental or site condition reporting requirements.

NatureScot, through consultation during 2020-21, outlined 10 principles to be used in formulating the transition to delivering healthy ecosystems (Figure 1, see Appendix A for full details). This transition requires the development of a framework based on the principles that will address a broader data set, by deploying a monitoring approach that is more inclusive, identifies pressures and risks, and informs management decision making. Alongside this, the Habitats Directive requires member states to report on the conservation status of protected species and habitat types every six years and Scotland, as a devolved administration, remains committed to this through revised legislation despite the UK's departure from the European Union (EU).

The next cycle of SCM is due to begin in 2025/26. During this cycle there may be an increase in the designation of protected areas, alongside the introduction of the 'Other effective area-based conservation measures' (OECMs). These represent a fresh approach to conservation and are geographically defined areas other than a Protected Area. OECMs offer an alternative to traditional protected areas by recognising areas that deliver positive and sustained outcomes for biodiversity (with the associated ecosystem functions and services) as a result of the land management, regardless of the primary objective of this management (NatureScot, 2024a). In planning the approach to implementing the Biodiversity Strategy to 2045, it is accepted that:

- The current SCM approach is no longer fit for purpose given the need to inform management actions for the effective restoration of freshwater and wetland ecosystems at the pace and scale now required.
- A change in approach is needed in the face of the twin challenges of the climate and biodiversity crises, and almost certain real-terms decline in public body spending.

Figure 1: Principles of the Monitoring to Deliver Healthy Ecosystems proposal (adapted from Davidson *et al.*, 2024).

2 Project Background and Scope

Globally it is estimated that since the 1970s, monitored populations of freshwater species have declined by an average of 85% (Moburg et al., 2024). The UK is one of the most nature-depleted countries in the world and freshwater ecosystems are among the most threatened ecological communities in Scotland. Restoring biodiversity and promoting the resilience of key ecosystems to withstand current pressures and the effects of climate change is therefore vital (State of Nature, 2023). The aim of this project is to review and make recommendations on a monitoring framework that will support transition from feature-based assessments towards informing the effective delivery of healthy ecosystems for Scotland's protected rivers, burns, lochs and inland wetlands.

This review is guided by six key research questions:

RQ1. What are the key issues that need to be acted on to deliver healthy ecosystems and (building from Site Condition Monitoring) what must be measured to facilitate this?

RQ2. Define 'ecosystem health' in the specific context of Scotland's freshwater and wetland protected areas. What are the key elements of healthy lakes, rivers, and wetlands in terms of hydrology, biology, chemistry and morphology and the pressures and threats that may act upon these?

RQ3. For lakes, rivers and wetlands what are the thresholds for "good" health, "bad" health, and the stages in between? Understanding this is a key step in knowing what to monitor and how to assess condition.

RQ4. Which indicators should be used in assessing ecosystem health, including for key biodiversity elements such as ecosystem functioning, habitat diversity and connectivity? Consider scale, including site-level and wider catchment indicators.

RQ5. What datasets exist to support analysis of ecosystem health and what gaps need to be filled for an effective approach? Consider new survey methods, new technologies, ease of access and integration, data flows.

RQ6. How can monitoring results and assessments be developed to better inform site management and tackle the pressures that currently account for biodiversity loss?

NatureScot is prioritising the reversal of the declining trend in freshwater biodiversity by protecting and improving the health of ecosystems in protected areas. A refocussing of activities toward delivering ecosystem health requires a review of existing monitoring and an evaluation of alternative data sets and methods to achieve a broader monitoring approach to freshwater and wider landscape biodiversity conservation.

To assist in transitioning to the new system, NatureScot recognises the need to utilise all available tools and new collaborative approaches in smart, deliberate and creative ways. Thus Figure 1 effectively represents a roadmap to the transformation from recurrent (different periodicity) site-based condition monitoring practices to annualised (or alternative epoch) assessment of national biodiversity trends. Such data provides the basis for reporting and prioritizing actions consistent with the 30x30 strategic ambition (Davidson *et al.,* 2024). As part of NatureScot's design considerations three thematic working groups (Freshwater and Wetland; Woodland; and Marine) were set up to test the proposal in their respective ecosystems and explore the opportunities and challenges.

Developing monitoring methodologies to deliver healthy ecosystems is complicated by connectivity, dynamism and position in the landscape. In most cases, SCM and OECMs will be insufficient on their own to safeguard these systems against the range of threats originating upland, upstream, downstream or through groundwaters. In recognising these limitations, NatureScot has an opportunity to catalyse more effective, inclusive, holistic and creative conservation solutions that are focused on delivering healthy ecosystems rather than site-specific feature-based targets. This task becomes more complex if the area of protected freshwaters and wetlands is to be expanded, amid the constraints of constrained public funding.

3 Methodology

The key research questions presented in section 2 provided the framing for the project's methodology. The project has taken a staged process (Figure 2) to build an understanding of the monitoring requirements critical to stakeholders' existing policy objectives and actions taken to address climate and biodiversity crises.

Stages 1 to 3 of the project focused on gathering the evidence base to inform how SCM can be transitioned from a feature/attribute focused process to one which focuses on delivering healthy ecosystems and informing proactive, timely and effective site management. A combination of literature review and stakeholder engagement was used to agree a common understanding of 'healthy ecosystems' and review current practices, gaps and opportunities for NatureScot to revise or improve its current SCM programme. Details of these evidence gathering exercises are presented in Appendices C and D.

The stakeholder consultation process (via structured interviews and a workshop) involved NatureScot, the Project Steering Group (PSG), associated practitioners and other stakeholders involved in ecosystem monitoring across Scotland. The activities undertaken provided access to practical, managerial and policy expertise to aid in the development of the ecosystems-based health monitoring system. The interviews and the workshop focused on:

- Exploring views on the definition of healthy freshwater and wetland ecosystems
- Understanding the level of support for NatureScot's key principles for monitoring to deliver healthy ecosystems.
- Identifying what indicators could be used to deliver an ecosystem-based monitoring approach that prioritises informing management.
- Identifying collaboration opportunities and new techniques that could support the new approach.
- Identifying any challenges or concerns raised by the participants related to the potential revision of SCM.

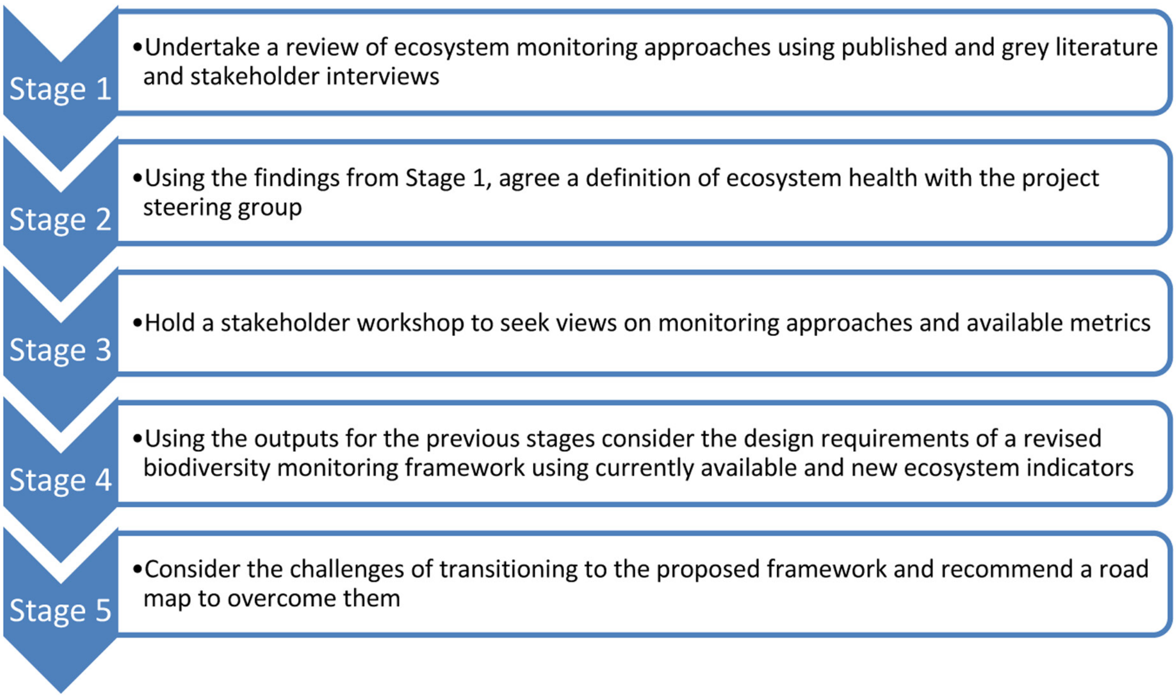

Figure 2: The key stages of the project.

Based on stakeholder expertise and guidance from the PSG, the definition of ecosystem health proposed in the Literature Review (Appendix C) was refined and expanded to ensure it was explicitly relevant to Scotland's fresh waters and wetlands.

The workshop explored the current biodiversity and environmental monitoring activities and data collection methods used by the different organisations represented. Through structured discussion, the workshop identified opportunities to maximise the use of existing data; considered areas for potential collaboration between organisations; and what metrics would best support effective delivery of healthy ecosystems. Using the evidence gathered from the literature review and stakeholder engagement, a set of recommendations for an evidence gathering framework that aligns with NatureScot's monitoring principles (Figure 1) have been developed and are presented in Section 6 (Stage 4). The final stage of the project assessed the key challenges in transitioning to this new assessment framework and provides recommendations on how these can be overcome (Stage 5 – Section 7).

4 Evidence required to inform the effective delivery of healthy ecosystems

4.1 Defining healthy ecosystem

Ecosystem health is a metaphor used to portray the condition and functionality of a system of ecological processes. Using the analogue of 'health' has the benefit of being easily understood by a wide audience since we intuitively understand the concepts of good or poor health from our own experiences. Yet when applied to ecosystems, there is no universally agreed definition.

The ecological theories upon which the targets for "good ecological status" in the Water Framework Directive (WFD) and "favourable conservation status" in the Habitats Directive (HD) are not explicit, but there is an assumption towards maintaining or restoring naturally connected ecosystems. This recognises that species and the interactions between them within natural ecosystems have evolved to cope with variability and change, making them better able to adjust to disturbances. To assess the "naturalness" of elements of ecosystems to support state of the environment reporting within the WFD and HD, metrics have been developed that compare observed values against a set of reference conditions. These reference conditions aim to represent a state of no or minimal disturbance against which, the observed state can be compared and classified.

However, a healthy ecosystem is not one that is fixed in a stable parameter space and devoid of all pressures, but rather an open system, varying under constant disturbance, that can maintain its vigour, organisation and function over time through its property of resilience (Costanza, 1992). Ecosystem attributes refer to both structural (composition, diversity, abundance or architecture) and functional (process) indicators of status that change over time providing an indication of health trends (Figure 3). The monitoring and assessment of ecosystem health should recognise that natural systems provide benchmarks that have developed resilience over time but that ecosystems are open and unstable systems that are rarely free of pressures.

The literature review (Appendix C) highlighted that some studies have considered ecosystem services within the assessment of whether an ecosystem is deemed to be healthy or not. The provisioning, regulating and cultural services delivered by healthy ecosystems are recognised as important drivers for ecosystem restoration, with biodiversity being seen as their bedrock (NatureScot, 2024c). These services are being assessed and reported upon through the Natural Capital Asset Index (NCAI), a composite index derived using data on the scale and characteristics of Scottish habitats. It was the project steering group's view that delivering a heathy ecosystem is a key route to restoring the

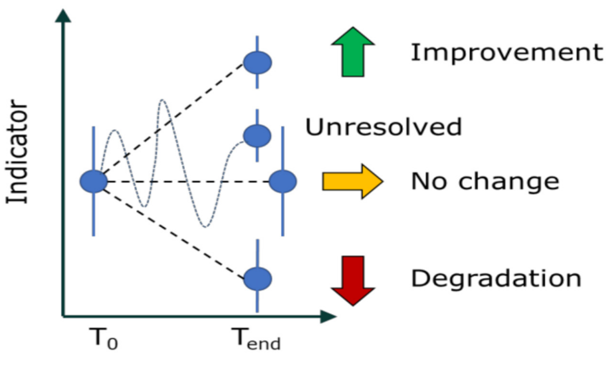

Figure 3: Assessing ecosystem health and identification of changes in health over time (Maes *et al.*, 2020).

ecosystem services they deliver, but that accounting for these services directly within the definition of a healthy ecosystem was beyond the scope of this project. After considering the literature review, a definition of healthy ecosystems in freshwater and wetland ecosystems was agreed by the project steering group (Box 1).

Box 1: The definition of healthy ecosystems agreed by the project steering group.

Defining healthy ecosystems

Ecosystem health is a measure of the capacity of an ecosystem to maintain its structure and function over time in the face of external stress.

In the context of freshwater and wetland protected area restoration in Scotland, healthy ecosystems are defined as having reached the least degraded and most ecologically dynamic.

When asked for their views on the definition of a healthy ecosystem at the project workshop, stakeholders reported that they would expect them to be characterised by resilience, which is largely driven by high abundance and biodiversity, both structural and genetic. This diversity contributes to ecosystem stability and offers various benefits to humans, like carbon sequestration and flood mitigation.

Ecosystem health, therefore, is taken here to be a measure of the status of ecosystems, through a combination of structure, function and resilience such that a healthy ecosystem is one in which:

- the organisation and condition of biotic ecosystem components and the abiotic elements that support them closely reflect natural conditions (structure);
- the function and capacity of a system is maintained and can deliver a range of ecosystem service benefits (function); and
- the health and capacity of ecosystems and benefits are sustained under human and environmental pressures (resilience).

4.2 Indicators of ecosystem health

A definition of ecosystem health that incorporates structure, function and resilience, once applied to biotic and abiotic features across a range of habitat types, yields myriad monitoring and assessment options. The challenge then is to find the optimum mix of metrics to encompass this complexity and provide the key information to understand the structure and functions of an ecosystem whilst not relying on an unsustainable level of resource to collect and analyse these data. In transitioning to ecosystem health assessments, it is essential that the indicators of ecosystem health, if they are to be useful for informing the management of protected areas, should also identify the key pressures and mechanisms leading to ecosystem health degradation.

A review of indicators that have been used to assess ecosystem health can be found in Appendix C. In terms of current practice in the UK, this review found that the indicators used to assess both conservation and ecological status (Habitats and Water Framework Directives respectively) strongly orientate toward the assessment of physical and chemical (state) and biological (impacts) parameters. Feedback from stakeholders during this project strongly suggested that pressure indicators should also be part of ecosystem condition assessment. In essence, the physicochemical and biological indicators identify what is wrong with the health of an ecosystem while pressure indicators point to why it is wrong.

Using these different indicator categories to ensure that the various aspects of ecosystem health are accounted for is an approach that has been used by Maes *et al.* (2020) who classify pressure, state and impact indicators in a manner shown in Table 1.

A focus on biological impact indicators can allow the monitoring of ecosystems to be largely contained to within the area of conservation interest. However, within freshwater and wetland habitats, the incorporation of pressures indicators to understand why degradation happens necessitates a wider field of view. Changes to the physicochemical state of the water environment can propagate quickly over large areas, particularly in high relief, low bedrock permeability environments that are frequently found in Scotland.

The need to look beyond protected areas for indicators of the cause of ecosystem degradation was a key message delivered by stakeholders with this project (Appendix D). There are also advantages to be gained in doing this from a resource point of view as many of these wider scale indicators are already being collected by other monitoring agencies and organisations within Scotland. However, to bring these different data types together into a coherent assessment of ecosystem condition requires a new assessment framework to be developed.

<table>
<caption>Table 1: Hierarchical structure and classification of pressure and condition indicators (from Maes et al., 2020).</caption>
<tr><td rowspan="6">Pressures</td><td colspan="3">Habitat conversion and degradation (land conversion)</td></tr>
<tr><td colspan="3">Introductions of invasive alien species</td></tr>
<tr><td colspan="3">Pollution and nutrient enrichment</td></tr>
<tr><td colspan="3">Over-exploitation</td></tr>
<tr><td colspan="3">Climate change</td></tr>
<tr><td colspan="3">Other pressures</td></tr>
<tr><td rowspan="7">Ecosystem Condition</td><td colspan="3">Environmental Quality (physical and chemical quality)</td></tr>
<tr><td rowspan="6">Ecosystem attributes (biological quality)</td><td rowspan="4">Structural ecosystem attributes</td><td>Structural ecosystem attributes (general)</td></tr>
<tr><td>Structural ecosystem attributes based on species diversity and abundance</td></tr>
<tr><td>Structural ecosystem attributes monitored under the EU nature directives</td></tr>
<tr><td>Structural soil attribute</td></tr>
<tr><td rowspan="2">Functional ecosystem attributes</td><td>Functional ecosystem attributes (general)</td></tr>
<tr><td>Functional soil attributes</td></tr>
</table>

5 Ecosystem Health Assessment Frameworks

An assessment framework is a structured system that organises the guidance for methods of data collection, analysis and collation of results into an output that meets the objectives of the monitoring. It can also determine the monitoring networks required to meet these objectives and the frequency, spatial resolution and system of prioritisation of resources to support data collection.

For the current SCM in Scotland, the monitoring framework was developed to achieve the objectives set out in the Habitats Directive (HD) and is supported by:

- The Common Standards Monitoring Guidance (CSMG) – these set out the monitoring methods, attributes to be assessed and targets to achieve favourable conservation status.
- A six-year reporting cycle in line with the HD that informs monitoring frequency.
- Latterly, the three-tiered risk-based monitoring approach developed by NatureScot to ensure monitoring resource is targeted to gain the greatest information on impacts on feature condition.

Informed by the findings of the literature review and taking on board NatureScot's monitoring principles, the feedback from stakeholders indicated that a change in framework will be required to transition to an ecosystem approach to monitoring. The key points that were raised to support this conclusion were that:

- Recognising feedback loops and dependencies within ecosystems is critical. Understanding these interrelationships can help identify where actions may have the greatest impact and prevent unintended consequences.
- There are key challenges given limited resources. The focus should be on identifying indicators that reflect ecosystem health and resilience, prioritising those that are sensitive to pressures and management actions. Collaboration and data sharing can help address resource constraints.
- Contextualising site-based monitoring with wider area monitoring can provide better assessments to inform management.
- Making effective use of existing data, even if collected for different purposes, requires careful consideration of scale, granularity, frequency, and context. A pragmatic approach is needed to make the best use of available data.

Given this feedback and the need to incorporate more information on pressures, this project recommends using a multi-indicator approach using conceptual models linking indicators to ecosystem health informed by the Driver-Pressure-State-Impact-Response (DPSIR) model. The DPSIR Framework provides a structure that houses the

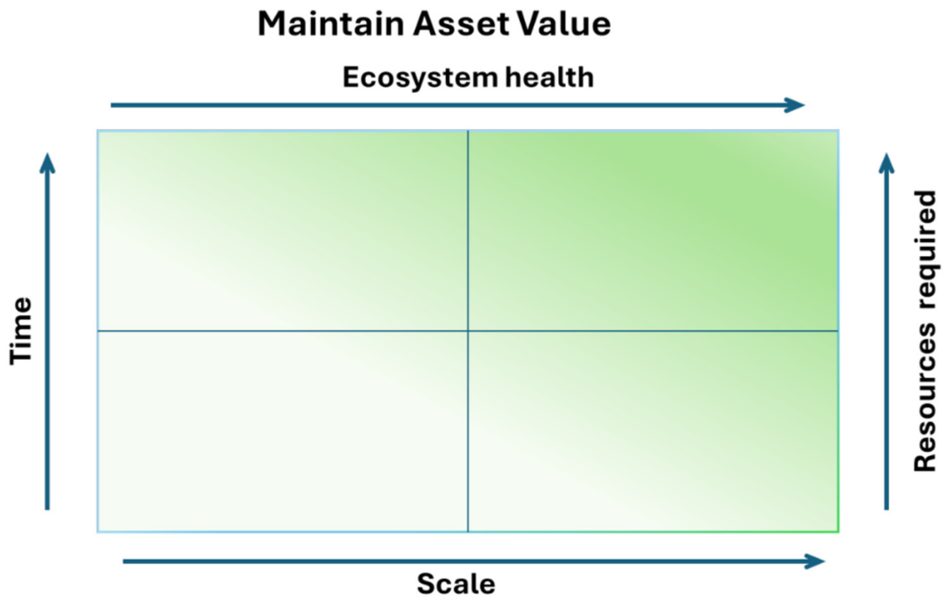

Figure 4: Change in effort and resources needed to maintain ecosystem health over time with the monitoring investment increasing with shifts in scale of asset monitored (site-landscape-region).

indicators needed to enable feedback to decision-makers on ecosystem health resulting from impacts on the system (Smeets and Weterings, 1999). A suite of indicators that identify both the nature of ecosystem degradation and the causes, organised in a structured framework such as this can be used to create an integrative process to inform where and how to target action to deliver healthy ecosystems. Such a framework can provide an opportunity to link performance metrics to management interventions. This will also enable decision-makers to determine the level of monitoring resources required to ensure the delivery of ecosystem health at a particular site, ecosystem, time or scale (Figure 4).

Understanding source, type and scale of monitoring is key to understanding what data to collect, and at what scale and frequency, to account for relevant changes in the ecosystem. These types include:

- Targeted monitoring: describes local to regional monitoring, with several re-visits per year, designed with the aim of understanding ecosystem processes occurring in particular environments.
- Surveillance monitoring: designed to detect when change is occurring, what that change is and the magnitude of that change, using standardised methods to collect a broad suite of variables at regional to national scales.
- Landscape monitoring: conducted over large areas, provides spatially continuous data and is primarily concerned with where and when change is occurring and provides information that cannot be feasibly collected using other methods.

