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Enhancing data mobilisation through a centralised data repository for Atlantic salmon (*Salmo salar L.*): Providing the resources to promote an ecosystem-based management framework.

Graeme Diack[a,*], Colin Bull[a,b], Scott A. Akenhead[c], Tim van der Stap[d], Brett T. Johnson[d], Etienne Rivot[e], Rémi Patin[e], Pierre-Yves Hernvann[e,f], Aidan Schubert[g], Tom Bird[h], Mark Saunders[g], Walter Crozier[a]

[a] Atlantic Salmon Trust, Battleby House, Redgorton, Perth PH1 3EW, UK
[b] Biological and Environmental Sciences, University of Stirling, Stirling FK9 4LA, UK
[c] Independent. 11810 Fairtide Road, North Oyster, BC V9G1K5, Canada
[d] Hakai Institute, PO Box 25039, Campbell River, BC V9W 0B7, Canada
[e] DECOD (Ecosystem Dynamics and Sustainability), Institut Agro, INRAE, IFREMER, 35042 Rennes, France
[f] Institute of Marine Sciences, University of California, Santa Cruz, Santa Cruz, California, USA
[g] North Pacific Anadromous Fish Commission, Suite 502, 889 West Pender Street, Vancouver, B.C. V6C 3B2, Canada
[h] Fisheries and Oceans Canada, Pacific Biological Station, 3190 Hammond Bay Rd, Nanaimo, BC V9T 6N7, Canada

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ABSTRACT

Data and knowledge mobilisation are significant challenges in ecology and resource management, with the journey from data collection through to management action often left incomplete due to difficulties sharing information across diverse and dispersed communities. This disconnect between science and management must be resolved if we are to successfully tackle the increasing impact of human activity on our ecosystems. Across their North Atlantic range, Atlantic salmon (*Salmo salar* L.) populations are in steep decline in many areas and urgent actions are required to curb this decline. Being commercially important this species has been subject to intense research, but management action often suffers from both a lack of access to this knowledge resource and support for its integration into effective management strategies. To respond to this challenge, the science and management communities must place higher priority on mobilising existing and emerging knowledge sources to inform current and future resource use and mitigation strategies. This approach requires a more complete picture of the current salmon ecology data and knowledge landscape, new mechanisms to enable data mobilisation and re-use, and new research to describe and parameterise the responses of wild populations to habitat changes. Here we present a unique interface for registering and linking data resources relevant to the Atlantic salmon life cycle that can address the data mobilisation aspect of these challenges. The Salmon Ecosystem Data Hub is a salmon-specific metadata catalogue, natively interoperable with many existing data portals, which creates a low resistance pathway to maximise visibility of data relevant to Atlantic salmon. This includes the capacity to annotate datasets with life-stage domains and variable classes, thereby permitting dispersed data to be formally contextualised and integrated to support hypotheses specific to scenario-based modelling and decision-making. The alignment and mobilisation of data within the Salmon Ecosystem Data Hub will help advance the development of appropriate environmentally driven forecast models and an ecosystem-based management approach for Atlantic salmon that optimises future management strategies.

1. Introduction

Data in the modern world is generated at an incredible rate, with global data creation rates estimated at incomprehensible figures such as the 463 exabytes (10^{18} bytes) per day by 2025 (Raconteur Publishing, https://www.raconteur.net/infographics/a-day-in-data/). The

* Corresponding author.
E-mail address: graeme@atlanticsalmontrust.org (G. Diack).

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environmental and ecological sciences exist very much in the midst of this large-scale data generating revolution. Enabling technologies such as satellite remote sensing and autonomous vehicles are advancing at pace (e.g., De Robertis et al., 2021; Ohman et al., 2019), and data creation in these sciences is set to become faster and wider in scope as observation techniques improve in tandem (Sharma et al., 2021). This rapid increase is creating an urgent requirement for simple but effective curation tools. Both creator and primary user communities need these to ensure data streams, old and new, efficiently feed research and management activities.

The implementation of data curation solutions that improve openness and re-use is often labelled Data Mobilisation (Baker et al., 2015; Schulman et al., 2021). This term, though not precisely defined, conveys the understanding that to facilitate reproducible and replicable science the sharing of data and repeatable methods are of critical importance. The basic tenets of data mobilisation; accessibility, discovery, re-use, preservation, and sharing of data resources, are becoming increasingly valued elements of the scientific method across the natural sciences (Tenopir et al., 2011) facilitating efficient integration of these resources and enhancing their legitimacy (Gorospe et al., 2016). This shift is supported by the reported upward trend of familiarity among researchers of principles such as Findable, Accessible, Interoperable and Reusable Data (FAIR, Wilkinson et al., 2016) in the State of Open Data reports (Digital Science et al., 2021) as well as the growth of online repositories, e.g., Global Biodiversity Information Facility (GBIF), Knowledge Network for Biocomplexity (KNB), Long Term Ecological Research Network (LTERN), and Ocean Tracking Network (OTN). Alongside an increasing online presence, the use of persistent Digital Object Identifiers (DOI) has emerged as a method for citing datasets, creating an incentive to publish data that parallels established academic norms for scientific publications (Data Citation Synthesis Group, 2014). Knowledge mobilisation is then of prime importance during knowledge exchange between researchers, resource managers, and policy makers so that science may be implemented as actions in the real world (Geijzendorffer et al., 2016; Young et al., 2013). It is integral to effective decision-making by improvement of the auditable reasoning behind management decisions, thus servicing a need for evidence-based management (Hvenegaard et al., 2021). In many ways, data and knowledge mobilisation principles are the modern, digital expression of the concept of scientific repeatability and accountability.