(Sparrow *et al.*, 2020; see Appendix C Table C.2 for a full description of monitoring types)

Based on stakeholder feedback, it was agreed that the new approach would better inform management decision making and practical biodiversity conservation by:

- transitioning away from site-based 'condition' assessments,
- prioritising indicators that inform management and decision-making, and
- incorporating the wider landscape and catchment to allow for the identification and management of pressures at appropriate scales.

At the heart of the proposed framework there sits a revised suite of indicators of ecosystem health, representative of the wider influencing environment. It is anticipated that these indicators will include those derived from data collected by other organisations (Figure 5). When integrated at the protected area level, this assessment will inform the condition of the ecosystem and the causes of degradation.

Taking the broader view, requires an understanding of ecological integrity in freshwaters and wetlands which is fundamentally linked to their basin context, hydrologic regime, water quality, physical habitat and biotic composition. Several existing ecosystem health assessment frameworks recognise the importance of accounting for each of these core components to ensure an integrated assessment of ecosystem health (e.g., Clapcott *et al.*, 2018; Moburg *et al.*, 2024). Through developing this understanding, it will be possible to infer how

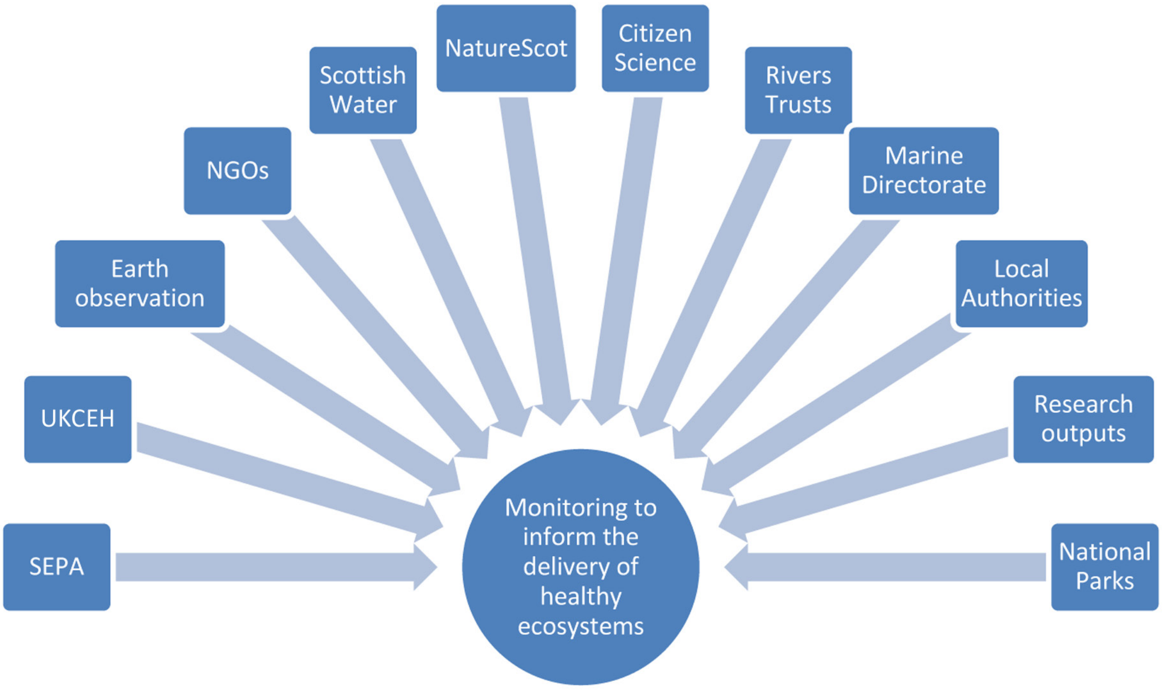

Figure 5: Example potential data sources for assessing drivers, pressures and risks to NatureScot's protected areas or OECMs. Note: this list of potential sources is not exhaustive.

threats translate into impacts upon key ecological attributes that determine ecosystem health (Table 2).

Threats transfer to impacts via functional pathways. For example, impacts on river flow lead to changes in hydraulic conditions which can influence the hydromorphological characteristics of a river. These changed characteristics may manifest in alterations to physicochemical characteristics such as temperature and dissolved oxygen which translate into impacts upon biology. Identifying functional hierarchies such as these for habitat types can be valuable for choosing the indicators which are likely to provide the link between pressures and impacts.

An example of such a hierarchy has been used extensively in the US in the form of the Stream Quantification Tool to determine stream restoration potential and effectiveness (EPR, 2022). The basis of the methodology is a functional hierarchy proposed for river environments that builds on work by the US Army Corps of Engineers (Fischenich, 2006). The hierarchical framework describes how higher-level functions, such as biodiversity are supported by lower-

Table 2: Key ecological attributes, threats and sources (Moburg *et al.*, 2024, Table 2.1).

Key Ecological Attribute	Threats		Sources of Threat
Hydrologic regime timing, magnitude, frequency, duration, rate of change	Climate Change	Flow and lake level regime alteration, water withdrawals, inter-basin transfers	Dams, irrigation, energy or water resource development, land use change
Connectivity longitudinal, lateral, vertical, temporal		Fragmentation from obstructions; obstructions to species migration/ movement; obstructions to sediment and nutrient transport	Dams, energy or water resource development, levees, berms and channel lining for flood-risk, road development/ undersized and poorly designed culverts
Water quality temperature, clarity, chemical, biological		Basin runoff or point sources of excess sediments and/or nutrients, bacteria, toxic chemicals, thermal pollution from dams	Agriculture, deforestation, animal management, sewage or wastewater, industry, mining, hydroelectric developments
Physical habitat distribution, abundance, structure, condition		In-stream and lake shoreline gravel mining, channelisation, floodplain and/or riparian and other wetland destruction/ conversion	Land use change, development, aggregate extraction, agriculture including crops and livestock grazing and watering
Biotic composition composition, abundance, distribution		Over-harvesting, invasive alien species (which may include species that may be found elsewhere in the region but are invasive to a particular habitat)	Poorly managed fisheries, aquaculture, pet and landscaping trades, aquascaping, introduced species, species range changes due to habitat modification (e.g. changes in flows) and climate change

level functions such as the quantity and dynamics of flow.

The framework is used to identify the functional parameters associated with each functional level and the indicators (and associated performance standards) that could be used to assess them. Such a method, if extended to other freshwater and wetland habitats, would provide a useful approach for prioritising the use of indicators appropriate to the management objectives of protected areas. These indicators sit at the heart of the evidence and decision framework that is proposed to transition to an ecosystem approach to site condition monitoring.

6 The evidence and decision-making framework

The proposed framework is a risk-based approach that aims to make the maximum use of existing and new evidence to support the delivery of healthy ecosystems. The aim is to enable efficient, evidenced and effective decision making for management of freshwater and inland wetland protected areas to both sustain and restore ecosystem health. The framework is flexible and can encompass significant expansion of Scotland's existing protected areas network. The framework can also account for the water network context, for example, by incorporating relevant indicator data arising from beyond protected area boundaries. Management decisions can relate to whether and how areas are restored, but also what protection measures may be required or whether there is a need for further evidence collection to better understand the impacts upon the protected area ecosystems.

The approach utilises the DPSIR model that aims to explain the interaction between society and the environment to inform intervention. In the proposed framework, the response i.e. the management of protected areas, is informed by:

- The condition of ecosystem health, indicated by the state of the environment and the subsequent impacts upon ecosystem structure, function and resilience; and
- The causes of degradation, indicating which restoration measures are likely to deliver healthy ecosystems (Figure 6).

The flow of consequences from drivers to impacts belies a more complex picture given that the social-environmental interactions are dynamic and involve feedback mechanisms. Indeed, the DPSIR model has faced criticism for suggesting a unidirectional causal chain of processes leading to impacts and does not provide clear cause and effect relationships between the stages in the model (e.g., Elliott and O'Higgins, 2020; Patrício *et al.,* 2016). However, supporters of the model point to the way it can help aid communication between ecosystem specialists and decision makers (e.g., Timmerman, 2011). It also provides a framework for redressing the bias away from ecosystem impact monitoring to better identify the causes and the management of pressures (Song and Frostell, 2012).

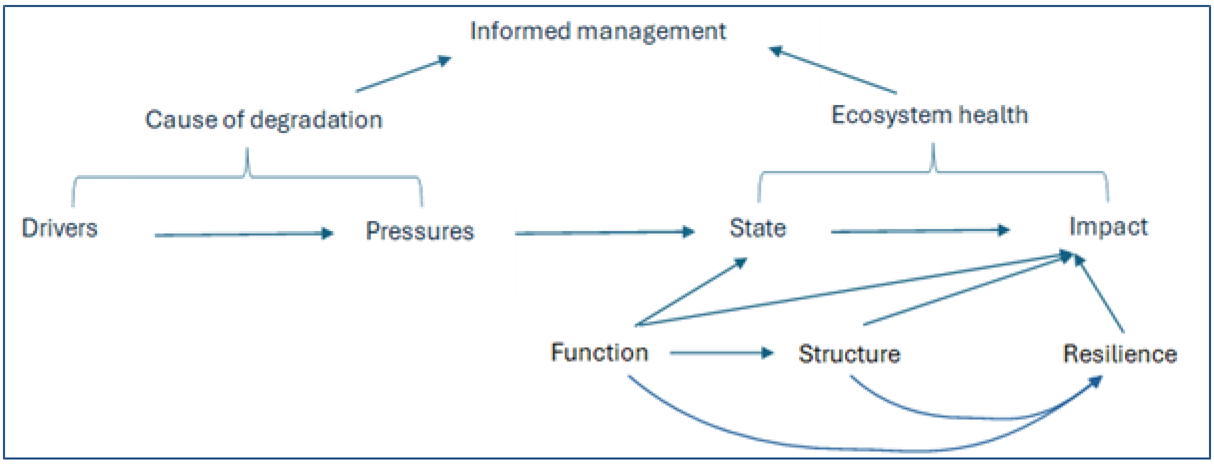

Figure 6: Informed management to deliver healthy ecosystems using the DPSIR framework.

By considering the drivers and pressures, the model provides a starting point to developing the weight of evidence required to understand impacts on ecosystem health and their causes. Moving through the framework, there is the potential to progressively gather evidence of the risk of harm to relevant ecosystems whilst at the same time gathering evidence of the causes of those potential harms. Provided there is a good understanding of the causal links between pressures and impacts it is possible to reach a point at which confidence in the risk of harm has reached a sufficient level to warrant a management intervention in response to the pressures and impact on the ecosystem health. Where this confidence level lies depends upon factors such as the cost of remediation and the value of the restored habitat. As such, a useful framework for informing decision making should be flexible enough to accommodate these, potentially site-specific, variables.

6.1 Developing the proposed evidence framework

A key feature of the proposed framework is the way disparate sources of evidence are accommodated to allow an assessment of site condition to be made. These sources of evidence can come from assessments of pressures, state or impact provided there is an understanding of how they influence ecosystem health. The proposed framework achieves this by recognising that indicators will come with several attributes, namely:

- The indicator state e.g. good, poor etc.
- The uncertainty associated with this assessment.
- The strength of evidence indicating current site ecosystem health.
- The pressure(s) associated with the indicator.

These features and how they impact decision making are illustrated in the examples provided in Table 3.

Table 3: Two examples of indicators assessed in terms of state, strength of evidence and uncertainty and how this would impact decision making.

Example	Indicator Assessment	Outcome	Decision making impact
1	An assessment carried out six years ago of the population density of juvenile Atlantic salmon indicated that densities were consistent with the reference condition.	**Good condition** may be assigned to the indicator, but it is recognised that, due to the localised nature of carrying capacity, there would be a degree of uncertainty in the state assessment, and it is ascribed **medium uncertainty**. Finally, it is considered that juvenile salmon densities may be influenced by several factors less related to the overall health of the site's ecosystem such as stocking, disease and external factors influencing the numbers of returning adult (parent) salmon. In addition, as time passes between the monitoring and assessment dates (in this case six years) the currency of the indicator diminishes. As such it is designated as a **low strength** indicator of the current site ecosystem health.	Presents a medium uncertainty, low strength indication of a healthy ecosystem. On its own it provides some information that there are no major issues on the site, but the evidence is weak, and other indicators should be sought to provide stronger evidence that the river ecosystem is healthy.
2	An assessment of a blanket bog carried out by a peatland expert last summer identified that 30% of the total feature area showed signs of active drainage because of ditching	**Poor condition** may be assigned to the indicator. The survey was conducted by an expert who understands how bogs drain and can identify other indicators of drainage such as changes to vegetation cover. As such it is ascribed **low uncertainty**. There is high confidence that excessive active drainage through ditching (pressure) leads to lowering water tables (state) which will result in a changed structure, function and resilience of the blanket bog ecosystem health (impact). As a result, this is identified as a **high strength** indicator of ecosystem health.	Presents a high strength, low uncertainty indication of an unhealthy blanket bog ecosystem caused by ditching. Other indicators such as a vegetation survey or hydrological monitoring may be used to support this or alternatively it may be deemed strong enough evidence to inform management action.

6.2 A scoring methodology to incorporate multiple lines of evidence

The examples shown in Table 3 demonstrate how individual indicators may be assigned attributes (state, uncertainty, strength of evidence and associated pressures) that are useful for informing management decisions. However, the evidence gathered from existing literature and through stakeholder engagement points towards multiple ecosystem indicators being required to understand the nature of impacts on ecosystem health and how to address them.

The current Common Standards Monitoring Guidance details a range of attributes that should be assessed to determine the condition of a range of species, habitat and Earth science features which occur on UK protected sites. The assessment of feature condition generally requires each of the mandatory attributes to achieve a target before the feature can be in favourable condition. In essence, this is a "one out, all out" approach. Whilst this may be aligned with the precautionary principle, it does not clearly reflect the uncertainties associated with the indicators. It also results in a broadly binary pass/fail result whereas a more scaled result could better inform prioritisation within management decisions.

An alternative approach has been used in multi-index assessments that use a scoring system to combine the information provided by indicators into a scaled assessment of ecosystem health (e.g. Jakobsson *et al.,* 2021; Certain and Skarpaas, 2010). This is an approach currently being adopted by the Cairngorms National Park Authority (CNPA) in their development of the Cairngorm Nature Index (CNPA, 2022).

The recommendation in this report is to take this multi-index approach by developing a set of rules applied to the indicator attributes which result in a scaled assessment of ecosystem health combined with a level of confidence in this assessment. Each indicator can be assigned a set of scores representing the indicator's condition, uncertainty, and strength of evidence. These transformations should be based upon a common set of guidelines to allow alignment between habitat types.

For example, in terms of the ecosystem condition score a common value should define a healthy ecosystem. The assignment of this condition score for any indicator should reflect how closely the ecosystem component being measured approaches the conditions expected in a healthy ecosystem, defined as "having reached the least degraded and most ecologically dynamic state possible". An example of how such a set of indices and the rules to combine them could work is given in Appendix B – A multi-index monitoring framework to inform the delivery of healthy ecosystems.

This example, and the calculations involved are presented for illustrative purposes to demonstrate how a framework for combining indices could operate. Such methodologies require considerable development before they can be implemented and recommendations for this development are presented in section 7.3. It may be that through this process, alternative methods for combining indices are deemed more appropriate.

6.3 Choosing indicators

Ecological indicators are chosen as integrative metrics that strike the appropriate balance between measurement effort and explanatory power for assessing ecosystem health. To strike this balance some indicator frameworks have been set up to ensure that core ecosystem components are covered by the metrics (e.g. Clapcott *et al.*, 2018, Harwell *et al.*, 2019). Figure 7 illustrates how the New Zealand assessment of freshwater ecological integrity (Tier 1) is generated from the assessment of the core components: aquatic life, physical habitat, water quality and quantity, and ecological processes (Tier 2).

Clapcott et al. (2018), the authors of the New Zealand framework, recognise some indicators (Tiers 3 and 4) can be representative of more than one ecosystem component, can be both direct and indirect, and include indicators that characterise pressures and stressors on the system. For pragmatic reasons, they also identify that it is advantageous to select the smallest set of indicators that can best represent the core components.

To select a parsimonious set of indicators for specific management objectives it is possible to make use of functional hierarchies (e.g., Fischenich 2006). For example, the stream function pyramid highlights that the foundational aspects of the pyramid (hydrologic and physical processes) support the higher-level biologic functions (Figure 8). These approaches typically build upon developing conceptual ecosystem models of habitats and using these to understand the linkages between drivers, pressures, states and impacts. Building upon these approaches, the recommendation of this report is to determine indicators in the following steps:

- Develop conceptual DPSIR models for each habitat type and spatial scale combination

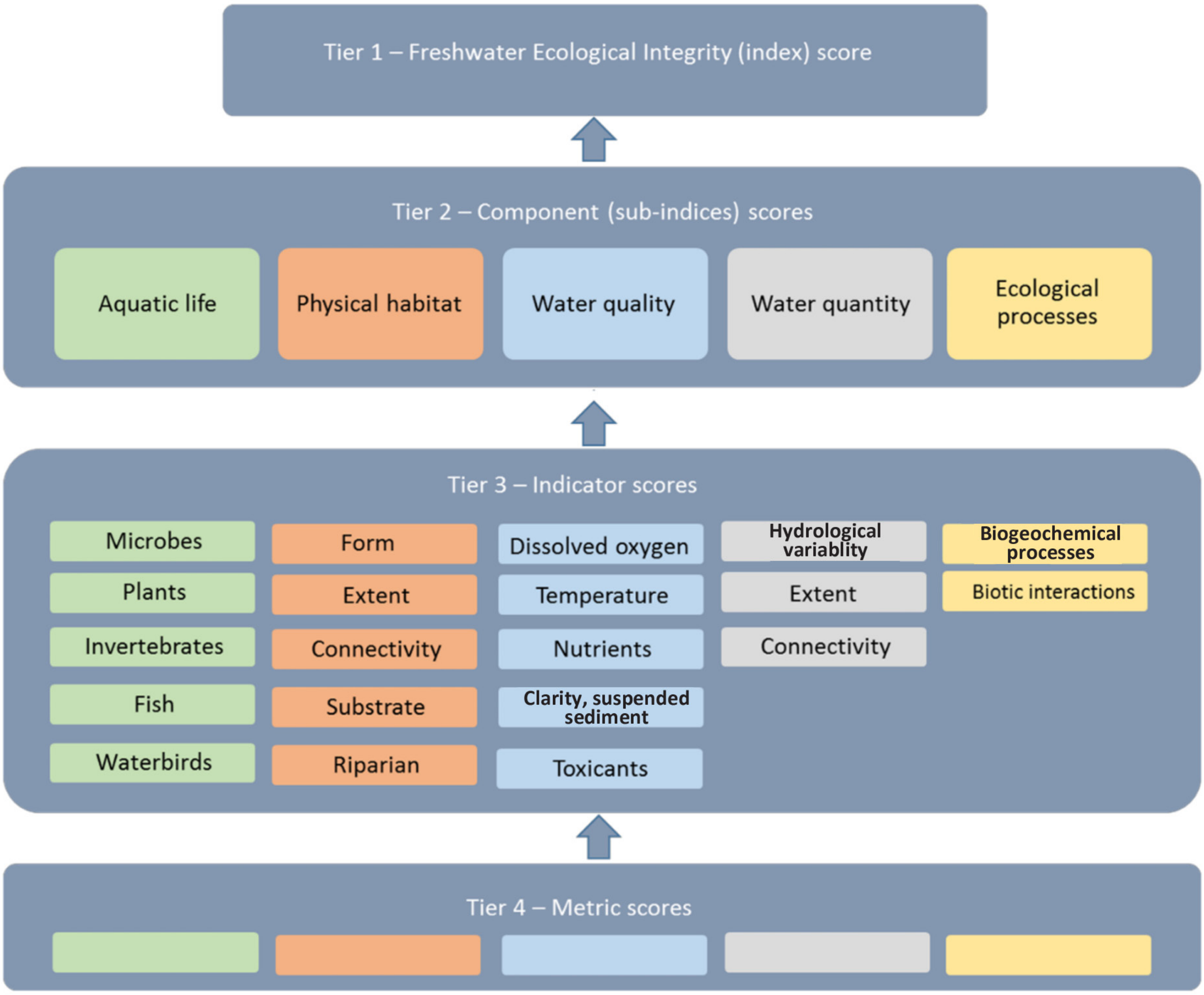

Figure 7: A tiered framework to assess freshwater ecosystem health in New Zealand (Figure 8, Clapcott *et al.*, 2018).

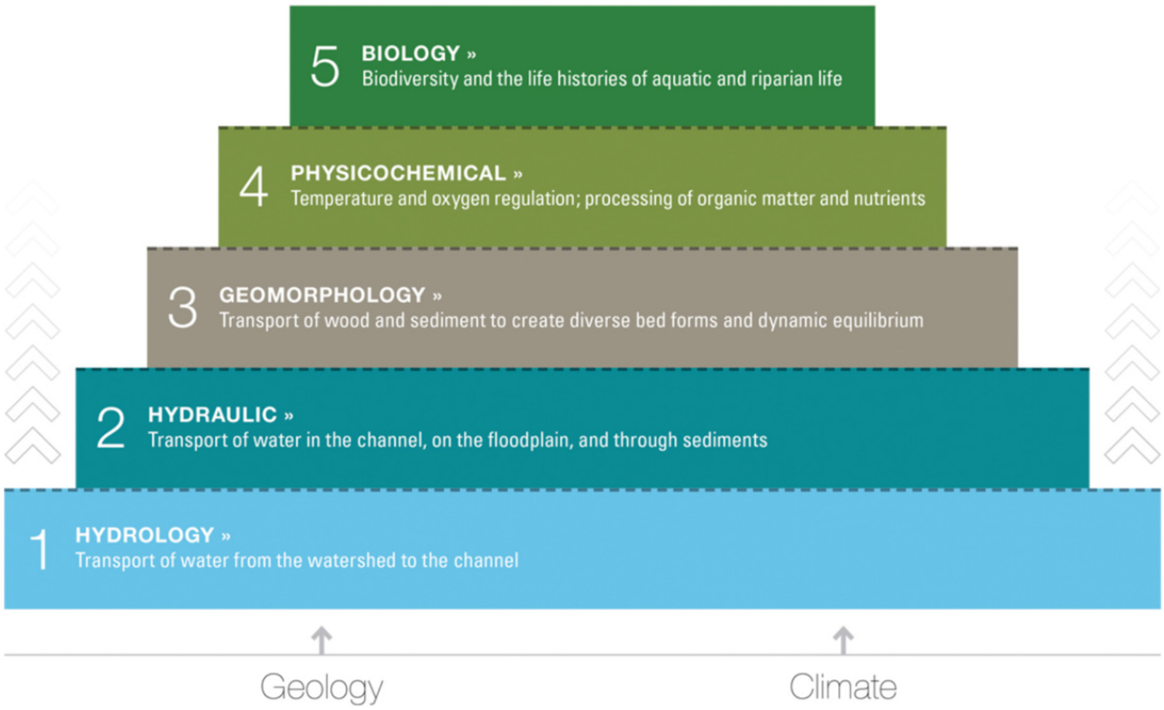

Figure 8: The Stream Functions Pyramid Framework (Harman *et al*. 2012).

deemed appropriate for management purposes. The conceptual model will identify the factors that exert most influence on habitat functions. It should be developed with cognisance of the key pressure types likely to be relevant in the region of influence of the protected area and will explore the degree to which pressures are likely to impact the structure, function and resilience of the protected area's ecosystem. For example, current wetland site condition monitoring does not stipulate the assessment of the deposition of aerial pollutants, whereas conceptual modelling might identify this as a key potential impact.

- Select an appropriate suite of indicators for each conceptual model. The conceptual model along with habitat-specific functional hierarchies (e.g. Figure 8) should be used to select a parsimonious set of indicators that represent the key ecosystem components. A balance will need to be struck between indicators of functions at the base of the hierarchy (e.g., hydrology as an indicator of stream function), that may be fundamental to ecosystem health but may not be integrative. An altered hydrology may work through the hierarchy impacting hydromorphology, chemistry and biology but direct pressures on these other components of stream function must also be addressed (e.g., point source pollution). This is why the DPSIR conceptual model is a key first step and should ensure all likely pressures are accounted for. Selected indicators should be sought from existing data sets in the first instance.
- Define thresholds for good and bad ecosystem health. It is important to recognise that thresholds for healthy ecosystems do not necessarily equate to those of unimpacted reference systems. A healthy freshwater and wetland ecosystem is one that has reached the least degraded and most ecologically dynamic state possible (Box 1). Ecologically dynamic refers to a state in which the biotic and abiotic components vary in abundance and composition much as they do in appropriate reference systems (Palmer *et al.*, 2005). This definition should underpin the thresholds chosen for indicators. For current CSMG and WFD indicators, thresholds consistent with this definition of a healthy ecosystem may already exist. For others, thresholds will need to be developed. Recognising that the UK is one of the most nature depleted countries in the world (a process that has been underway

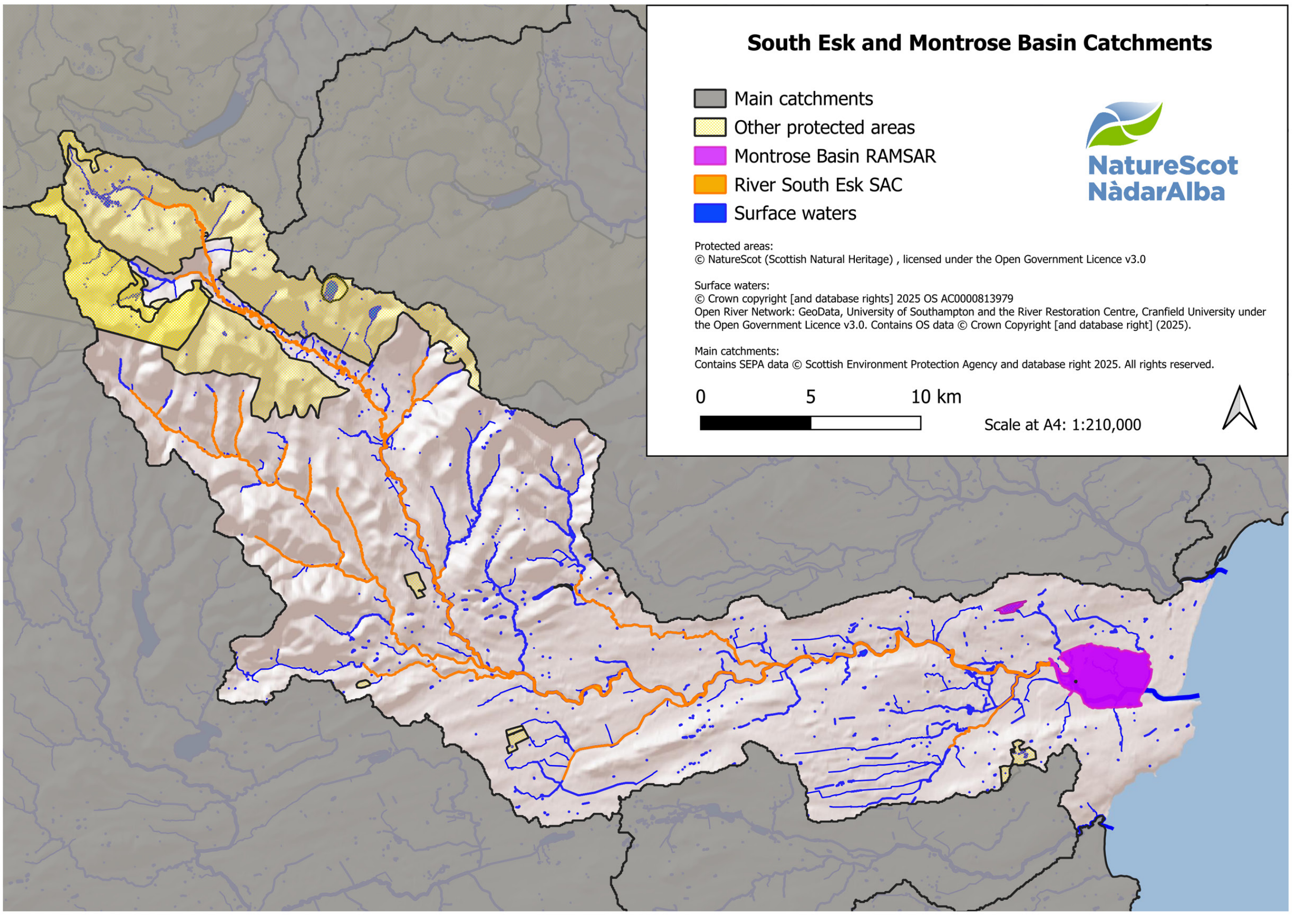

Figure 9. The protected areas of the South Esk Catchment.

for several centuries – State of Nature 2023), setting reference conditions that reflect systems completely devoid of anthropogenic influence is becoming increasingly unrealistic, particularly when set against the background of a changing climate.

The example of the River South Esk SAC detailed in Appendix B can be used to demonstrate how these steps to choosing indicators may be used. In this case the SAC covers the river catchment from the upland sources in the Angus glens to the outflow to the North Sea at Montrose (Figure 9).

Pressures throughout the catchment can influence the SAC at different spatial scales from river reach to catchment wide. A suite of 7 pressures have been identified from the existing site condition monitoring as impacting the SAC's two features (Atlantic Salmon and Freshwater Pearl Mussels – NatureScot, 2025). The existing River South Esk SAC Conservation Advice Package (NatureScot, 2020) provides a good basis for a conceptual model of the catchment helping to identify the potential mechanisms that influence overall ecosystem health via impacts on water quality, flow alteration and channel modification. An understanding of the drivers and pressures within the catchment would indicate that many of these are related to agricultural operations concentrated in the lower parts of the catchment. In addition, there is a suggestion that forestry operations and other land use changes in the upper catchment may be mobilising fine sediment that can clog channel bed habitats. Given this understanding, it may be decided that the catchment should be divided into two or more sub-catchments to better target the monitoring and management of these pressures.

The current site condition monitoring of the two features within the SAC identifies 17 mandatory indicators (Appendix B Table B.3). Most of these indicators measure habitat state influencing the features or the direct biological impact upon them. It can also be seen that many of these existing indicators provide information at a local scale such as the reach or sub-catchment. As such they may provide limited information on overall ecosystem health and the pressures upon it in the absence of a comprehensive programme of reach-by-reach surveys. Freshwater river habitats are characterised by high natural variability in both flow and quality conditions over time, and channel form, spatially. Indicators specific to a species or location may require a high monitoring resolution to ensure changes can be attributable to artificial influences. Given this, it would be beneficial to incorporate other indicators that can aggregate at the catchment or sub-catchment scale, particularly those that identify pressures more directly and which may be less variable over time, such as channel modification, barriers to fish or loss of riparian woodland. Examples of such potential indicators were identified during the project's stakeholder workshop (Appendix D) and those that could be applied in the South Esk SAC have been highlighted in Table 4.

Table 4 highlights potential indicators and their sources. Most of these indicators are currently collected by 3rd parties, as indeed are many of the existing CSM indicators for this SAC. SIMCAT water quality and eDNA are indicators that have been developed but are currently not operationalised widely across Scotland's freshwaters.

6.4 Identifying pressures associated with indicators

In addition to the attributes of condition, confidence and strength of evidence, to aid protected area management each indicator should be associated

Table 4 Potential indicators of ecosystem health for the South Esk SAC.

Potential indicator	Scale	Main DPSIR category	Potential 3rd party sources
Fish barriers	Catchment	Pressure	SEPA
Effluent discharge points and compliance level	Catchment	Pressure	SEPA
SIMCAT[1] water quality and source apportionment modelling	Catchment	Pressure	SEPA
% Riparian woodland	Catchment	State	NatureScot Open Data
River water temperature	Catchment	State	SEPA and SRTMN
Environmental DNA	Catchment	Impact	SEPA/Rivers Trust
Hydromorphological alteration	Sub-catchment	Pressure	SEPA
Macroinvertebrate indices	Sub-catchment	State	SEPA

[1]SIMCAT (SIMulation of CATchments) water quality model (Environment Agency 2006)

with the key pressure or pressures that influence the condition score. These pressures should be identified during the conceptual modelling phase for each habitat and scale combination of protected area. All significant pressures, whether they are local, regional, national or international should be considered. This is critical to inform protected area management. For example, a decline in species may be because of a global disease outbreak or climate change and it will be important to identify the sensitivities of indicators to these pressures to understand any degradation of indicator condition.

As indicators move from identifying the impacts at the local protected area to understanding the pressures and environmental state at the wider catchment or even regional scale, it will be necessary to consider the influence of scale more explicitly. In some instances, indicators downstream or in adjacent catchments may inform protected areas condition e.g., deer density indicating pressures on neighbouring peatlands or downstream fish barriers impacting upstream adult migratory fish populations. The proposed framework should be supported by a system of spatial referencing that will allow either a rules-based assessment of indicator influence or a spatial modelling framework that can quantify these influences. For example, SEPA uses location codes for each monitoring point that have attributes associated with them that identify their relative locations on Scotland's river network. In such a system it is possible to identify all points hydrologically connected with one another and, through modelling, predict for other parts of the catchment/water network e.g. juvenile salmon (NEPS) or water temperature (SRTMN). These tools can also be used to predict the potential gain from undertaking a management action such as barrier removal for salmon (Buddendorf *et al*. 2019).

In some instances, the pressures themselves can be indicators, in which case there is likely to be a one-to-one relationship e.g. hydromorphological alteration to a river channel for agricultural drainage. In other instances, the state of an indicator may pick up influences from multiple potential pressures e.g. the pH of a large river may pick up pressures from forestry operations, peat degradation, effluent discharges, atmospheric deposition etc. This requires a balance to be struck when choosing appropriate indicators. There are benefits to be had in using holistic indicators that assess overall ecosystem structure and function (high strength of evidence) but some of this benefit may be lost if they do not contribute to identifying the causes of degradation.

6.5 Using the framework to inform the management of protected areas

A multi-index assessment framework as described would provide an assessment of site condition and the uncertainty associated with this assessment. After an initial assessment, it may be felt that there is insufficient confidence to warrant a management intervention. At this point there are some options.

In the early stages of transitioning to this evidence framework it may be that investigating additional or alternative indicators with high evidence strength and lower uncertainty could increase confidence, for example, the application of eDNA techniques. Over time though, it is anticipated that indicator suites for each habitat type will become more robust and will only change when new technologies or assessment methods are developed. If an existing indicator has low uncertainty but data have not been collected for a long time and the strength of evidence has diminished, then an updated assessment of this indicator would increase its contribution to reducing overall uncertainty.

Confidence in the assessment is key to taking action. Initially, this would be determined by a mixture of established assessments of uncertainty and, where not available, expert opinion. The confidence assessment would form a key part of choosing the monitoring effort required to deliver healthy ecosystems. The confidence will provide a framing for how well the suite of indicators inform both causes and status of ecosystem health within a particular site assessment. If level of confidence is high, then informed management decision can be undertaken. Low levels of confidence will require decisions to be taken on further monitoring and analysis to improve confidence levels.

The information on pressures identified in the conceptual modelling and attributed to each indicator will be retained throughout the process of determining the multi-index ecosystem assessment. If an ecosystem is judged to be unhealthy, the assessment will provide valuable information on the likely causes of degradation. The example framework detailed in Appendix B demonstrates a method for ranking the likely causes of degradation for each site assessment. This information will assist in prioritising management actions most likely to deliver healthy ecosystems.

The proposed assessment framework will provide a structure that will draw in diverse data sets from a range of ecosystem monitoring partners to generate an assessment of site condition and information on the key pressures. It is anticipated this framework can be incorporated into the platform being developed by NatureScot. The platform is expected to have the capacity to incorporate and recombine data from alternate sources to deliver the:

- flexible configuration of monitoring instances
- addition of novel attributes and targets
- setting of targets at multiple scales
- integration with a wider range of data sources
- development of intelligent prioritisation protocols
- efficient resource allocation
- system-level analysis, including pressures, confidence and data insights

With these capabilities the new system will facilitate the evolution of NatureScot's current approach towards monitoring. While the system itself may have the capabilities for data assimilation and interpolation, decision making requires an understanding of the hierarchical nature of data collected and the specific pressures that are influencing protected areas. This will require understanding the ecosystem functions of each habitat type and how they relate to the conservation of designated features.

7 Key Findings and Recommendations

Overall, the review of the current SCM method for freshwater and wetlands has shown that there are many specific tools and techniques, and examples of potential frameworks to sit them within, that can be deployed by NatureScot in transitioning towards developing a healthy ecosystem approach to monitoring and conserving biodiversity assets. These have been highlighted through the literature review, stakeholder interviews and collaborative workshop.

A set of ecosystem monitoring approaches have been explored through the project, and the recommendations that have followed aim to shift the emphasis of site condition monitoring of freshwaters and wetlands onto informing the management that will deliver healthy ecosystems. This will require a shift in operational procedures and initially expert interpretation and support in developing the data integration and interpretation platform and in field monitoring methodologies (see Figure 10 – Roadmap).

7.1 Opportunities

From the stakeholder workshop, there was a large degree of validation of, and suggestions on how to achieve, many of the 10 monitoring principles put forward by NatureScot (described in Appendix A). Opportunities to assist in the transition towards a refined and modified monitoring system based on using DPSIR approach are positioned within seven themes identified and described in the workshop report (Appendix D, Table D.2).

In relation to the first three monitoring principles, there was strong agreement among stakeholders that protected area monitoring should prioritise informing management and incorporate the wider landscape. It was also agreed that a hierarchy of monitoring scales with a combination of rapid and more detailed assessments, could deliver a comprehensive and scalable approach to monitoring healthy ecosystems. This could provide a better understanding of influences on ecosystems by linking landscape, catchment and site-level data that in turn would inform protected area management, OECMs or Protected Conservation Areas (PCAs).

PCAs and OECMs are among the most important conservation tools available in conjunction with new (or revamped) technologies, partnerships and strategic data sharing collaborations to transform NatureScot’s monitoring approach. There are potential beneficial activities, data sets and monitoring currently undertaken by other agencies, organisations and citizens that could complement the current SCM methodology. These wider datasets, including information on the drivers and pressures that lead to changes in site condition, could be harnessed to support monitoring ecosystem health.

By strengthening existing and developing new partnerships to deliver collaborative monitoring and data sharing, and by harnessing new technologies (e.g., eDNA and remote sensing), there is the potential to increase data richness, reduce redundancies and optimise resource use. With the addition of automation and citizen science there could be an expansion of monitoring capacity and, at the same time, enhance a sense of stakeholder ownership (Principles 5 and 6, See Appendix D Table D.2 for details). Data sharing would also give access to monitoring that captures long-term trends and risks such as those data collected as part of the UK Environmental Change Network (https://ecn.ac.uk). This would help discriminate between local and global threats at different levels of severity. In addition, focussed long-term monitoring post-intervention, even if just at sentinel sites, could ensure adaptive management feedback loops are based upon sound evidence (Principles 4 and 7).

7.2 Key Challenges

The potential challenges and barriers that may need to be overcome in transitioning towards a refined and modified ecosystem monitoring system based on using DPSIR approach are positioned within seven themes identified and described in the workshop report (Appendix D Table D.2). Firstly, and perhaps most fundamentally, there are the risks created by introducing any significant change to an approach whilst it is still in use. Whilst there are many ecosystem indicators that are well established and can be adopted with little additional development, there are others that will require more work to implement.

In some cases, changes in methodologies could lead to the risk of fragmented or incompatible datasets unless a period of parallel monitoring is undertaken. How significant a task this is, or how feasible it is, would likely depend upon the currency and frequency of existing monitoring.

Although data sharing and collaboration has been identified as a way of optimising resource use, prudence should be exercised in understanding the ease with which this integration/optimisation can occur. Different monitoring locations, data formats, frequencies, protocols and the requirement for data sharing agreements must form part of the cost-benefit and prioritisation considerations for a new monitoring approach.

Finally, a word of caution was associated with the expectation of a rapid shift in emphasis to wider, landscape-scale monitoring. This is highlighted in Table D.2, with concerns raised by stakeholders that the transitioning could lead to a neglect of site-specific needs, local stakeholder engagement or species-specific conservation goals, and a need to ensure that standards and guidelines are available for alternate data sources (e.g. citizen science) that will meet NatureScot's needs. Whilst this is not inevitable, it is a valid concern that should be addressed.

7.3 Recommendations

For NatureScot to transition from a feature-based monitoring programme to a broader landscape approach, there should be a consideration of the resources, policy and legislative implications anticipated during and after the transition period. There is a need to address the potential for immediate gains, as well as the medium to longer term opportunities and challenges (Figure 10).

Short-term key steps are:

- Understand the indicator data availability, cost, type, format, granularity, temporal variability and access.
- Develop the skills to interpret and collate data.

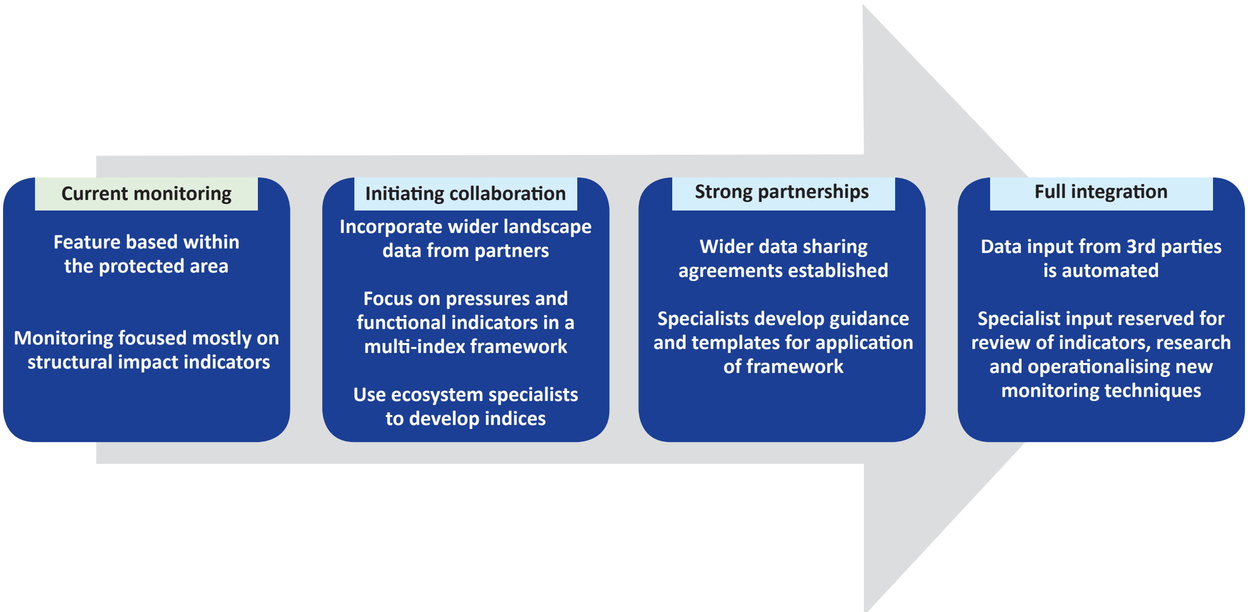

Figure 10. Roadmap for monitoring to inform the delivery of healthy freshwaters and wetlands in Scotland.

- Ensure the availability of expertise to conceptualise protected area ecosystems, develop modelling frameworks, interpret data and ensure confidence levels in data and outputs are well understood.
- Make resources available for the purchase of datasets, licencing software, digital spatial frameworks, integration software, in-field exploration, and for ground-truthing new monitoring techniques.

Medium-long term key steps are:

- Data sharing agreements and data source and differentiation issues need to be resolved
- Automate data input, cataloguing and integration from third parties.
- Retain specialist input to interpret indicators.
- Continue research into linking pressure indicators to ecosystem health.
- Operationalise new technologies and techniques as they are identified and adopted.

8 References

Abbott, K.C., Heggerud, C.M., Lai, Y.C., Morozov, A., Petrovskii, S., Cuddington, K. and Hastings, A. (2024). When and why ecological systems respond to the rate rather than the magnitude of environmental changes. *Biological Conservation*, 292, p.110494. DOI: 10.1016/j.biocon.2024.110494.

Australian Government (2024). Natural Resource Management Monitoring, Evaluation, Reporting and Improvement (MERI) Framework. Published online at https://www.dcceew.gov.au/environment/land/natural-heritage-trust/monitoring-reporting/meri [Last accessed 09/01/2025]

Boori, M. S. Choudhary, K. Paringer R. and Kupriyanov A. (2021). Ecosystem Health Assessment Based on Pressure State Response Framework Using Remote Sensing and Geographical Information System. *Earth and Environmental Science*, 767: 012038. DOI: 10.1088/1755-1315/767/1/012038

Bouleau, G. and Pont, D. (2015) Did you say reference conditions? Ecological and socio-economic perspectives on the European Water Framework Directive'. *Environmental Science and Policy*, 47: 32–41. DOI: 10.1016/j.envsci.2014.10.012.

Bruce, K., Blackman, R.C., Bourlat, S.J., Hellström, M., Bakker, J., Bista, I., Bohmann, K., Bouchez, A., Brys, R., Clark, K. and Elbrecht, V. (2021). *A practical guide to DNA-based methods for biodiversity assessment*. Pensoft Advanced Books. DOI: 10.3897/ab.e68634

Buddendorf, W.B., Jackson, F.L., Malcolm, I.A., Millidine, K.J., Geris, J., Wilkinson, M.E and Soulsby, C. (2019) Integration of juvenile habitat quality and river connectivity models to understand and prioritise the management of barriers for Atlantic salmon populations across spatial scales. *Science of The Total Environment*, 655: 557-566. DOI.org/10.1016/j.scitotenv.2018.11.263. https://www.sciencedirect.com/science/article/pii/S0048969718346199

Bunn, S.E., Abal, E.G., Smith, M.J., Choy, S.C., Fellow, C.S., Harch, B.D., Kennard, M.J. and Sheldon, F. (2010). Integration of science and monitoring of river ecosystem health to guide investments in catchment protection and rehabilitation. *Freshwater Biology*, 55: 223-240. DOI: 10.1111/j.1365-2427.2009.02375.x

Cairngorms National Park Authority, CNPA (2022). *Cairngorms National Park Partnership Plan 2022-2027*. Published online at https://cairngorms.co.uk/working-together/partnershipplan [Accessed 09/01/2025].

CBD (2022). *Post -2020 Global Biodiversity Framework*. Published online at https://www.cbd.int/doc/c/409e/19ae/369752b245f05e88f760aeb3/wg2020-05-l-02-en.pdf [Accessed 09/01/2025].

Certain, G. and Skarpaas, O. (2010). *Nature Index: General framework, statistical method and data collection for Norway.* NINA Report 542. 47 pp. Published online at http://hdl.handle.net/11250/2564901 [Accessed 09/01/2025].

Chen, Y. (2023). Spatial–temporal dynamics of grassland net primary productivity and its driving mechanisms in northern Shaanxi, China. *Agronomy*, 13(11): 2684. DOI: 10.3390/agronomy13112684

Cheung, W. (2024). Structural and functional indicators in freshwater ecosystem monitoring programs. *Ecological Management and Restoration*, 25(1): 3-13. DOI: 10.1111/emr.12599

Clapcott J, Young R, Sinner J, Wilcox M, Storey R, Quinn J, Daughney C, and Canning A. (2018). *Freshwater biophysical ecosystem health framework*. New Zealand Ministry for the Environment. Cawthron Report No. 3194. Published online at https://environment.govt.nz/assets/Publications/Files/freshwater-ecosystem-health-framework.pdf [Last accessed 09/01/2025].

Convention on Biological Diversity, CBD (2010). *2010 Biodiversity Target*. Published online at https://www.cbd.int/2010-target [Accessed 09/01/2025].

Costanza, R. (1992) Toward an operational definition of ecosystem health. In: Costanza, R., Norton, B.G. and Haskell, B.D. (Eds) *Ecosystem Health: New Goals for Environmental Management*, Island Press, Washington, 239–256 pp.

Dakos V, Carpenter SR, Brock WA, Ellison AM, Guttal V, Ives AR, *et al.,* (2012) Methods for Detecting Early Warnings of Critical Transitions in Time Series Illustrated Using Simulated Ecological Data. *PLoS ONE* 7(7): e41010. DOI: 10.1371/journal.pone.0041010

Dale, V.H. and Beyeler, S.C. (2001). Challenges in the development and use of ecological indicators. *Ecological indicators*, 1(1): 3-10. DOI: 10.1016/S1470-160X(01)00003-6

Davidson, L.P., Genney, D.R. and McGrory, S.M. (2024). *Monitoring to deliver healthy ecosystems in Scotland's protected areas, workshop feedback report, 2023*. NatureScot Research Report 1351. Published online at https://www.nature.scot/doc/naturescot-research-report-1351-monitoring-deliver-healthy-ecosystems-scotlands-protected-areas [Last accessed 09/01/2025]

Davy-Bowker, J., Murphy, J.F., Rutt, G.P., Steel, J., and Furse, M.T. (2005). The development and testing of a macroinvertebrate biotic index for detecting the impact of acidity on streams. *Archiv Fur Hydrobiologie*, 163: 383-403. DOI: 10.1127/0003-9136/2005/0163-0383.

Donangelo, R., Fort, H., Dakos, V., Scheffer, M., and Nes, E.H. (2010). Early Warnings for Catastrophic Shifts in Ecosystems: Comparison between Spatial and Temporal Indicators. *International Journal of Bifurcation and Chaos*, 20: 315-321. DOI: 10.1142/S0218127410025764

Ecosystem, Planning and Restoration, EPR (2022). *Stream Quantification Tool and Debit Calculator*. Published online at https://stream-mechanics.com/stream-quantification-tool/ [Last accessed 09/01/2025]

Elliott, M., O'Higgins, T.G. (2020). From DPSIR the DAPSI(W)R(M) Emerges… a Butterfly – 'protecting the natural stuff and delivering the human stuff'. In: O'Higgins, T., Lago, M., DeWitt, T. (eds) *Ecosystem-Based Management, Ecosystem Services and Aquatic Biodiversity*. Springer, Cham. DOI: 10.1007/978-3-030-45843-0_4

Environment Agency (2006). SIMCAT9.4 - *A Guide and Reference for Users*. Environment Agency of England and Wales

Erb, K.H. (2015). Land-Use Indicators. In Wright, J.D. (Ed.), *International Encyclopedia of the Social & Behavioral Sciences* (Second Edition) (pp. 238-244). Elsevier. DOI: 10.1016/B978-0-08-097086-8.91058-4

Extence, C.A., Chadd, R.P., England, J., Dunbar, M. J., Wood, P. J. and Taylor, E.D. (2013). The assessment of fine sediment accumulation in rivers using macro-invertebrate community response. *River Research and Applications*, 29(1): 17–55. DOI: 10.1002/rra.1569

Eyre, T.J., Fisher, A., Hunt, L.P.and Kutt, A.S. (2011). Measure it to better manage it: a biodiversity monitoring framework for the Australian rangelands. *The Rangeland Journal*, 33(3): 239–253. DOI: 10.1071/RJ10071

Fischenich, J.C. (2006). F*unctional Objectives for Stream Restoration, EMRRP Technical Notes Collection* (ERDC TN-EMRRP-SR-52). US Army Engineer Research and Development Center, Vicksburg, Mississippi. Published online at http://el.erdc.usace.army.mil/elpubs/pdf/sr52.pdf [Last accessed 09/01/2025].

Freshwater Habitats Trust (2024). Environmental DNA (eDNA). Published online at https://freshwaterhabitats.org.uk/advice-resources/survey-methods-hub/edna/ [Last accessed 09/01/2025].

Fu, S., Zhao, L., Qiao, Z., Sun, T., Sun, M., Hao, Y., Hu, S., & Zhang, Y. (2021). Development of Ecosystem Health Assessment (EHA) and Application Method: A Review. *Sustainability*, 13(21), 11838. https://doi.org/10.3390/su132111838

Govaert, L., Hendry, A. P., Fattahi, F., & Möst, M. (2024). Quantifying interspecific and intraspecific diversity effects on ecosystem functioning. *Ecology*, 105(1). https://doi.org/10.1002/ecy.4199.

Ham, K.D., Adams, S., and Peterson, M. (1997). Application of multiple bioindicators to differentiate spatial and temporal variability from the effects of contaminant exposure on fish. *Ecotoxicology and environmental safety*, 37(1): 53-61. DOI: 10.1006/eesa.1997.1522

Harman, W., R. Starr, M. Carter, K. Tweedy, M. Clemmons, K. Suggs, C. Miller. (2012). *A Function-Based Framework for Stream Assessment and Restoration Projects*. US Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Washington, DC EPA 843-K-12-006. Published online at https://www.epa.gov/sites/default/files/2015-08/documents/a_function_based_framework_for_stream_assessment_3.pdf [Last accessed 09/01/2025]

Harwell, M.A., Gentile, J.H., McKinney, L.D., Tunnell, J.W., Jr, Dennison, W.C., Kelsey, R.H., Stanzel, K.M., Stunz, G.W., Withers, K. and Tunnell, J. (2019). Conceptual Framework for Assessing Ecosystem Health. *Integrated environmental assessment and management*, 15: 544-564. DOI: 10.1002/ieam.4152

Holling, C. S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, 4: 1-23. http://www.jstor.org/stable/2096802

IPBES (2019). *Global Assessment Report on Biodiversity and Ecosystem Services*. Brondizio, E. S., Settele, J., Díaz, S., and Ngo, H.T. (eds). IPBES secretariat, Bonn. 1,148 pages. DOI: 10.5281/zenodo.3831673.

Jakobsson, S., Evju, M., Framstad, E., Imbert, A., Lyngstad, A., Sickel, H., Sverdrup-Thygeson, A., Töpper, J.P., Vandvik, V., Velle, L.G., Aarrestad, P.A. and Nybø, S. (2021). Introducing the index-based ecological condition assessment framework (IBECA), *Ecological Indicators*, 124: 107252. DOI: 10.1016/j.ecolind.2020.107252

JNCC (2004). *Common Standards Monitoring Guidance for Terrestrial Mammals*, Version August 2004, JNCC, Peterborough, ISSN 1743-8160. Published online at https://hub.jncc.gov.uk/assets/485b119e-ccb9-479f-b181-0904e212b434 [Last accessed 09/01/2025]

JNCC (2009). *Common Standards Monitoring Guidance for Upland Habitats*, Version July 2009, JNCC, Peterborough, ISSN 1743-8160. Published online at https://hub.jncc.gov.uk/assets/78aaef0b-00ef-461d-ba71-cf81a8c28fe3 [Last accessed 09/01/2025]

JNCC (2016). *Common Standards Monitoring Guidance for Freshwater Habitats*, Version 2016, JNCC, Peterborough. Published online at https://hub.jncc.gov.uk/assets/1b15dd18-48e3-4479-a168-79789216bc3d [Last accessed 09/01/2025]

Keeler, B.L., Polasky, S., Brauman, K.A., Johnson, K.A., Finlay, J.C., O'Neill, A., Kovacs, K., Dalzell, B.. (2012). Linking water quality and well-being for improved assessment and valuation of ecosystem services, *Proceedings National. Academy Science*. U.S.A. 109 (45): 18619-18624. DOI: 10.1073/pnas.1215991109 .

Kruse, M. (2019). Ecosystem Health Indicators. In: Fath, B. (ed). *Encyclopedia of Ecology*, 1: 404-414. Elsevier. ISBN 978-0-444-64130-4.

Large, S. I., Fay, G., Friedland, K. D., & Link, J. (2015). Critical points in ecosystem responses to fishing and environmental pressures. *Marine Ecology Progress Series*, 521, 1–17. https://doi.org/10.3354/meps11165

Leese, F., Bouchez, A., Abarenkov, K., Altermatt, F., Borja, Á., Bruce, K., Ekrem, T., Čiampor Jr, F., Čiamporová-Zaťovičová, Z., Costa, F.O. and Duarte, S. (2018). Why We Need Sustainable Networks Bridging Countries, Disciplines, Cultures and Generations for Aquatic Biomonitoring 2.0: A Perspective Derived from the DNAqua-Net COST Action. *Advances in ecological research*, 58: 63-99. DOI: 10.1016/bs.aecr.2018.01.001

Li, Z., Xu, D., & Guo, X. (2014). Remote Sensing of Ecosystem Health: Opportunities, Challenges, and Future Perspectives. *Sensors*, 14(11), 21117-21139. https://doi.org/10.3390/s141121117

Maes, J., Liquete, C., Teller, A., Erhard, M., Paracchini, Paracchini, M.L., Barredo, J.I., Grizzetti, B., Cardoso, A., Somma, F., Petersen, J.E. and Meiner, A. (2016). An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. *Ecosystem Services*, 17: 14-23. DOI: 10.1016/j.ecoser.2015.10.023

Maes, J., Teller, A., Erhard, M., Conde, S., Vallecillo, S., Barredo, J.I., Paracchini, M.L., Abdul Malak, D., Trombetti, M., Vigiak, O. and Zulian, G. (2020). *Mapping and assessment of ecosystems and their services: an EU wide ecosystem assessment in support of the EU biodiversity strategy*. Publications Office of the European Union, Luxembourg, JRC120383. DOI: 10.2760/757183.

Mainstone, C., Hall., R. and Diack, I. (2016). A narrative for conserving freshwater and wetland habitats in England. Natural England Research Reports, NERR064. Published online at https://publications.naturalengland.org.uk/publication/6524433387749376 [Last accessed 09/01/2025]

Marzin, A., Delaigue, O., Logez, M., Pont, D. (2014). Uncertainty associated with river health assessment in a varying environment: the case of a predictive fish-based index in France. *Ecological Indicators*, 43: 195–204. DOI: 10.1016/j.ecolind.2014.02.011

Millennium *Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Wetlands and Water Synthesis*. World Resources Institute, Washington, DC. Published online at: https://www.millenniumassessment.org/en/Synthesis.html [Last accessed 14/02/2025].

Moberg, T., Abell, R., Dudley, N., Harrison, I., Kang, S., Rocha Loures, F., Shahbol, N., Thieme, M., and Timmins, H. (2024). *Designing and managing protected and conserved areas to support inland water ecosystems and biodiversity*. IUCN WCPA Technical Guidance Series, No. 8. IUCN. DOI: 10.2305/ZOKC6253

NatureScot (2020). River South Esk Special Area of Conservation. Conservation Advice Package. Published online at https://www.nature.scot/sites/default/files/special-area-conservation/8364/conservation-advice-package.pdf [Last accessed 09/01/2025]

NatureScot (2024a). Looking to the future. Published online at https://www.nature.scot/professional-advice/protected-areas-and-species/protected-areas/site-condition-monitoring/looking-future [Last accessed 09/01/2025]

NatureScot (2024b). Protected Areas Monitoring Reform. Scientific Advisory committee Discussion Paper. SAC/2024/03/03. Published online at https://www.nature.scot/sites/default/files/2024-03/sac-2024-03-03-protected-areas-monitoring-reform-march-2024-a4462333.docx [Last accessed 09/01/2025]

NatureScot (2024c). Scotland's Natural Capital Asset Index. Published online at https://www.nature.scot/professional-advice/social-and-economic-benefits-nature/natural-capital/scotlands-natural-capital-asset-index [Last accessed 09/01/2025]

NatureScot (2025) River South Esk SAC Overview https://sitelink.nature.scot/site/8364 [Last accessed 09/02/2025]

Norwegian Institute for Nature Research (2024). The Norwegian Nature Index. Published online at https://www.nina.no/english/Biodiversity/The-Norwegian-Nature-Index [Last accessed 09/01/2025]

O'Brien, A., Townsend, K., Hale, R., Sharley, d. and Pettigrove, V. (2016) How is ecosystem health defined and measured? A critical review of freshwater and estuarine studies. *Ecological Indicators*, 69: 722-729. DOI: 10.1016/j.ecolind.2016.05.004

Oberdorff T., Pont D., Hugueny B., Porcher J.P. (2002) Development and validation of a fish-based index for the assessment of 'river health' in France. *Freshwater Biology*, 47(9): 1720 – 1734. DOI: 10.1046/j.1365-2427.2002.00884.x

Palmer, M.A., Bernhardt, E.S., Allan, J.D., Lake, P.S., Alexander, G., Brooks, S., Carr, J., Clayton, S., Dahm, C.N., Follstad Shah, J., Galat, D.L., Loss, S.G., Goodwin, P., Hart, D.D., Hassett, B., Jenkinson, R., Kondolf, G.M., Lave, R., Meyer, J.L., O'Donnell, T.K., Pagano, L. And Sudduth, E. (2005), Standards for ecologically successful river restoration. *Journal of Applied Ecology*, 42: 208-217. DOI: 10.1111/j.1365-2664.2005.01004.x

Patrício, J., Elliott, M., Mazik, K., Papadopoulou, K.N. and Smith, C.J. (2016). DPSIR - two decades of trying to develop a unifying framework for marine environmental management? *Frontiers in Marine Science*, 3: 177. DOI: 10.3389/fmars.2016.00177

Petersen, J., Leip, A., Koeble, R., Schroder, C., Mancosu, E. and King, S. (2020). *Methodological Proposal and Results for compiling EU-level Spatial Nutrient Condition Accounts*. EEA. Copenhagen.

Pettorelli, N., Laurance, W.F., O'Brien, T.G., Wegmann, M., Nagendra, H. And Turner, W. (2014). Satellite remote sensing for applied ecologists: opportunities and challenges. *Journal of Applied Ecology,* 51(4): 839–848. DOI: 10.1111/1365-2664.12261

Postel, S. (2003). Securing water for people, crops, and ecosystems: New mindset and new priorities. *Natural Resources Forum*. 27. 89-98. Balckwell Publishing. Oxford. UK.

Rapport, D. (1999). Epidemiology and ecosystem health: natural bridges. *Ecosystem Health*, 5(3): 174-180. DOI: 10.1046/j.1526-0992.1999.09927.x

Richter, B.D., Baumgartner, J.V., Powell, J. and Braun, D.P. (1996), A Method for Assessing Hydrologic Alteration within Ecosystems. *Conservation Biology,* 10: 1163-1174. DOI: 10.1046/j.1523-1739.1996.10041163.x

Saidi, N. and Spray, C. (2018). Ecosystem services bundles: challenges and opportunities for implementation and further research. *Environmental Research Letters*, 13: 113001. DOI: 10.1088/1748-9326/aae5e0

Scheffer, M., Carpenter, S., Foley, J.A., Folke, C., Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, 413(11): 591–596. DOI: 10.1038/35098000

Scottish Government (2020). Scottish biodiversity strategy post-2020: statement of intent. Published online at https://www.gov.scot/publications/scottish-biodiversity-strategy-post-2020-statement-intent/ [Last accessed 09/01/2025]

Scottish Government (2023). *Biodiversity strategy to 2045: tackling the nature emergency.* Published online at https://www.gov.scot/publications/scottish-biodiversity-strategy-2045-tackling-nature-emergency-scotland-2/ [Last accessed 09/01/2025]

Scottish Government (2024a). *Explore ecosystem health indicators*. Published online at https://www.environment.gov.scot/our-environment/state-of-the-environment-previous-reports/ecosystem-health-indicators/explore-ecosystem-health-indicators/ [Last accessed 09/01/2025]

Scottish Government (2024b). *Natural Capital Asset Index – Technical Background*. Published online at https://www.nature.scot/professional-advice/social-and-economic-benefits-nature/natural-capital/scotlands-natural-capital-asset-index/natural-capital-asset-index-technical [Last accessed 09/01/2025]

Simberloff, D. (1998). Flagships, umbrellas, and keystones: Is single-species management passé in the landscape era? *Biological Conservation*, 83(3): 247-257. DOI: 10.1016/S0006-3207(97)00081-5

Smeets, E. and Weterings, R. (1999) Environmental Indicators: Typology and Overview. Report No. 25, European Environment Agency, Copenhagen.

Smyth, A.K. and James, C.D. (2004). Characteristics of Australia's rangelands and key design issues for monitoring biodiversity. *Austral Ecology,* 29(1): 3-15. DOI: 10.1111/j.1442-9993.2004.01360.x

Society for Ecological Restoration, SER (2004). *The SER International Primer on Ecological Restoration*. SER International Science and Policy Working Group, Version 2. Published online at https://www.ctahr.hawaii.edu/littonc/PDFs/682_SERPrimer.pdf [Last accessed 09/01/2025].

Song, X. and Frostell, B. (2012). The DPSIR Framework and a Pressure-Oriented Water Quality Monitoring Approach to Ecological River Restoration. *Water*, 4: 670-682. DOI: 10.3390/w4030670.

Soubry, I., Doan, T., Chu, T., and Guo, X. (2021). A systematic review on the integration of remote sensing and GIS to forest and grassland ecosystem health attributes, indicators, and measures. *Remote Sensing*, 13(16): 3262. DOI: 10.3390/rs13163262

Sparrow, B. D., Edwards, W., Munroe, S. E. M., Wardle, G. M., Guerin, G. R., Bastin, J. F., Morris, B., Christensen, R., Phinn, S., and Lowe, A. J. (2020). Effective ecosystem monitoring requires a multi-scaled approach. *Biological Reviews*, 95(6): 1706-1719. DOI: 10.1111/brv.12636

State of Nature (2023). *State of nature report*. Published online at https://stateofnature.org.uk/ [Last accessed 09/01/2025]

Suresh, K., Tang, T., Van Vliet, M.T., Bierkens, M.F., Strokal, M., Sorger-Domenigg, F. and Wada, Y. (2023). Recent advancement in water quality indicators for eutrophication in global freshwater lakes. *Environmental Research Letters*, 18(6): p.063004. DOI: 10.1088/1748-9326/acd071

Tett, P., Gowen, R.J., Painting, S.J., Elliott, M., Forster, R.M., Mills, D.K., Bresnan, E., Capuzzo, E., Fernandes, T.F., Foden, J., Geider, R.J., Gilpin, L.C., Huxham, M., McQuatters-Gollop, A., Malcolm, S.J., Saux-Picart, S., Platt, T., Racault, M., Sathyendranath, S., Molen, J.V., & Wilkinson, M. (2013). Framework for understanding marine ecosystem health. *Marine Ecology Progress Series*, 494, 1-27. https://doi.org/10.3354/MEPS10539

Timmerman, J.G., Beinat, E., Termeer, C.J., and Cofino, W.P. (2011). Developing transboundary river basin monitoring programmes using the DPSIR indicator framework. *Journal of Environmental Monitoring*, 13(10): 2808-18. DOI: 10.1039/C1EM10092K

Udy, J., Fellows, C.S., Bartkow, M., Bunn, S.E., Clapcott, J., and Harch, B.D. (2006). Measures of Nutrient Processes as Indicators of Stream Ecosystem Health. *Hydrobiologia*, 572, 89-102. DOI 10.1007/s10750-005-9006-1

UK-SCAPE (2024). Environmental DNA (eDNA). Published online at https://uk-scape.ceh.ac.uk/our-science/projects/eDNA [Last accessed 09/01/2025]

UKTAG (2013). *Updated Recommendations on Environmental Standards River Basin Management (2015-21) Final Report November 2013*. Published online at https://www.wfduk.org/sites/default/files/Media/Environmental%20standards/UKTAG%20Environmental%20Standards%20Phase%203%20Final%20Report%2004112013.pdf [Last accessed 09/01/2025]

UNEP (2024). Data Reporting Tool for Multilateral Environmental Agreements - DaRT. Published online at https://dart.informea.org/ [Last accessed 09/01/2025]

Vadas, R.L., Hughes, R.M., Bae, Y.J., Baek, M.J., Gonzáles, O.C.B., Callisto, M., Carvalho, D.R.d., Chen, K., Ferreira, M.T., Fierro, P., Harding, J.S., Infante, D.M., Kleynhans, C.J., Macedo, D.R., Martins, I., Silva, N.M., Moya, N., Nichols, S.J., Pompeu, P.S., Ruaro, R., Silva, D.R.O., Stevenson, R.J., Terra, B.d.F., Thirion, C., Ticiani, D., Wang, L. and Yoder, C.O. (2022). Assemblage-based biomonitoring of freshwater ecosystem health via multimetric indices: A critical review and suggestions for improving their applicability. *Water Biology and Security,* 1(3): 100054. DOI: 10.1016/j.watbs.2022.100054.

van Andel, J. and Aronson, J. (Eds) (2006). *Restoration Ecology: The New Frontier*, First Edition. Malden MA, USA, Blackwell Publishing. ISBN: 978-1-444-33635-1

Walker, B., Holling, C. S., Carpenter, S. R., and Kinzig, A. (2004). Resilience, Adaptability and Transformability in Social–ecological Systems. *Ecology and Society*, 9(2): 5. http://www.jstor.org/stable/26267673

Walker, J. and Reuter, DJ. (1996). *Indicators of Catchment Health: Technical Perspective*. CSIRO Publishing. Collingwood. Victoria. Australia.174 pp.

WFD (2020). *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy*. Published online at https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A32000L0060 [Last accessed 09/01/2025]

Willby, N.J., Pitt, J.A., and Phillips, G.L. (2009). *The ecological classification of UK lakes using aquatic macrophytes for the implementation of the EU Water Framework Directive.* Environment Agency Report SC010080/R2. Published online at https://www.gov.uk/government/publications/the-ecological-classification-of-uk-lakes-using-aquatic-macrophytes [Last accessed 09/01/2025]

Wright, J.F., Furse, M.T. and Armitage, P.D. (1993). RIVPACS-a technique for evaluating the biological quality of rivers in the UK. *European Water Pollution Control*, 3(1):15-22. DOI: 10.1016/0145-2126(79)90004-3

9 Appendices

Appendix A – Principles for Monitoring to Inform the Delivery of Healthy Ecosystems

Table A.1: NatureScot's principles for revised SCM monitoring methodology to deliver healthy ecosystems (SAC, 2024; NatureScot, 2024a).	
Principle	**Description**
Principle 1: Prioritise information that informs management	Refocusing monitoring to prioritise collecting data on attributes that inform management action, but ensuring a sub-sample still measure 'response' or 'state'.
Principle 2: Adopt a site-based approach	NatureScot's current approach monitors features in isolation of each other. This can result in duplicated sampling of similar attributes and conflicting targets. To improve the efficiency NatureScot propose eliminating duplicate sampling by enabling a site-based approach.
Principle 3: Incorporate the wider landscape/seascape	NatureScot's existing monitoring results show that the most frequent and impactful pressures act at a landscape/seascape-scale. The new approach will gather certain information at a scape-scale to inform assessments of a site's health and management at the most effective scale.
Principle 4: Assess attributes on a scale	Currently, NatureScot employs a simplistic pass/fail system for assigning condition at a feature level. This principle proposes to use a gradient approach (which can also work at different scales) similar to that used in an energy performance certificate (EPC).
Principle 5: Make best use of existing data	The existing SCM approach has built-up 20-years of detailed feature assessment data. The proposed rationalising of the existing attribute set (as opposed to a completely new set of indicators) will enable ongoing comparison and ensuring our continued ability to meet feature-level reporting requirements
Principle 6: Incorporate innovative technology	New monitoring technologies are becoming more accessible due to increasing maturity and affordability and will offer significant opportunities. NatureScot will therefore explore ways of integrating new data collection methods into our national monitoring programme, e.g., EO, LiDAR, eDNA etc. This may include early adoption of less mature technologies, but with the ability to assign confidence levels (qualitatively and quantitatively) to that evidence.
Principle 7: Species monitoring considered in wider context of a species-monitoring framework	NatureScot currently monitor some species only within protected areas for which they are designated. However, many species populations are determined by larger scale processes. This is often reflected in the scale of regional and national monitoring programmes, with extracts used to inform within-site assessment. This principle explores whether the protected area scale is the most appropriate for all species that a site is notified for. It has been added in response to the important concern that the healthy ecosystem approach could result in a reduction in species monitoring on protected areas.
Principle 8: Validation against current approach	This principle helps address risks of rationalising attributes as proposed in the other principles. It emphasises the need for assurance that by primarily monitoring and informing responses to pressure and threats, NatureScot are also delivering the outcomes of the SBS, i.e. halting the loss of species and delivering functional and resilience ecosystems. Furthermore, it highlights the importance of calibrating the new approach to ensure continuity of the Official Statistic on Protected Areas.
Principle 9: Maintain ecological expertise and skills	This principle acknowledges the significance of nurturing in-house ecological skills and emphasises the value of site-visits for staff's understanding of those sites and the cultivation of relationships with landowners. This principle is borne out as a direct response to concerns about the loss of connection between staff and their sites alongside lower morale due to work being more desk-based.
Principle 10: Improved links with funding mechanisms	This principle acknowledges that the ability to implement effective management normally requires access to funding. Monitoring can help prioritise funding to support both on-site and wider landscape action.

Appendix B – A multi-index monitoring framework to inform the delivery of healthy ecosystems

The recommendation in this report is to take a multi-index approach to assessing ecosystem condition in protected areas. This can be achieved by developing a set of rules applied to ecosystem indicator attributes which result in a scaled assessment of ecosystem health combined with a level of confidence in this assessment. Each indicator can be assigned a set of scores representing the indicator's condition, uncertainty, and strength of evidence. An example of such a framework is set out in the following sections.

The approach presented here, that generates a numerical ecosystem health index score, should be considered illustrative only. There may be alternative ways for NatureScot to implement this multi-index framework in future.

B.1 Condition index (I_c)

The condition score expresses the observed indicator value in relation to that of a value expected within a healthy ecosystem. The expected value reflects an ecologically sustainable state for the indicator. Any type of indicator e.g. a pressure, state or impact metric, can be assigned a condition score provided there is a well-understood link between the metric and the sustainability of the relevant habitat's ecosystem health. Each condition value is then scaled to a dimensionless value ranging from 0 to 1 where 1 represents the expected reference value (or greater) and 0 is a completely degraded state. Exactly where the observed value sits on this scale will be indicator dependant and can be determined by existing guidance e.g. CSMG or WFD targets or through expert judgement. As use of the indicator evolves it is expected that expert judgement will be translated into more formal guidance. Where sufficient evidence exists, the reference condition for a given indicator may also vary regionally, between protected areas, between catchments or within catchments.

B.2 Uncertainty index (I_u)

The uncertainty score relates to the data used, the methods with which they are obtained and the degree of natural variability in the data. Monitoring-based data, model-based estimates and expert judgement may each have different levels of data uncertainty. In addition, those indicators measuring parameters with a high degree of natural variability or offsite effects (those with a high degree of distant connectivity out with the protected area boundary), may have higher uncertainty than those assessing a less dynamic metric. Some existing indicators will already have uncertainty scores associated with them whereas for others, this uncertainty will need to be estimated. As with the condition score, the uncertainty score is scaled from 0 to 1 where 0 reflects maximum uncertainty i.e. the indicator has no value in describing the condition score and 1 reflects 100% certainty in the condition score.

B.3 Strength of evidence index (I_s)

The strength of evidence index expresses the degree to which an indicator represents the current ecosystem health outcomes of the site. Some regional indicators such as changes in catchment land use or nutrient load may be helpful background indicators but, due to multiple intervening factors which may buffer or exacerbate the impact pathways, may provide weak evidence of impacts on a specific site. Other indicators where those impact pathways are more direct or where the indicator more directly measures ecosystem function within the site itself may been deemed to present a strong line of evidence for assessing ecosystem health. The strength of evidence score also incorporates a consideration of the currency of the assessment, with the strength of evidence diminishing as time between the most recent assessment and site condition reporting increases.

The strength of evidence index expresses the relative contribution the indicator plays to the overall understanding of ecosystem health provided by a suite of indicators identified for each habitat type. For each habitat type, the evidence provided by the full suite of indicators is assigned a value of 1. Each individual indicator's strength score will therefore lie in the range 0 to 1 and express the relative weight that indicator's condition should be given to assessing overall ecosystem condition (Figure B.1).

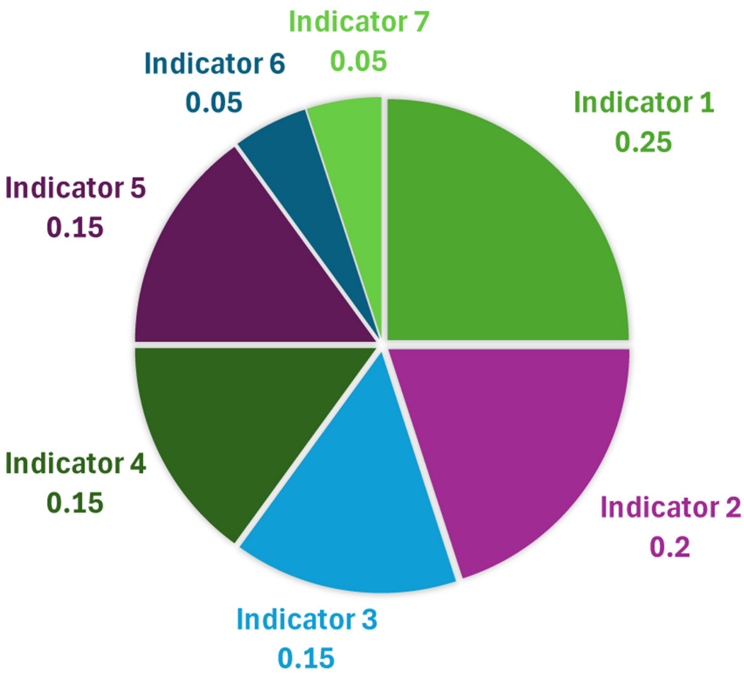

Figure B.1: A representation of the strength of evidence index for a suite of 7 ecosystem health indicators.

B.4 Combining indices into an assessment of ecosystem health

For monitoring to inform the delivery of healthy ecosystems, it should provide information on the current state of ecosystem health, the confidence in this assessment and an indication of which pressures are leading to any degradation. The recommendation of this project is to choose a suite of indicators for each habitat type that, in combination, can most effectively express the structure, function and resilience of the habitat's ecosystem. Each indicator is assigned a score related to its condition, uncertainty and strength of evidence, as outlined in sections 6.1 to 6.4. Overall ecosystem condition and associated uncertainty in this condition assessment is then calculated using a weighted average, where the weight of each indicator score is determined by the strength of evidence.

For example, we can imagine the 7 indicators presented in Figure 1 have been assessed and the resultant ecosystem condition and uncertainty indices have been recorded. The sum of all condition indices (Ic) multiplied by their associated strength of evidence indices (Is) will produce the overall ecosystem health index (*EHI*) (Eq.1).

$$EHI = \sum_{i=1}^{i=n} \mathrm{Ic}_i.\mathrm{Is}_i \; (Eq.1)$$

Where, *EHI* is the ecosystem health index, and *n* is the number of indicators (*i*).

The uncertainty associated with the *EHI* can be represented by the sum of all uncertainty indices (I_u) multiplied by their associated strength of evidence indices (I_s) (Eq.2).

$$U = \sum_{i=1}^{i=n} \mathrm{I}u_i.\mathrm{Is}_i \; (Eq.2)$$

An example of the calculation of the Ecosystem Health Index is shown in Table B.1.

Although two of the indicators (6 and 7) would suggest that ecosystem condition is close to reference conditions (condition indices = 0.9), these have little influence on the overall assessment ecosystem health index (0.5). This is because those indices have been identified as having a low strength of evidence (0.05 respectively). Looking at the uncertainty associated with the Ecosystem Health Index (Table B.1) there is a high level of confidence that can be attached to the overall assessment (uncertainty value of 0.7). This is because those indicators which were deemed to provide the strongest evidence (indicators 1 and 2) also had low uncertainty (0.9 and 0.8 respectively) and these contributed more to the assessment of confidence than the weaker indicators 6 and 7.

Table B.1 An example illustrating the calculation of the Ecosystem Health Index and associated uncertainty.					
Indicator number	**Condition index (I_c)** (0 = totally degraded, 1 = reference condition)	**Uncertainty index (I_u)** (0 = maximum uncertainty 1 = maximum certainty)	**Strength of evidence index (I_s)** (indices add up to 1)	**Ecosystem health index** (sum of I_c weighted by I_s)	**Uncertainty** (sum of I_u weighted by I_s)
1	0.4	0.8	0.25	0.5	0.7
2	0.5	0.9	0.2		
3	0.7	0.5	0.15		
4	0.3	0.4	0.15		
5	0.6	0.5	0.15		
6	0.9	0.3	0.05		
7	0.9	0.3	0.05		

B.5 Using the framework to inform the management of protected areas.

The ecosystem health index provides an assessment of site condition, and the uncertainty associated with this assessment. After an initial assessment, it may be felt that there is insufficient confidence to warrant a management intervention. At this point there are some options.

In the early stages of transitioning to this evidence framework it may be that investigating additional or alternative indicators with high evidence strength and lower uncertainty could increase confidence, for example, the application of eDNA or remote sensing techniques. Over time though, it is anticipated that indicator suites for each habitat type will settle down and will only change when new technologies or assessment methods are developed.

If an existing indicator has low uncertainty but data have not been collected for a long time and the strength of evidence index has diminished, then an updated assessment of this indicator would increase its contribution to reducing the overall uncertainty.

Assuming the required level of confidence in the assessment has been achieved, the evidence framework can be used to identity the most likely causes of degradation since each indicator is associated to a pressure or pressures. Again, the strength of evidence index is used here to weight the contributions of each indicator and, by association, each pressure, to the level of degradation.

It is helpful to express the contribution of each pressure in terms of the degree to which it degrades an ecosystem. An idealised pristine ecosystem where all indicators achieve their reference values would result in an ecosystem health index of 1. Degradation is therefore expressed as the condition index (I_c) – 1 e.g. a condition score of 0.7 would result in a degradation value of -0.3.

To understand the overall contribution of a pressure to an ecosystem failing to achieve reference conditions, each pressure is assigned a degradation value that expresses the weighted degradation across all indicators (D_p) (Eq.3).

$$D_n = \sum_{i=1}^{i=n} \frac{(Ic_i - 1).Is_i\,a}{k} \quad (Eq.3)$$

Where, D_n is a weighted measure of degradation due to a pressure; α is either 1 or 0 depending upon whether pressure p is associate with the indicator (i) or not; and k is the total number of pressures associated with each indicator (i).

B.6 Testing the framework

This framework has been applied to 2 protected areas using, where possible, real data to inform indicator index values. This testing is designed to be as realistic as possible but must be interpreted as indicative only given that condition, uncertainty and strength of evidence indices have yet to be developed for all indicators. For those indicators that have no existing rules to apply to their condition assessment it has been necessary to apply a best estimate approach to condition indices from the available data.

Some indicators used in this test are those collected as part of SEPA's water body ecological status classification to meet the requirements of the Water Framework Directive. This classification uses quality elements that inform on the ecological condition of the biological, chemical and hydromorphological aspects of the water environment. Typically, a score is derived from measured or modelled quality elements that relates the assessed condition to a reference condition such as an observed over expected (O/E) macroinvertebrate score or a % deviation of flow from a natural condition. For the purposes of the Water Framework Directive, these continuous data are classified into ordinal data (High, Good, Moderate, Poor or Bad status). The method proposed here requires the use of continuous data and, as such, would use SEPA's underlying quality element assessment data rather than the status classes. For the purposes of this test, it has not been possible to obtain these underlying data and therefore the ecological status class has been used as indicative of these data values in the form: High status represents a condition index of 1, Good represents 0.8, Moderate represents 0.6, Poor represents 0.4 and Bad represents 0.2

The association of key pressures with indicators have been included using a best estimate to test the framework. Again, these should be considered indicative.

For each site the results of applying the assessment framework are compared with NatureScot's existing site condition monitoring results and the pressures identified causing any impacts.

Table B.2: Site condition monitoring results for the river South Esk.

Feature	Condition	Assessment year	Pressures
FWPM*	Unfavourable declining	2013	Invasive species, Water management Wildlife crime
Atlantic salmon	Unfavourable recovering	2011	Agricultural operations Climate Change Forestry operations Invasive species Over grazing Water management Water quality

* FWPM - Freshwater pearl mussels

The current site condition monitoring uses indicators identified in the CSMG guidance for Atlantic Salmon, FWPM and river habitats. Each indicator has been assessed in this project in terms of the scale of habitat to which it applies along with the main DPSIR category it is associated with (Table B.3).

Table B.3: Current SCM indicators for the river South Esk and their associated spatial scale and main DPSIR category.

Indicator	Scale	Status	Main DPSIR category
Non-native species	Catchment	CSMG mandatory for Rivers	State
Flow regime (high, medium and low flows)	Catchment	CSMG mandatory for Rivers	State
Juvenile salmonid densities	Sub-catchment	CSMG mandatory for FWPM and Salmon	Impact
Adult salmonid densities	Sub-catchment	CSMG mandatory for Salmon	Impact
Filamentous algae	Sub-catchment	CSMG mandatory for Rivers	State
Fine sediment (redox and PSI)	Sub-catchment	CSMG mandatory for Rivers	State
Habitat structure (River Habitat Survey)	Sub-catchment	CSMG mandatory for Rivers	State
Organic pollution	Sub-catchment	CSMG mandatory for Rivers	State
Reactive phosphorus	Sub-catchment	CSMG mandatory for Rivers	State
Trophic Diatom Index	Sub-catchment	CSMG mandatory for Rivers	State
Other pollutants	Sub-catchment	CSMG mandatory for Rivers	State
Acidification	Sub-catchment	CSMG mandatory for Rivers	State
Salmon Exploitation	Sub-catchment	CSMG mandatory for Salmon	Pressure
FWPM Population density	Reach	CSMG mandatory for FWPM	Impact
FWPM Age structure	Reach	CSMG mandatory for FWPM	Impact
FWPM % Dead shells	Reach	CSMG mandatory for FWPM	Impact
Weed-cutting	Reach	CSMG mandatory for Salmon	Pressure

B.6.1. Example 1. The River South Esk Special Area of Conservation (NatureScot site code 8364)

The River South Esk Special Area of Conservation (SAC) has 2 qualifying features for which the site is designated: Freshwater pearl mussel *(Margaritifera margaritifera)* and Atlantic salmon *(Salmo salar)*. The results of the latest site condition monitoring are shown in Table B.2.

Section 6.3 of the main report details the recommended process for choosing indicators to monitoring ecosystem health and identifies alternative potential indicators that could be usefully employed in this catchment to help deliver a healthy ecosystem. In order to compare the framework results with existing SCM results on the South Esk SAC, only those indicators and their associated condition values available from publicly accessible datasets and reports have been applied. The results of this test are shown in Table B.4.

Table B.4: The application of the assessment framework on the river South Esk.

Indicator	Assessment year	Associated pressure(s)	Condition index (I_c)•	Uncertainty index (I_u)	Strength of evidence index (I_s)	Ecosystem health index	Uncertainty
SEPA WFD[+] fish assessment	2022	Diffuse pollution, climate change, water abstraction	0.4	0.6	0.05	0.54	0.7
Marine Directorate juvenile salmon NEPS[*] assessment	2021	Diffuse pollution, climate change, water abstraction	0.5	0.8	0.1		
SEPA WFD hydromorphology (RIVER MImAS % capacity used)	2023	Agricultural drainage	0.4	0.6	0.2		
SEPA WFD % flow deviation at low flows	2023	Water abstraction	0.6	0.5	0.25		
SEPA WFD % flow deviation at high flows	2023	Flow regulation	0.8	0.8	0.05		
SEPA WFD Macroinverts RiCT/WHPT O/E ratio	2023	Diffuse pollution	0.6	0.8	0.1		
SEPA WFD phytobenthos	2023	Diffuse pollution	0.6	0.8	0.1		
NBN atlas Himalayan Balsam	2018	Alien species	0.4	0.7	0.1		
SRTMN[†] Water temperature management priority score	2018	Climate change Riparian vegetation loss	0.8	0.7	0.05		

+ WFD – Water Framework Directive

* NEPS - National Electrofishing Programme for Scotland conducted by Marine Scotland Science

† SRTMN - Scotland River Temperature Monitoring Network

In this example, the ecosystem health index of 0.58 would indicate the site has a degree of degradation that would be consistent with unfavourable condition. An uncertainty value of 0.7 indicates that a confidence in this assessment is moderate to high and, depending upon the restoration options available, may be sufficient to warrant management intervention.

By evaluating the degree of degradation associated with each pressure, the assessment can inform which measures may have the greatest benefit to delivering a healthy ecosystem in the South Esk. The key pressures contributing to degradation of ecosystem health in this catchment are agricultural drainage, water abstraction and diffuse pollution (Table B.5).

B.6.2 Example 2. Caenlochan SAC (NatureScot site code 8216)

Caenlochan SAC has 2 freshwater and wetland qualifying features for which the site is designated: Base-rich fens and Blanket bog. The results of the latest site condition monitoring are shown in Table B.6.

The proposed assessment framework has been applied using indicators and their associated condition values available from publicly accessible data sets and reports and results are shown in Table B-7. To test the sensitivity of results to the inclusion of additional indicators with high strength of evidence, vegetation surveys and dipwell water levels taken across the 2 habitat types have been included with hypothetical survey results.

Table B.5: Degradation values of pressures identified in the river South Esk SAC.

Pressure	Degradation value
Agricultural drainage	-0.12
Water abstraction	-0.12
Diffuse pollution	-0.11
Flow regulation	-0.05
Alien species	-0.03
Climate change	-0.02
Riparian vegetation loss	-0.01

Using the proposed framework with existing available data gives a health index score of 0.62 showing a significant degradation from pristine condition that could be consistent with unfavourable condition. An uncertainty score of 0.7 indicates that, for the indicators chosen, there is a reasonable degree of confidence in the result. The addition of 2 high strength indicators (vegetation survey and water levels) with low (hypothetical) condition scores demonstrates the influence indicator choice can have on the assessment dropping the ecosystem health index to 0.45.

The analysis of degradation scores for each pressure, deer management and active drainage are indicated as being the key pressures. With the addition of vegetation surveys and water levels these remain the key pressures (Table B.8). Burning was not identified as a pressure using the initial choice of indicators but with the inclusion of a vegetation survey it has been identified a contributory factor.

Table B.6: Site condition monitoring results for Caenlochan.

Feature	Condition	Assessment year	Pressures
Base-rich fens	Unfavourable No change	2018	Over grazing and trampling by deer
Blanket bog	Unfavourable No change	2018	Over grazing and trampling by deer Burning

Table B.7 The application of the assessment framework on Caenlochan SAC. Note the final 2 indicators in brackets are hypothetical and have been used to assess the sensitvity of results Ecosystme helath index and uncertainty shown in brackets.							
Indicator	**Assessment year**	**Associated pressure(s)**	**Condition index (I_c)•**	**Uncertainty index (I_u)**	**Strength of evidence index (I_s)**	**Ecosystem health index**	**Uncertainty**
CNPA* % Eroded peat	2022	Deer management, active drainage	0.3	0.7	0.1	0.62 (0.45)	0.71 (0.76)
CNPA % Drained peat	2022	Active drainage	0.5	0.7	0.1		
Sentinel 2 % Bare peat	2023	Deer management, active drainage	0.3	0.7	0.15		
NatureScot Deer density	2023	Deer management	0.5	0.7	0.1		
Outflow water body pH	2023	Forestry, active drainage, deer management, climate change	0.8	0.8	0.05		
Outflow water body TOC	2023	Forestry, active drainage, deer management, climate change	0.8	0.8	0.05		
(Vegetation survey)	2024	Deer management, burning, active drainage, climate change	0.4	0.8	0.2		
(Dipwell water levels)	2024	Active drainage, deer management, climate change	0.4	0.9	0.25		
SRTMN† Water temperature management priority score	2018	Climate change Riparian vegetation loss	0.8	0.7	0.05		

* CNPA – Cairngorm National Park Authority

Table B.8: Degradation values of pressures identified in Caenlochan SAC.		
Pressure	**Degradation value**	**Degradation value with additional indicators**
Deer management	-0.22	-0.22
Active drainage	-0.27	-0.22
Climate change	-0.01	-0.09
Forestry	-0.01	-0.01
Burning	N/A	-0.03

Appendix C – Literature Review Report

The overall aim of this project is to review and make recommendations on what metrics to measure, to support the effective delivery of ecosystem health for Scotland's protected fresh waters and wetlands. There are 6 key questions set out within this project. This literature review addresses the first 2 of these which are:

1. Define 'ecosystem health' in the specific context of Scotland's freshwater and wetland protected areas.
2. What are the key issues that need to be acted on to deliver healthy ecosystems and (building from Site Condition Monitoring) what must be measured to facilitate this?

These will contribute to prioritising informed management decision making key research 6.

C.1 What is ecosystem health?

Ecosystem health is a metaphor used to portray the condition and functionality of a system of ecological processes. Using the analogue of 'health' has the benefit of being easily understood by a wide audience since we intuitively understand the concepts of good or poor health from our own experiences. Yet when applied to ecosystems, there is no universally agreed definition. This is largely because the term tries to encapsulate the complexity of human-environmental systems, and the diverse range of environmental pressures which impact the supply of ecosystem services necessary for environmental and human wellbeing (Kruse, 2019).

In some instances, the assessment of ecosystem health relates the current condition of the system to a reference pristine or natural condition appropriate to its ecological state of development (e.g. van Andel and Aronson, 2006; Mainstone *et al.,* 2016) in the same way that human health might be assessed against a reference "healthy" range of indicators such as blood pressure. In other uses it identifies how well a management objective is achieved such as maximising the production of a set of ecosystem services (e.g. Keeler *et al.,* 2012; Postel, 2003). The corollary in human health might be that of assessing the ability to perform a physical or mental task. Alternatively, ecosystem health assessments might more directly consider structure and function through habitat connectivity, food webs and, intra- and interspecies diversity (e.g. SER, 2004; Govaert *et al.,* 2024). Here we might compare this assessment to that of a blood test, or an analysis of the gut biome, as indicators of healthy functioning immunity or metabolism.

What links these different approaches to defining the health of an ecosystem? Costanza (1992) argues that these concept definitions represent "pieces of the puzzle", but that a comprehensive definition should, at its highest level, observe that a healthy ecosystem is one which can maintain its structure and function over time in the face of external stress. Although many studies of freshwater ecosystem health fail to define the term (O'Brien *et al.,* 2016), for those that do, this overarching definition has been adopted widely (e.g. Fu, 2021; Tett 2013). The definition is applicable to any complex system in that it is comprehensive and multiscale and allows for the fact that systems may be growing and developing as a result of natural or anthropogenic influences (Costanza, 1992). The definition recognises that ecosystems adjust over time in response to environmental conditions. By incorporating the attribute of resilience, it also implies that a healthy ecosystem need not be devoid of pressures altogether, but it does require that the vigour and organisation of the ecosystem is such that the system is able to maintain its function over time under the action of these pressures.

Walker *et al.* (2004) frame, the definition of the resilience of systems, by recognising that systems are dynamic and operate in a "state space" that is defined by the 'current values' they exhibit at any point in time. Ecosystems respond to pressures, disturbances and actors that shape the response of systems, its resilience, adaptability and transformability. Within a notional multi-dimensional landscape that encompasses all possible combinations of the variables that constitute the system (e.g. water quality and hydraulics) thus sustainability and management strategies will need to be context dependent, with a knowledge and understanding of local and regional attributes of the system being monitored (Walker *et al* 2004). Including projections of adaptability, resilience and transferability of the ecosystem of interest, if appropriate monitoring is to be applied, and informed management decision-making is to be undertaken.

Palmer *et al.* (2005) recognised resilience in their approach to assessing river habitat restoration. They identify the endpoint of a successful restoration project as one where the habitat has reached the least degraded and most ecologically dynamic state possible given the regional context. Again, recalling the concepts of health in relation to a reference condition, they define an ecologically dynamic state as one in which biota vary in abundance and composition, and channel morphology changes in response to flow variability, as they would do in appropriate reference systems.

Seen through these definitions, we may consider a healthy ecosystem not as one fixed in a stable parameter space and devoid of all pressures, but rather an open system, varying under constant disturbance, that can maintain its vigour, organisation and function over time through its property of resilience. Utilising an ecosystem approach to resource condition monitoring relies on understanding the interconnectedness of these systems in the management of land, water and living resources (CBD, 2010).

Box C.1: Ecosystem Health Definition

A definition of ecosystem health.

'Ecosystem health is a measure of the capacity of an ecosystem to maintain its structure and function over time in the face of external stress.

In the context of freshwater and wetland protected areas restoration in Scotland, healthy ecosystems are defined as having reached the least degraded and most ecologically dynamic state possible.

C.2 Indicators of ecosystem health

It is one thing to define ecosystem health but quite another to determine how to assess good or bad health or some condition in between. A definition that points to incorporating the elements of structure, function and resilience, once applied to biotic, abiotic features and potentially ecosystem services, across a range of habitat types, yields a myriad of monitoring and assessment options. Assessing ecosystem health will extend beyond observing individual components; by necessity it involves understanding the interconnectedness of various elements and their impact on overall ecosystem function, resilience and wellbeing (Rapport, 1999).

A review by Dale and Beyeler (2001) of studies of ecosystem health indicators concluded that the use of ecological indicators was often hampered by the fact that monitoring programmes often depended upon a small number of indicators that failed to consider the full complexity of the ecological systems. The challenge then is to find the optimum mix of metrics to encompass this complexity and provide the key information to understand the structure and functions of an ecosystem whilst not relying on an unsustainable level of resource to collect and analyse these data. A further challenge is to ensure that indicators of ecosystem health inform actions to restore health where required. The rationale behind this project is that the urgency to halt biodiversity loss dictates that indicators of health must promote prompt restoration actions. This requires them to give a clear indication of not only the state of the ecosystem but also the pressures that are acting upon them from both within the protected area site and the wider landscape. The monitoring framing should also inform management decision-making and actions to deliver timely interventions.

In this review of indicators, we first consider how they are used to assess the condition of ecosystem health within freshwater environments and examine how the current site condition monitoring in Scotland makes use of them. We then go on to consider what additional metrics may be available to better understand the specific pressures acting upon them.

C.3 Overview of quantitative site indicators used to assess ecosystem structure and function

C.3.1 Biological Indicators

Arguably, biological indicators can be more meaningful to land managers and the public than chemical and physical indicators when it comes to understanding the condition of a protected ecosystem (Vadas *et al.,* 2022), particularly when the indicator relates to the species or assemblages identified as a feature in the site designation.

The presence, absence or abundance of a specific species can serve as an indicator of both ecosystem structure and function if they are sensitive to stressors seen as relevant in the landscape, or if they are keystone species that play essential roles in ecosystem processes (Simberloff ,1998). An invasive or non-native species (particularly INNS) that can create severe dysfunctionality or changed structure of system is of particular note in determining ecosystem health and sustainability.

For example, otters are identified as "an indicator of the quality of wetlands and waterways" (JNCC, 2004). Other biological indicators sample more widely and may target the assessment of species richness and diversity, population structure, the condition of functional groups or guilds, the structure of food webs or the composition of assemblages that might indicate a particular pressure type such as water quality.

In the UK, the environment agencies use several biological indices as functional ecosystem indicators to monitor ecosystem health and identify the stressors acting upon them. Examples include the Lake Macrophyte Nutrient Index (LMNI) (Willby *et al.,* 2009) and the Proportion of Sediment-sensitive Invertebrates Index (PSI) (Extence *et al.,* 2013).

C.3.2 Chemical Indicators

Water quality parameters like nutrient concentrations and dissolved oxygen levels can provide information on the state of the water environment that can be used to infer impacts upon the biotic elements of ecosystems. For example, based upon a comparison of wetland condition along a gradient of groundwater nutrient concentrations the UK Technical Advisory Group for the WFD have published threshold nitrate values to indicate a risk of wetlands not meeting good ecological status (UKTAG, 2013).

C.3.3 Physical Indicators

These indicators assess the local, or wider landscape, physical conditions and processes that influence the health of the water environment. They can include flow characteristics (e.g. riffles), turbidity and water temperature which can indicate whether corresponding physical and chemical elements of the water environment such as wetted widths, stream power and dissolved oxygen are conducive to a healthy functioning aquatic ecosystem. An example would be the Indicators of Hydrologic Alteration (Richter *et al.,* 1996). These are a suite of 32 parameters, derived by a tool analysing a flow time series, that represent ecologically significant flow features of surface and groundwater regimes influencing freshwater, wetland and riparian ecosystems.

C.3.4 Indicators of ecosystem processes

Measures of processes such as Gross Primary Productivity (GPP) and nutrient cycling can provide insights into the functioning and resilience of ecosystems. Due to their integrative nature, they can be efficient indicators of disturbance gradients and have been shown to have strong causal links with particular state variables such as water quality (Bunn *et al.,* 2010; Udy *et al.,* 2006).

C.4 Indicators used in current site condition monitoring

The current SCM in freshwaters and wetland protected areas in Scotland makes use of Common Standards Monitoring Guidance (CSMG) produced for each of the key habitat types as well as for freshwater fauna (JNCC, 2016). The guidance documents set out the attributes to be monitored and the targets to be met to meet favourable condition within the feature. They also set out the monitoring approaches to make these assessments. Where monitoring of attributes is carried out by the relevant environment agencies for the purposes of WFD classifications, the guidance advises using these, although different standards may apply for conservation and WFD objectives.

The CSMG for freshwater and wetland habitats prioritises biological, physical and chemical metrics. For example, the guidance for rivers identifies 13 universally mandatory and 6 typology-dependent targets covering flow, water quality, habitat structure, sediment and biological parameters.

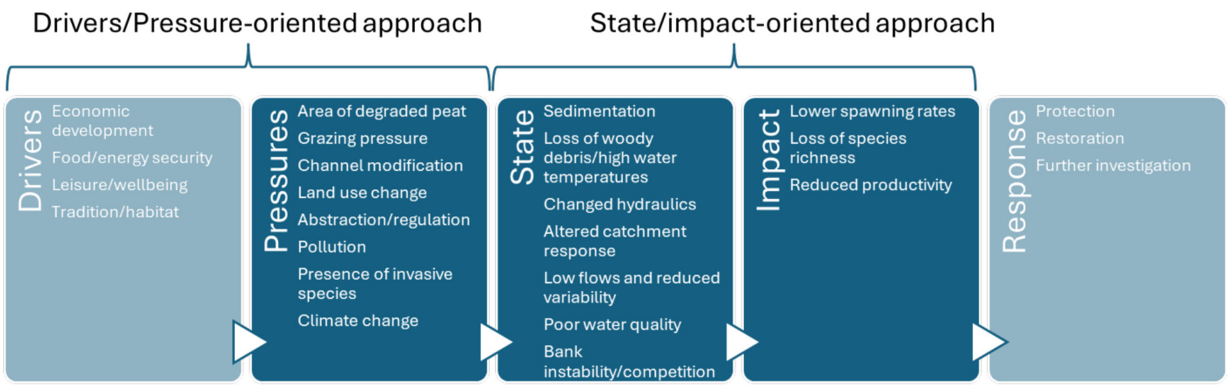

Figure C.1: Monitoring approaches in relation to the DPSIR framework using examples for a river environment.

Within a Drivers-Pressures-State-Impact-Response model these attributes take a state/impacts-oriented approach to monitoring features (Figure C.1). Some of the impact attributes can be used to infer state through the use of indices, such as the Acid Waters Indicator Community (AWIC) and PSI macroinvertebrate tools to indicate acidification and sedimentation respectively (Davy-Bowker *et al.,* 2005; Extence *et al.*, 2013). This concentration on state and impact monitoring can also be recognised in the application of quality elements monitoring for WFD water body classification of ecological status (Song and Frostell, 2012).

The ecological theories upon which the targets for "good ecological status" in the WFD and "favourable conservation status" in the HD, are aimed towards maintaining or restoring naturally connected ecosystems. This is consistent with the theory that natural ecosystems tend to maximise ecological resilience through biological diversity and complex interactions which generate negative feedback loops (Holling, 1973). Species and the interactions between them within resilient ecosystems have evolved to cope with variability and change, making them better able to adjust to disturbances.

To assess the "naturalness" of elements of biological, chemical and physical elements of ecosystems, metrics have been developed that compare observed values against a set of reference conditions. These reference conditions aim to represent a state of no or minimal disturbance against which, the observed state can be compared and classified.

In their critique of the ecological theories underpinning the monitoring of the WFD, Bouleau *et al.* (2015) argue that the basis of the reference condition concept was founded in an old paradigm of ecosystem development. This postulated that ecosystem development led to a stable climax state where they remain until perturbed by major changes in the wider environment. In terms of environmental management, the use of reference conditions to assess whether restoration has been successful implies reversibility, i.e. that elements measured to determine ecological condition will return to a historic, pre-impact reference state. Modern theories postulate the more open and unstable nature of ecosystems which can shift to alternate stable states following major disturbances (Scheffer *et al.,* 2001).

The issues of unstable environments and the challenge of identifying undisturbed environments has been recognised in the development of multi-metric predictive indices that model expected communities and assemblages in the absence of disturbances using site specific variables. Examples include the UK's River Invertebrate Prediction and Classification System (RIVPACS) (Wright *et al.,* 1993) and France's Fish Based Index (FBI) (Oberdorff *et al.,* 2002).

The Norwegian Nature Index takes a nuanced approach to the reference state. The reference state for each biodiversity indicator is chosen by the expert in charge of the indicator and should, "reflect an ecologically sustainable state for this indicator" (Certain and Skarpaas, 2011). There are several ways the reference values can be determined but whichever method is chosen, the reference state should be a value that minimises the probability of extinction of the indicator and maximises, or at least does not threaten, the biodiversity of the natural habitat. This latter condition ensures that reference states do not exceed the maximum sustainable value for a particular environment.

C.5 How do indicators identify pressures to inform environmental management?

It is understandable why single species indicators have been chosen for site condition monitoring where that species is a feature listed within the site designation. The HD requires signatories to report every six years on the conservation status of habitat types and species listed in Annexes 1 and 2 of the legislation. In addition, single species indicators can be used to infer information on the status of ecosystem structure and function and whether a pressure exists in a region influencing the protected area's ecosystem health. Generally, though, additional information is required to understand the state of the water environment that may be causing such an indicator to be in unfavourable status.

Functional indicators such as the LMNI and PSI have been developed to specifically identify a deviation in the state of the water environment such as nutrient enrichment or high levels of sediment. However, the influence of single stressors on ecosystem health are rare, particularly when considering major global pressures such as climate change. Additionally functional indicators may also respond to other changes in state such as hydrological or morphological degradations (Marzin *et al.,* 2014).

There is a strong orientation towards indicators of state and impact quality elements used for the classification of ecological status under the WFD and few that orientate towards pressures (Song and Frostell, 2012). NatureScot also recognise this bias in the current site condition monitoring of protected areas and have signalled a desire to address this through their principles for monitoring to deliver healthy ecosystems (Appendix A; Davidson *et al.,* 2024).

This is not to say that pressures impacting protected areas aren't being reported under the current SCM programme. The pressures are routinely identified and assigned a category type, e.g. invasive species, and can be assigned an assessment of level of impact they are thought to be having on the site. However, within the CSMGs for lakes and freshwaters, pressures are deemed to be an accompaniment to, but not part of, assessing feature condition (JNCC, 2016). Perhaps because they are not determinants of conservation status, there is little specific guidance on what evidence is required to assess the presence or absence of these pressures and how severely they are impacting the features within a site.

For fens, mires and bogs, impacts on physical structure, through active drainage and disturbed bare ground, are mandatory attributes to be assessed (JNCC, 2009). In this way pressures such as artificial drainage or deer trampling are used to infer state (lowering of water table, eroding peat) and impacts (change in vegetation composition). However, pressures are not routinely attributed to specific activities within or beyond the site or given a spatial reference to link to other data sets (e.g., Controlled Activities Regulations authorisations).

Understanding the key pressures influencing protected areas is important for both informing actions to improve conservation status and for targeting further ecosystem monitoring. For example, across the EU, agriculture is by far the most reported pressure on freshwater habitats reported under the HD (Maes *et al.,* 2020). As a result, the European Environment Agency and the EU Joint Research Centre have developed a nutrient pressure accounting tool to identify hotspots of nutrient pressure and understand where they threaten areas of high biodiversity. This uses gridded farm statistics, data on agricultural nutrient use and atmospheric nitrogen deposition data to model nutrient pressures spatially across ecosystem types (Petersen *et al.*, 2020).

Suresh *et al.,* (2023) argue that the prevalence of state and impact-only indicators hamper the assessment of lake eutrophication and sustainable nutrient management. They highlight the complex interrelationships among indicators that include the frequently missing linkages of the drivers and pressures and demonstrate how indicators of these, in themes such as water management, crop farming and livestock or fishing and aquaculture, can be used as proxies to better understand nutrient dynamics.

These drivers and pressures, and indeed, the state responses to them, occur over a range of scales from the river reach, loch or wetland themselves through the contributing catchment up to the global scale. Accounting for these pressures calls for a different type of monitoring and assessment such as the EU nutrient pressure accounting tool, highlighted earlier, or through the use of remote sensing (e.g. Large *et al.,* 2015; Boori *et al.,* 2021).

C.6 Indicator variability

Indicators of ecosystem health range widely in terms of their temporal and spatial variability (Sparrow *et al.,* 2020). High variability in an indicator can be valuable as it can indicate a sensitivity to a pressure which can be helpful in the diagnosis of a trend in ecosystem health, particularly where multiple indicators can be employed (Ham *et al.,* 1997). With sufficient monitoring resolution an analysis of indicator variation itself can be used as an early warning of an ecosystem crossing a threshold to an alternate "basin of attraction" such as eutrophication (Donangelo *et al.,* 2010) in the same way that indicator fluctuations can forewarn bifurcations in chaotic systems such as ocean circulation patterns or financial markets (Dakos *et al.,* 2012). These processes acknowledge that a once stable ecological state has either lost stability, been subject to large perturbation and transitions to an alternative stable state or has been subjected to a rate-induced tipping point (Abbott *et al.,* 2024).

However, indicators with a high degree of variability can also present a monitoring burden if they are to provide a robust assessment of ecosystem health. If the monitoring frequency or network density of an indicator is not commensurate with its temporal or spatial variability, then the assessments will have low confidence and may hamper the decision-making process.

To account for this explicitly, Maes *et al.,* (2020) have classified indicators of pressures and ecosystem condition in terms of their variability (Table C.1) and gone on to use this in conjunction with monitoring frequency and currency to assign a confidence classification in their mapping of ecosystem condition.

Table C.1: An example of annual dynamics of change in pressure and ecosystem variables (from Maes *et al.*, 2020).		
Annual dynamic of change	**Description**	**Examples of indicator types**
Highly variable	Strong year to year variations with long term and short-term time trends superimposed on each other due to a fast response of the variable to changed environmental conditions.	Abundance of species Recruitment processes Ecosystem productivity Ecosystem functions Climate variables
Moderately variable	Moderate year to year variations with a clear long term and deviations due to short term time trends	Species diversity (number of species) Physical-chemical variables of water quality and air quality Soil indicators Invasive alien species
Moderately stable	Low year to year variations with a clear, monotonous upward, stable or downward trend	Emissions of pollutants Deposition
Highly stable	Hardly any year-to-year variations; Slow processes which take years to manifest	Land cover and land use change. Fragmentation Landscape mosaic Land take (Natura 2000 coverage) Conservation status of habitats

C.7 A national framework for monitoring ecosystem health

A monitoring framework is a structured system that organises the guidance on methods of data collection, analysis and collation of results into an output that meets the objectives of the monitoring. It can also determine the monitoring networks required to meet these objectives and the frequency, spatial resolution and system of prioritisation of resources to support data collection. For the current SCM in Scotland, the monitoring framework was developed to achieve the objectives set out in the HD and is supported by:

- The Common Standards Monitoring Guidance – these set out the monitoring methods, attributes to be assessed and targets to achieve favourable conservation status.
- A 6-year reporting cycle in line with the HD that informs monitoring frequency.
- Latterly, the 3-tiered risk-based SCM approach developed by NatureScot to ensure monitoring resource is targeted to gain the greatest information on impacts on feature condition.

This project is part of a wider programme to review and revise the monitoring framework to meet the needs of Scotland's Biodiversity Strategy and the 30 x 30 target.

C.7.1 National Frameworks

In shifting from a site/features-based monitoring system to an ecosystem approach to establish the 'state' of Scotland's natural capital assets, or biodiversity and habitat health, there is a need to understand the differences in data collected, performance measures and the influences that impacts these. As established earlier, ecosystem health is a measure of the status of ecosystems, through a combination of three inter-related elements (Scottish Government, 2024a):

- **Structure** – the organisation and condition of biotic ecosystem components and the abiotic elements that support them.
- **Function** – assessment of the natural function and capacity of a system to be maintained and continue to deliver a range of ecosystem service benefits
- **Sustainability** or **resilience** – the extent to which the health and capacity of ecosystems and benefits are sustained under human and environmental pressures

The global biodiversity framework (GBF) provides a framing and direction for the conservation management, sustainability and recovery of global biodiversity, including a set of global goals, targets and indicators, adopted by signatory countries. These targets and indicators guide the development of the definition of national biodiversity targets which can be referenced to the Global Assessment Report of Biodiversity and Ecosystem Services issued by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019). The framework can be utilised as a catalyst, drive urgent and transformative action by Governments, with the involvement of all of society to create a system that assesses the health, wellbeing and resilience of the country's biodiversity and inform management actions (CBD, 2022). As such, parties to CBD, should seek to align national biodiversity policy frameworks with the GBF and this ought to be reflected in the targets and indicators utilised in the national biodiversity monitoring strategy.

Shifting to a national biodiversity monitoring framework (NBMF) is prescribed under the Convention on Biodiversity (CBD, 2022) to which the Scottish Government is a signatory. An NBMF is used to (UNECE, 2022):

- identify evidence needs,
- link biodiversity monitoring systems to policy objectives,
- structure indicator sets,
- inform the policy arena, and
- support decision-makers.

As signatory, the Scottish Government is obliged to create a national biodiversity monitoring framework based on ecosystem health. Scotland's response to the Aichi Targets (2010) set by the United Nations Convention on Biological Diversity (2010) and the EU's Biodiversity Strategy for 2020 (2011) was the update of Scotland's Biodiversity Strategy (Scottish Government, 2004), delivered through the 2020 Challenge for Scotland's Biodiversity (Scottish Government, 2013), and latterly expanded in the ***Biodiversity strategy to 2045: tackling the nature emergency*** (Scottish Government, 2023). Other countries have adopted similar measures to determine ecosystem health and thus ecosystem services delivery e.g. Norwegian Nature Index (Norwegian Institute for Nature Research, 2024); New Zealand Freshwater Biophysical Ecosystem Health Framework (Clapcott *et al.,* 2018); Australian Government's Natural Resource Management Monitoring, Evaluation, Reporting and Improvement Framework (Australian Government, 2024)]; and incorporated this into a National Capital Accounting procedure similar to Scotland's Natural Capital Asset Index (NCAI).

The NCAI is based on 38 data sources that are reviewed annually and cover not only environmental indicators but includes socio-economic parameters as a measure of Scotland's health and wellbeing (Scottish Government, 2024b). Thus, the NCAI is a composite index used to monitor variations in the capacity of terrestrial, freshwater and marine ecosystems to provide ecosystem services or benefits (NatureScot, 2024c).

In most cases to ensure consistency and long-term relatability this requires the use of a 'standardised' monitoring framework. Some examples of national biodiversity monitoring frameworks include:

1. **DPSIR (drivers, pressures, state, impact, and response model of intervention) framework:** A framework that classifies biodiversity indicators into five categories. It can be used to:

- Assemble evidence along cause-effect networks
- Identify areas where policy interventions may have particular impact
- Decide what evidence may be effective in highlighting impacts

2. ***Biodiversa+***: A transnational network of national biodiversity monitoring schemes. It aims to:

- Address pre-defined priorities
- Be tightly linked to the research and innovation ecosystem
- Be grouped on Earth Observations Biodiversity Observation Network (GEO BON)
- Provide framework that aims to provide a general framework for biodiversity monitoring

Other initiatives related to biodiversity monitoring include:

1. **National Biodiversity Strategies and Action Plans (NBSAPs):** Countries are required to develop NBSAPs to implement the UN Convention on Biological Diversity (CBD), planned action to include national targets, and integrate them into relevant sectoral and cross-sectoral plans, programmes and policies, and submit national reports (NRs) on the effectiveness of measures for implementation.
2. **Data Reporting Tool (DaRT) for Multilateral Environmental Agreements (MEAs)** – A tool that supports parties to effectively use synergies in the field of knowledge and information management for national reporting to biodiversity-related conventions. DaRT is developed by the United Nations Environment Programme (UNEP) with support of the SCBD, was endorsed by the InforMEA Initiative which brings together MEAs and is financially supported by the European Union and Switzerland (UNEP, 2024).

C.7.2 Frameworks and Monitoring Ecosystem Health

As detailed, ecosystem health monitoring involves the assessment of a combination of indicators to evaluate the function, resilience and wellbeing of ecosystems (Cheung, 2024). These indicators are measurable attributes or elements of the system that can be independently monitored through the application of in-field observation, feature sampling, automated monitoring, remote sensing or through compilation and analysis of existing data sets (Walker and Reuter, 1996).

The continuous refinement of indicator frameworks and incorporation of new methodologies into the monitoring programme will enable the monitoring agency's ability to assess, monitor, and preserve ecosystem health and resilience. As noted in the previous section the process of selecting indicators for monitoring ecosystem health can and should be meticulous, considering both the structural and functional aspects of ecosystems (Cheung, 2024), particularly if monitoring is to be undertaken across multiple scales, across ecosystems and species assemblages.

To deliver healthy freshwater ecosystems then, measuring and monitoring change and taking effective action is critical for conservation management. To maintain structure, function and resilience in the face of external stressors, this includes monitoring both biotic and abiotic components, as well as performance and indices of resilience over time. These indicators can act as proxies for the overall state or performance of ecosystems and are vital for assessing their sustainability and functionality (Chen, 2023).

C.8 Ecosystem Health Evaluation Frameworks

If it is agreed that ecosystem health mostly addresses how well a system is functioning (performance), the other indices that measure the 'temporal functionality' of the ecosystem can be summarised as the system integrity. Integrity encompasses a system's entire trajectory of past and future configurations and refers to (Erb, 2015):

(1) capacity to withstand stress (resilience, resistance, and so forth).

(2) maintaining the capability for the greatest possible developmental options; and

(3) continued ability for ongoing change and development, unconstrained by human perturbations.

A 'System of Indicators' utilised in a structured framework can be used to create an integrative process that categorises indicators into driving forces, pressures, states, impacts, and responses (e.g. DPSIR). Maes *et al.* (2016) show that assessing ecosystems through this interactive framing allows for a comprehensive assessment of various dimensions and drivers related to sustainability and function (Figure C.2). The conceptual framework presented here links socio-economic systems with ecosystems though the flow of ecosystem services. It demonstrates how the drivers of change exert pressures on ecosystems including biodiversity either as consequence of service use/depletion or as indirect impacts due to human activities (Millenium Ecosystem Assessment, 2005).

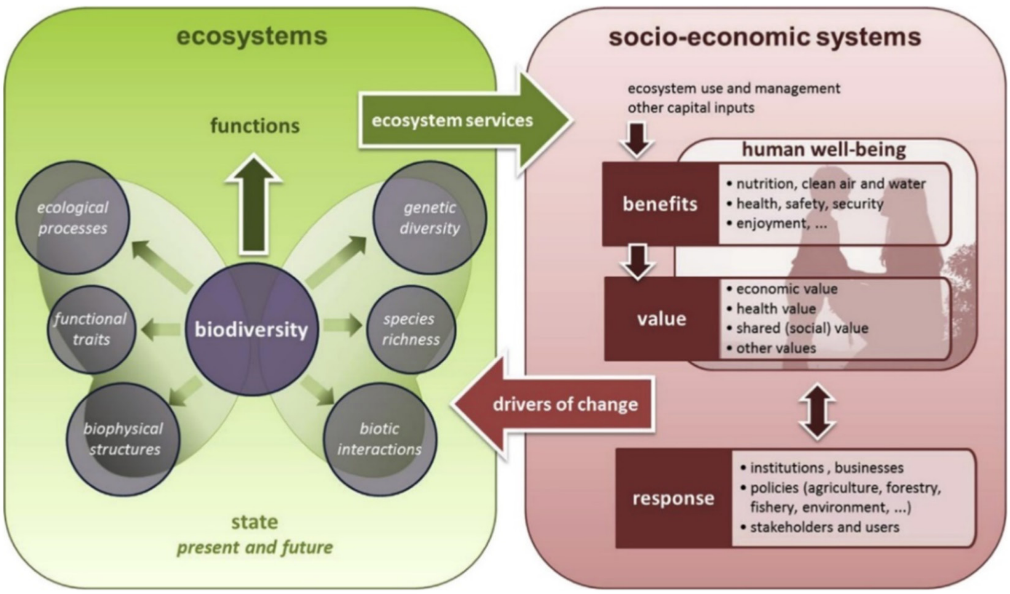

Figure C.2: Conceptual framework for EU and national ecosystem assessments under Action 5 of the EU Biodiversity Strategy to 2020 (Maes *et al.*, 2016).

C.8.1 Monitoring Framing

Utilising a continuous improvement approach will provide an opportunity to link key system elements or performance measures to management interventions or strategies to enable decision-makers to determine the level of monitoring resources required to ensure the delivery of ecosystem health at a particular site, ecosystem, time or scale. Scale, interconnectivity and issues are driving decision-making to assess and assign resources to mitigate potentially negative impacts within an ecosystem (Sparrow *et al.,* 2020).

Informed decisions are crucial when developing management actions, with the fundamental information required for best-practice decision making provided by dedicated monitoring programmes. These are necessary to inform planning, design, and budgeting phases (Smyth and James, 2004; Pettorelli *et al*., 2014). In Scotland's case these could be integrated across-agencies to deliver sufficient detail and at appropriate spatial and temporal scales and provide the most effective use of available resources.

As a guide to understanding how different types of monitoring provides various forms of essential functional and descriptive information to deal with the significant environmental and ecosystem challenges, Sparrow *et al.*, (2020) have suggested opting for the classification of ecosystem monitoring into the framework described in Eyre *et al.*, (2011). This devolves into *targeted monitoring, surveillance monitoring and landscape monitoring* (Table C.2; Sparrow *et al.,* 2020):

- **Targeted monitoring:** describes local to regional monitoring, with several re-visits per year, designed with the aim of understanding ecosystem processes occurring in particular environments.
- **Surveillance monitoring:** designed to detect when change is occurring, what that change is and the magnitude of that change, using standardised methods to collect a broad suite of variables at regional to national scales.
- **Landscape monitoring:** conducted over large areas, provides spatially continuous data and is primarily concerned with where and when change is occurring and provides information that cannot be feasibly collected using other methods.

Table C.2: Key trait types of monitoring (from Sparrow *et al.,* 2020).

	TYPES OF MONITORING		
Attribute	**Targeted**	**Surveillance**	**Landscape**
Spatial Extent	Small discrete areas restricted to site of study area	Local area to continents	Regional to Global
Temporal Extent	Usually, multiple visits per year	Revisits commonly every 3-10 years	Daily, weekly, monthly all common
Ecological Information Extent	Highly detailed-often species focused	Moderately detailed	Limited to phenomena that can be correlated to reflectance
Specialist Skill Set Required	Process based ecological skill set required	Ecological skillset required	Spatial science skill set required
Primary Audience	Restricted to those interested in the hypothesis	Broad and multidisciplinary	Widespread
Methods	Specific to the question posed	Standardised across all sites	Standardised and in some cases able to be automated
Hypothesis Based	Yes, specific questions posed	Only general questions, or questions posed *post hoc*	Most commonly *post hoc*
Level of Ecological Response Measured	Individual or population	Population, community or ecosystem	Community, ecosystem or biome
Able to Identify Cause of Change?	Directly	Correlative	Correlative
Adaptable to New Post Hoc Question	Rarely	Commonly	Commonly
Good Understanding of How the System Works Prior to Implementation	Necessary	Possible	Not necessary
Types of Change Identified	Expected	Expected and unexpected	Expected and unexpected
Use for Management and Policy	Not well integrated, but could be	Well integrated	Well integrated - lots of operational examples

C.8.2 Remote Sensing

Remote sensing technologies are valuable tools for assessing ecosystem health, providing opportunities for early detection of environmental degradation and identification of underlying issues (Li *et al.*, 2014). By utilising remotely sensed data and integration with geographic information systems (GIS), a process of identification of key ecosystem elements and indicators can be initiated to improve the assessment of definitive ecosystem health attributes, indicators, and measures, contributing to a greater understanding of ecosystem dynamics (Soubry *et al.*, 2021) necessary to inform management actions and policy initiatives.

Recent developments in the type (i.e. photo-grammetry processing, lidar, gravimetric, spectral resonance), resolution, sensitivity and temporality of remotely sensed data have greatly enhanced their suitability for providing supporting data, documentation, evidence of stability, degradation, or event-based changes at different scales within ecosystems, landscape, or regions.

A collaborative approach to remote sensing and digital monitoring technologies (i.e. gauging, water sampling) is suggested to counter resourcing issues, but it is suggested that on-ground expert assessments remain as integral to the quality assurance and real-time observation of system health and function.

C.8.3 Environmental DNA Monitoring

In addition, the utilisation of different sampling technologies or techniques that can be combined either within NatureScot or in collaboration with other stakeholders may provide the basis for developing environmental DNA (eDNA) of particular 'sites' or systems. Environmental DNA provides a unique signature of the system and is composed of the DNA that's released into the water by plants and animals (e.g. from their skin, faeces, mucous, hair, eggs and sperm, or when they die). Monitoring the freshwater species that utilise freshwater bodies can be instigated by utilising common water sampling methods and analysing the samples for traces of DNA that provides a signature for the site of interest (UK-SCAPE, 2024; Freshwater Habitats Trust, 2024).

Undertaking this approach to monitoring will by necessity require a scientific robustness that is balanced with consideration of the practical realities faced by those charged with managing and conserving the environment (Bruce *et al,* 2021). Developing the techniques, targeted sampling regime and determining database design initially requires an increased need for strong quality assurance for settings where non-expert field samplers (i.e. external stakeholders) or where alternative commercial laboratories are used. In Europe, the EU COST Action DNAqua-Net (Leese *et al.,* 2018) has been working towards incorporating molecular monitoring tools for Biological Quality Elements (BQEs, e.g., fish, macroinvertebrates and phytoplankton-benthos) into the Water Framework Directive (WFD, 2000).

Using DNA based approaches for assessing biodiversity and systems composition does have the potential to reduce overall monitoring costs, by minimising sampling and reducing identification time. Additionally, the procedure has the capability to identify cryptic genetic diversity and provide insights into minor or non-targeted organisms (UK-SCAPE, 2024). Emerging research has demonstration that using eDNA detection methods (such qPCR – quantitative Polymerase Chain Reaction), a range of aquatic organisms can be identified in water samples at very low concentrations (Freshwater Habitats Trust, 2024).

UK National monitoring agencies, including the SEPA, the Environment Agency, Natural Resources Wales and Natural England, are currently exploring the use of eDNA approaches to augment or replace their biological monitoring programmes. By leveraging existing or repurposing sampling programmes the eDNA methodology can potentially create a rapid cost-effective appraisal system for generating freshwater biodiversity data at a nationwide scale (UK-SCAPE, 2024).

However, this will place an increased emphasis on robustness, replicability, traceability and ease-of-use of data. If used appropriately in concert with infield ground-truthing and expert option, the methodology can generate a database that non-specialist decision-makers can rely on to inform management actions and potentially prevent the initiation of costly interventions (or non-actions) (Bruce *et al.*, 2021).

C.9 Summary

In recognition of the urgency of actions required to halt biodiversity loss set out in the draft Scottish Biodiversity Strategy, NatureScot have reviewed their current SCM and concluded that the existing approach will not meet the requirements to adequately assess conservation status on the expanded area of protected land (NatureScot, 2024b). There is a need for monitoring to better inform the management of protected areas by providing more information on the pressures and threats they are exposed to. This will require incorporating monitoring of the wider landscape and making the best use of existing data including those from other organisations.

The aim of this project is to review the current SCM and make recommendations on what metrics to measure, to support the effective delivery of ecosystem health for Scotland's protected freshwaters and wetlands. Ecosystem health can be assessed in many ways, depending upon management objectives, but what these approaches have in common is that they attempt to shine a light on the state of an ecosystem's structure, function and resilience. The monitoring and assessment of ecosystem health should recognise that natural systems can have benchmarks that have developed resilience over time but that ecosystems are open and unstable systems and today are rarely free from pressures.

This report provides examples of some of the indicator types that are used to measure ecosystem health. It demonstrates that most current indicators used within the SCM are focused on state and impact indicators. Relatively few formal indicators are used to assess the drivers and pressures which could inform actions to protect and restore sites. Several of the state/impact indicators have been shown to be highly variable in space and time and this places a large monitoring burden for these indicators to be used widely (Table B.1). Indicators at the Landscape-scale, such as those addressing land use change and connectivity or ongoing pressures such as diffuse pollution tend to be more stable and quantifiable at scale using modelling and/or remote sensing and as such may be valuable within a hierarchical monitoring framework.

If new metrics are to be employed or if monitoring attributes are to be rationalised, it is important to consider how a monitoring framework will ensure that the intended objectives of the HD and the Scottish Biodiversity Strategy will be realised. This framework should set out how monitoring can be retargeted to better inform on drivers and pressures, prioritised to maximise monitoring resources, and ordered to ensure monitoring types match specific objectives (Table C.2).

A series of ongoing stakeholder interviews was conducted in parallel with this literature review (Appendix D). The interviews seek the views of experts in ecosystem monitoring and practitioners in freshwater and wetland restoration. The interviewees were asked about what good ecosystem health means to them, what are the key pressures on ecosystems and what role they can play in contributing to the assessment of ecosystem health. They also were asked how site condition monitoring could be improved and this information, combined with the review presented in this report will inform the upcoming project workshop. The workshop aimed to develop both a common understanding of ecosystem health and recommendations on how that can be assessed within Scotland to support the aim of halting and reversing biodiversity loss.

Appendix D - Stakeholder Consultation and Workshop

D.1 Stakeholder interviews

Individuals or organisations with relevant expertise on the assessment of ecosystem health were identified by the PSG and the project team. Through the interviews, an expert opinion was sought on understanding the key factors that determine good or poor ecosystem health. In addition, interviewees were asked to consider alternatives ways in which ecosystem health of protected areas could be better assessed in the future. Organisations engaged in collecting data considered potentially relevant in assessing ecosystem health were also contacted. The project team sought to understand why this information was collected; in what form and type; and how accessible the data was (or could be) to external organisations such as NatureScot.

32 stakeholders have been contacted and 12 agreed to be interviewed (Table D.1). Through consultation the potential to improve confidence SCM using existing monitoring was considered. Evidence gaps, barriers and collaborations were identified, and role new technologies can play in addressing these was examined. Additionally, the robustness and potential use of proxy or representative indicators that can be derived from remote sensing, or cross-correlated as an indicator of ecosystem services or system health was discussed. Using databases for both collating and analysing these data streams to generate a site condition assessment of ecosystem health and the confidence associated with it was assessed.

Table D.1: Stakeholder Organisations interviewed by project team on ecosystem health and their approach to monitoring. (Note: 32 stakeholders were invited to interview).

Stakeholder Organisations	Numbers being interviewed
NatureScot	2
Marine Directorate	1
Fisheries Management Scotland	1
Buglife Scotland	1
Cairngorms National Park Authority	1
University of Stirling	1
SEPA	3
River Dee Trust	1
Forest and Land Scotland	1
Total	**12**

D.2 Stakeholder workshop

Following consultation with the stakeholder interviews, a workshop was held to bring together a wider group of practitioners.

D.2.1 Workshop methodology and format

The research team brought stakeholders together in a facilitated knowledge-exchange workshop held on Microsoft Teams on 22nd October 2024. The workshop built upon the information gathered through the project's literature review and stakeholder interviews conducted between August and October 2024. All interviewed stakeholders were invited to the online workshop, as well as wider stakeholders with either ecosystem monitoring expertise or a stake in freshwater and wetland management.

The 1-day workshop was attended by 22 participants representing 14 organisations (Table D.2). The workshop was facilitated by the project team from the University of Dundee who facilitated chat room discussions and coordinated feedback from the workshop discussion exercises. The coordinated activities were designed to ensure that the core principles of co-production: collaboration, diversity, respect, empowerment, and involvement, were fully embedded.

Table D.2: Agencies represented at the workshop.

Organisation	No. Participants
University of Dundee	5
JHI	2
UKCEH	1
NatureScot	2
SEPA	2
RSPB	1
EA	2
NRW	1
Scottish Government	1
Green Action Trust	1
Forestry and Land Scotland	1
University of Edinburgh	1
Land and Habitats consultancy	1
Fisheries Management Scotland	1

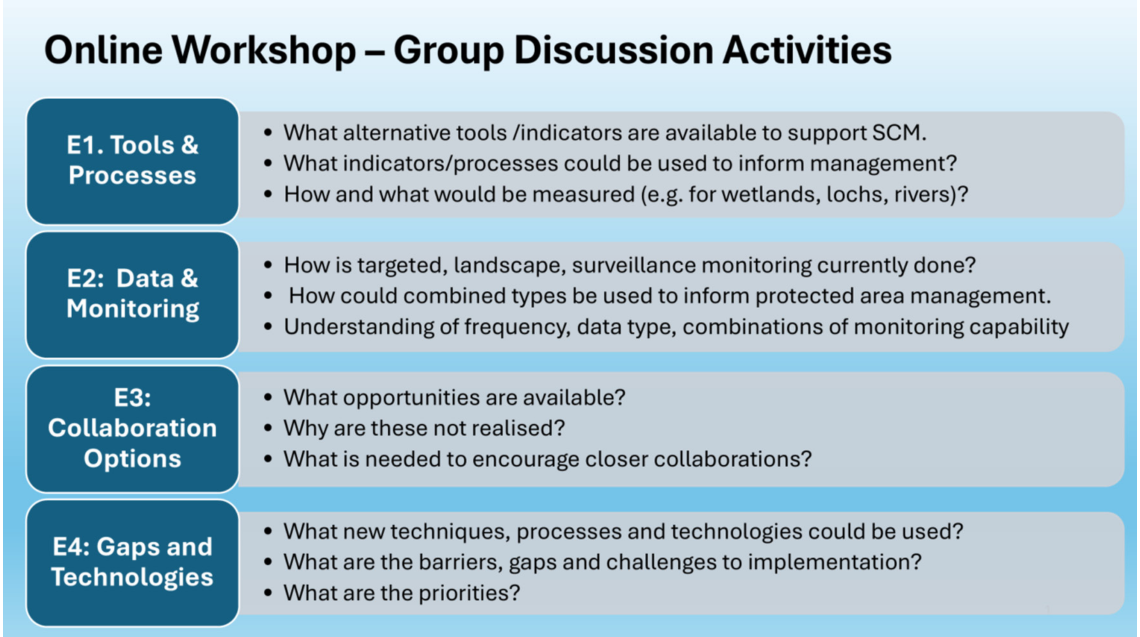

Figure D.1: The group discussion activities.

The interactive engagement tool Mentimeter was used to collect stakeholder responses, and questions and notes taken by the project team facilitators have also been used where these provided additional material to support the points made by the participants. To avoid bias, during the exercises and discussion activities participants were not shown the other responses until all had submitted.

D.2.2 Results and Discussion

The following sections report a synthesis of the Mentimeter results and participants comments.

D.2.2.1 Understanding of the concept of healthy ecosystems

When participants were asked "What 3 words spring to mind when you think about healthy ecosystems", the most common terms used were (in order of frequency): Diverse, Resilient, Functioning and Abundant (Figure D.2).

Figure D.2: A word cloud generated from participants responses to the question; "What 3 words spring to mind when you think about healthy ecosystems" (Number of responses = 16). Similar words with different forms were standardised to match the most common response form of the word e.g. the word "function" was transformed into "functioning".

Prior to the workshop, the definition of healthy ecosystems was agreed by the project steering group as:

> *Ecosystem health is a measure of the capacity of an ecosystem to maintain its structure and function over time in the face of external stress. In the context of freshwater and wetland protected area restoration in Scotland, healthy ecosystems are defined as having reached the least degraded and most ecologically dynamic state possible.*

Whilst comparing terms can involve a degree of subjectivity, an exercise to map the correspondence between terms used in the project definition and those terms put forward by the workshop participants can provide insight into the level of agreement between the two (Figure D.3). This term-mapping exercise highlights the focus upon structure when considering the definition of healthy ecosystems and corresponds with findings from reviews of ecosystems indicators showing a strong structural bias in ecosystem health monitoring (e.g. O'Brien *et al.,* 2016; Cheung and Burrows, 2024).

D.2.2.2 Feedback on the presentations by the project team and NatureScot

Following the presentations by the project team on the findings of the literature review and by NatureScot on the principles around delivering ecosystem health, a question-and-answer session revealed more participants' thoughts on monitoring to deliver healthy ecosystems.

The reflections capture the complex challenges inherent in better understanding and managing healthy ecosystems. The following key points were raised by the participants:

1. Recognising feedback loops and dependencies within ecosystems is critical. Understanding these interrelationships can help identify where actions may have the greatest impact and prevent unintended consequences.
2. There are key challenges given limited resources. The focus should be on identifying indicators that reflect ecosystem health and resilience, prioritising those that are sensitive to pressures and management actions. Collaboration and data sharing can help address resource constraints.
3. Optimising available resources may require tapping into broader funding streams by aligning ecosystem monitoring goals with the priorities of funding bodies. Linking ecosystem restoration efforts, such as woodland restoration, with landowners who may have access to targeted funds can leverage joint benefits.

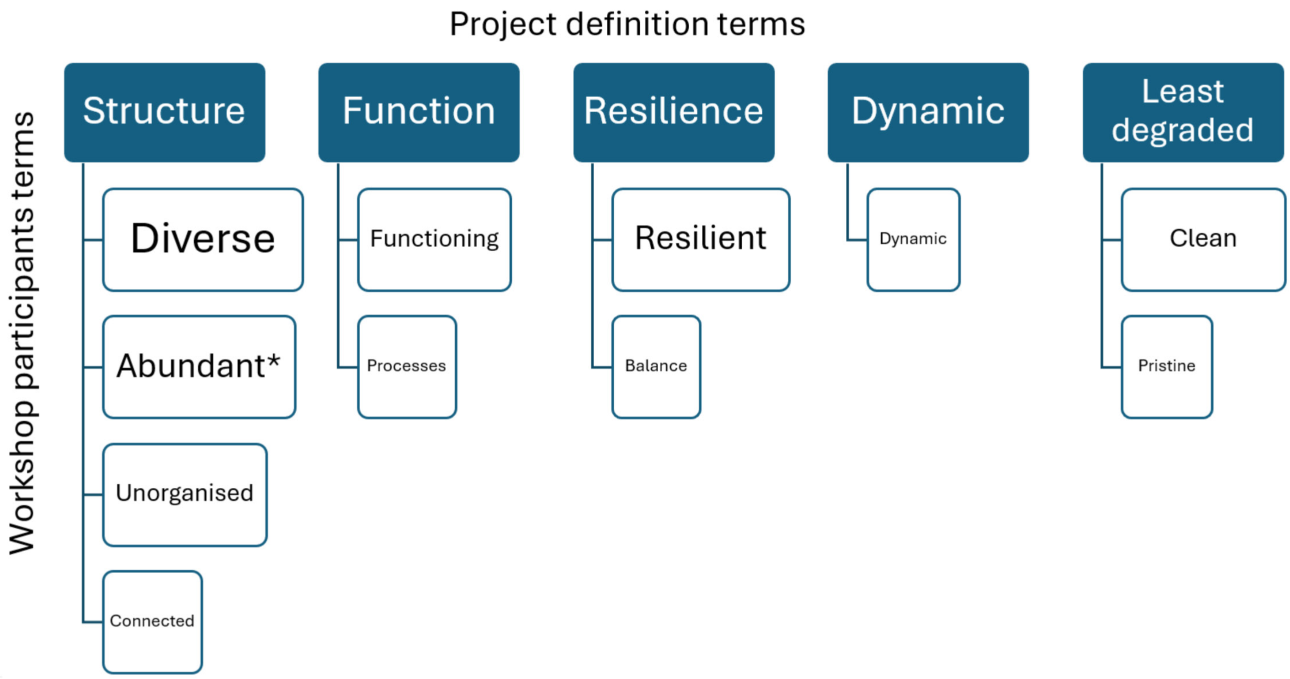

Figure D.3: The correspondence of terms used to describe healthy ecosystems as agreed by the project steering group and workshop participants. * For this exercise, the terms "Thriving" and "Luxuriant" have been taken to have similar meanings to the term "Abundant". The size of font of the participants terms is used to indicate their frequency within responses, i.e. large font = frequently used.

4. Contextualising site-based monitoring with wider area monitoring can provide better assessments to inform management. For example, using monitoring from the Environmental Change Network to understand how long-term environmental trends, such as disease, pests, and climate change combine with local pressures and translate into localised impacts can help tailor management responses.
5. Making effective use of existing data, even if collected for different purposes, requires careful consideration of scale, granularity, frequency, and context. A pragmatic approach is needed to make the best use of available data.

In addition to these comments, participants were asked to grade their level of agreement with 3 statements related to the preceding presentations (Figure D.4). The results indicate that participants were highly supportive of a monitoring approach that prioritised informing management by extending to the wider area where significant pressures and threats exist. On the whole, participants also agreed that naturally occurring species assemblages are a key part of healthy ecosystems although the range of agreement level was greater than the other questions. A quarter of respondents to this question neither agreed or disagreed with this proposal.

D.2.2.3 The break-out group discussion exercises

The comments from the 4 break-out group discussion activities (Figure D.1), each focused upon an aspect of the monitoring revision, were captured within Mentimeter.

The resultant 107 comments have been grouped by topic for each discussion point covered. Table D.2 summarises the key opportunities and challenges identified in these comments under the following themes:

- The transition to monitoring ecosystem health
- Monitoring to inform management
- Monitoring and data sharing to consider the wider landscape
- Additional indicators to support site condition monitoring
- Monitoring hierarchies
- New techniques
- Valuing data collected for site specific objectives

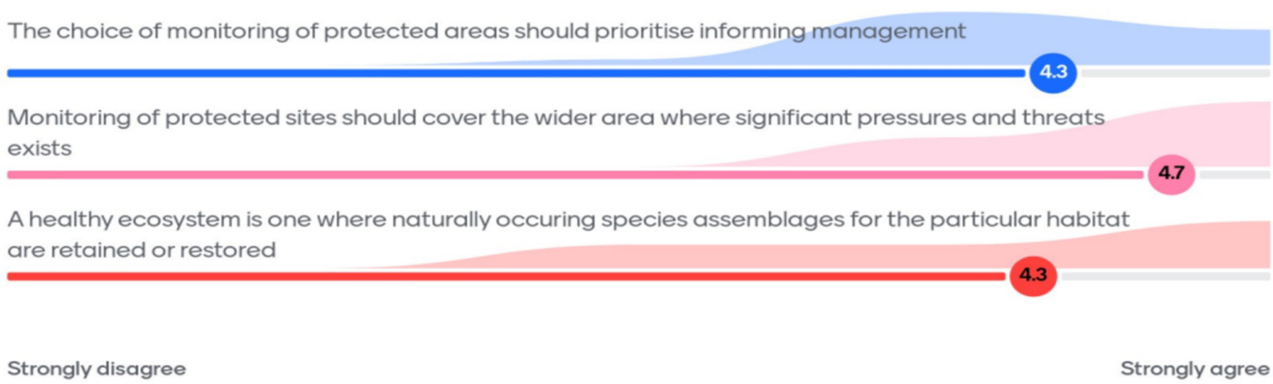

Figure D.4: Participants were asked to grade their level of agreement with the statements on a scale of 1-5 (Number of responses = 16).

Table D.3 Summary of the themes, opportunities and challenges elicited during the workshop to aid in developing a monitoring programme to deliver healthy ecosystems.

Theme	Opportunities	Challenges
The transition to monitoring ecosystem health	By identifying indicators directly tied to critical ecosystem functions for different waterbody types, it is likely that monitoring outcomes will link better with management actions. Understanding feedback loops and dependencies within ecosystems can help identify where actions may have the greatest impact and should prevent unintended consequences. Cost-effective methods that optimise sampling for maximum insight and coverage at different scales, can enhance the representativeness and value of monitoring data and better feed ecosystem modelling. Broader ecosystem health monitoring may detect unknown pressures and risks affecting sites or key landscape features.	There is a need to review how existing proxy indicators perform, ensuring they provide expected insights (e.g., using surface vegetation as a peatland health indicator). Agreements on data sharing, protocols, ownership and compatibility may be required. Upskilling may be required to interpret/integrate data at different time intervals, scales and sites
Monitoring to inform management	There was wide agreement that monitoring of protected areas should prioritise informing their management. To achieve this, indicators capable of identifying and understanding risks will be important. A process of linking risk assessments with intervention strategies is needed.	Current funding models for management actions typically support short-term assessments, making long-term or landscape-scale monitoring challenging. It will be necessary to understand how long-term environmental trends combine with local pressures to translate into localised impacts to tailor management responses
Monitoring and data sharing to consider the wider landscape	Contextualising site-based monitoring with wider area monitoring can provide better assessments to inform management. Casting a wider net allows additional existing datasets (e.g. UKCEH Land Cover Data) to be brought into site condition monitoring and will promote collaboration with other organisations and citizen science. Collaboration and data sharing should help identify redundancies in monitoring and make better use of available data. Raising awareness of potential data sources through publicly available metadata and encouraging wider access could promote collaboration.	There are gaps in the wider monitoring networks, such as smaller streams. Focusing on sites can facilitate collaboration between parties with a vested interest in local management. It will be important not to lose these benefits. Data from different organisations are collected for different purposes. There may be significant effort needed to make them compatible. There is a lack of understanding around what organisations are monitoring and what protocols are used to ensure how data quality is maintained.
Additional indicators to support site condition monitoring	There is a wide array of indicators that have the potential to better inform the delivery of healthy ecosystems. These indicators can help better understand the pressures acting upon protected areas. Some indicators can address structural bias by assessing ecosystem functioning Long-term datasets can inform model development and predictive tools, capturing ecosystem conditions when direct measurements aren’t feasible.	Resources will be required to increase skills and capacity to incorporate new indicators Using indicators monitored for different purposes, requires careful consideration of scale, granularity, frequency, and context. Identification of proxies to assess ecosystem changes efficiently needs to be both pragmatic and carefully considered.

Table D.3 Summary of the themes, opportunities and challenges elicited during the workshop to aid in developing a monitoring programme to deliver healthy ecosystems.

Theme	Opportunities	Challenges
Monitoring hierarchies	A hierarchy of monitoring scales—from landscape to local can help understand wider influences, such as environmental gradients and pressure impacts, while targeting specific sites or interventions. Combining landscape scale, rapid assessments, and responsive, targeted monitoring should increase resource efficiency.	Indicators are required that can identify and incorporate/understand risks that inform decision-making. (Meta) Data manipulation may be required to integrate data from different agencies or organisations. Careful consideration will be required to determine compatibility, confidence and representation.
New techniques	Combining new techniques (e.g. eDNA, new remote sensing products associated with high resolution satellites; drone imagery) can create monitoring resource efficiencies that deliver a more comprehensive understanding to inform management, and which are cost-effective and scalable. Using a cautious but pragmatic approach is needed to make the best use of integrating available data and monitoring activities. Utilising alternative technologies may open doors to alternative funding streams. Broad opportunities for incorporating remote sensing (e.g., drones, satellite, gravimetric) or alternative measures (i.e. flux tower data for greenhouse gas emissions) as a function of ecosystem health.	The implementation, testing and calibration takes a while to realise the efficiency benefits (SEPA at least another 2 years of development) May require additional resources to increase skills and capacity of NatureScot staff. Data sharing agreements may be necessary for existing or future applications of technology (i.e. Forth-ERA, SEPA).
Valuing data collected for site specific objectives	There is a large amount of ecosystem data being collected for site-specific purposes such as restoration projects or to support developers planning and licence applications. This is a largely untapped resource and could potentially add significant value to understanding and delivering healthy ecosystems	Site-specific data is not easy to access and may not be collected in a standard way. The challenge would be to work with the appropriate bodies e.g. NPA's, local authorities and rivers trusts to improve access to these data.

D.3 Considerations for a revised SCM approach

The opportunities available to revise the SCM approach identified within the workshop participants' comments (Table D.2) provide the project with a strong foundation upon which to make recommendations on monitoring to deliver healthy ecosystems. There was also a large degree of validation of, and suggestions on how to achieve, many of the 10 monitoring principles put forward by NatureScot (Appendix A).

In relation to the first 3 monitoring principles, participants strongly agreed that protected area monitoring should prioritise informing management and incorporate the wider landscape (Figure D.4). They also felt that a hierarchy of monitoring scales with a combination of rapid and more detailed assessments, could deliver a comprehensive and scalable approach. This could provide a better understanding of influences on ecosystems by linking landscape, catchment and site-level data that in turn would inform protected area management.

By strengthening existing and developing new partnerships to deliver collaborative monitoring and data sharing, and by harnessing new technologies (e.g. eDNA and specific remote sensing products), participants felt there was the potential to increase data richness, reduce redundancies and optimise resource use. With the addition of automation and citizen science there could be an expansion of monitoring capacity and, at the same time, enhance a sense of stakeholder ownership (Principles 5 and 6). Data sharing would also give access to monitoring that captures long-term trends and risks (e.g. ECN) that could help improve an understanding of ecosystem dynamics. This would help discriminate between local and global threats at different levels of severity. In addition, focussed long-term monitoring post-intervention, even if just at sentinel sites, could ensure adaptive management feedback loops are based upon sound evidence (Principles 4 and 7).

Some challenges to revising the approach were identified through the discussion and these will need to be considered carefully within the recommendations. Firstly, and perhaps most fundamentally, there are the risks created by introducing any significant change to an approach whilst it is still in use. There are resource implications in adopting a new approach that includes training, guidance development and the setting up of data sharing platforms. The work underway on developing these platforms should go some way to addressing this, but any change has resource, as well as institutional inertia issues, to overcome.

Whilst there are many ecosystem indicators that are well established and can be adopted with little additional development, there are others that will require more work to implement. In some cases, changes in methodologies could lead to the risk of fragmented or incompatible datasets unless a period of parallel monitoring is undertaken. How significant a task this is, or how feasible it is, would likely depend upon the currency and frequency of existing monitoring.

Although data sharing and collaboration have been identified as a way of optimising resource use, the recommendations will need to be mindful of the ease with which this can be done. Different monitoring locations, data formats, frequencies, protocols and the requirement for data sharing agreements must form part of the cost-benefit and prioritisation considerations for a new monitoring approach.

Finally, a word of caution was sounded about the shift in emphasis to wider, landscape-scale monitoring. Some participants highlighted a concern that this could lead to a neglect of site-specific needs, local stakeholder engagement or species-specific conservation goals. Whilst this is not inevitable, it is a valid concern that should be addressed.

Overall, the workshop findings provide a strong platform upon which to make recommendations. There are many specific tools and techniques, and examples of potential frameworks to sit them within, that have been highlighted through the literature review, stakeholder interviews and workshop outputs. In the next phase of this project, these will be developed into a set of monitoring recommendations that aim to shift the emphasis of site condition monitoring of freshwaters and wetlands onto informing the management that will deliver healthy ecosystems.

CENTRE OF EXPERTISE FOR WATERS

Centre of Expertise for Waters

James Hutton Institute
Craigiebuckler
Aberdeen AB15 8QH
Scotland UK

www.crew.ac.uk

CREW publications can be accessed here:
www.crew.ac.uk/publications

@crew_waters

CREW-scotland

CREW is a partnership between the James Hutton Institute
and all Scottish Higher Education Institutes and Research Institutes.
The Centre is funded by the Scottish Government.

Scottish Government
Riaghaltas na h-Alba
gov.scot