Physical earth sciences have been ahead of the curve in respect to data mobilisation, with oceanography being exemplary through efforts such as the United Nations Educational, Scientific and Cultural Organization's (UNESCO) Intergovernmental Oceanographic Commission (IOC). The IOC has provided support for the development of data exchange standards since the 1960's (Michener, 2015) and created the Global Ocean Observing System (GOOS) in the 1990's with the goal of systematic ocean monitoring and data sharing (Dexter and Summerhayes, 2010). Today oceanography thrives within a community where data sharing is a prized outcome of costly data creation activity, leading to the widespread advertisement and re-use of data, raw and derived products, via portals such as the National Oceanic and Atmospheric Administration's (NOAA) Environmental Research Division's Data Access Protocol (ERDDAP. Simons and Mendelssohn, 2012). This culture is beneficial within the ocean sciences, but also propagates to other scientific disciplines where this data may be of use to investigate driving forces behind observed trends. Arguably the nature of biological data flowing from ecology driven observation activities may present challenges for the application and uptake of a similar approach to low friction data sharing. In ecology, data curation tools and methods have been in development by the ecoinformatics communities since the 1990's (Coleman, 2010; Michener, 2015). Ecologists now have improved access to several online resources that can add value and longevity to their data (e.g., see repositories and standards listed in https://www.re3data.org/ or https://fairsharing.org/). Ecological research produces highly varied data outputs, not to mention the variability in methods, and complex curation solutions are to be expected, but the sheer volume of options and standards available (that often appear to overlap or compete) may lead to confusion among the targeted users of these tools and inhibit widespread adoption (Tenopir et al., 2015). The challenge needs to be met, as sufficiently rich, well-described data is one of the most valued attributes of open cooperative research programmes (Melero and Navarro-Molina, 2020).

Whilst efforts to improve data and knowledge mobilisation in the wider research community are ongoing (e.g.,Benson et al., 2021), there is still a recognised need to enhance the toolkit available to researchers to allow frictionless adoption of FAIR principles (Teperek et al., 2019). A disconnect remains between the complex requirements of mobilisation, and the limitations imposed on data providers by time constraints and technical understanding. Whilst this exists, mobilisation of historic or legacy data resources will be unachievable, and the quickly amassing new data resources are in danger of becoming fragmented and unrecoverable. There is a requirement for the creation of tools that make it easier to achieve mobilisation objectives, such as an online presence and interoperable metadata. A methodical, step-by-step approach to embracing/adopting FAIR principles universally within the ecological sciences is required, enabling incremental data mobilisation carried out by data providers and supported by research communities with interests in the data.

Exacerbating technological barriers, sociological barriers to data mobilisation are also prominent in the minds of data creators and owners. Concerns regarding privacy, ownership, poor interpretation and misuse, and failure to stay abreast of rapid technological advances in ecoinformatics, are often identified as challenges to effective knowledge exchange (e.g., Cvitanovic et al., 2015; Digital Science et al., 2021; Reichman et al., 2011; Tenopir et al., 2015), and these factors are often synergistic or compounding in nature. These aspects require advocacy and building confidence in the cataloguing infrastructure and understanding them can greatly enhance the utility of knowledge generated (Nguyen et al., 2018).

Here we introduce a response to data mobilisation challenges in support of an urgent requirement to advance cooperative research and the future management of Atlantic salmon (*Salmo salar* L.): an iconic fish species that is experiencing significant population declines.

2. Data challenges in advancing Atlantic salmon management

Atlantic salmon are a highly prized commercial species and arguably one of the most studied fish species on the planet (Birnie-Gauvin et al., 2019; Woodward et al., 2021). Ranging throughout the temperate and subarctic regions of the North Atlantic (Thorstad et al., 2011) this anadromous species exhibits an extremely diverse array of life histories (Fleming, 2011; Forseth et al., 2011; Thorpe, 1994) and their lifetime survival integrates risks of both natural and anthropogenic origins, from both freshwater and marine habitats. Populations have been in decline for decades and local extinctions have been recorded throughout their range (Chaput, 2012; Parrish et al., 1998).

As a result of the complex life cycle, the factors that ultimately shape the reproductive success of any individual Atlantic salmon will operate across wide ranging physical scales (e.g., North Atlantic basin to individual river reaches). Life-stage specific pressures will elicit responses in terms of salmon growth and survival, and these not only differ between life stages, but act alongside factors that will vary in their specificity between populations (e.g., Olmos et al., 2019; Vollset et al., 2022). In common with that of other species, salmon management now contends with new climate trends, with drivers of population change (e.g. increased variability, and unprecedented extreme events) occurring at scales that are often orders of magnitude larger than the scale of management experience. This new climate change context exacerbates the crisis of long-term, widespread, declines in abundance and highlights a need for improved efforts by management communities to save the species from further local extinctions.

Current management interests span multiple organisations across multiple jurisdictions. The provision of advice on managing high seas mixed stock fisheries is coordinated by the North Atlantic Salmon Conservation Organization (NASCO). This is supported by stock advice from the International Council for the Exploration of the Seas (ICES) (ICES, 2021a), geared towards the operation of nationally regulated coastal or individually managed in-river salmon fisheries. While the current NASCO-ICES stock assessment process fulfils its required international functions, it also underpins the production of some nationally scaled conservation advice and associated strategies (e.g., Conservation Regulations). Although the outputs of coordinated international stock assessments are freely available (ICES, 2021a), the underlying data are not, and the modelling outputs are not readily transferable for integration into regular management decision-making that is being undertaken by river managers at the scale of specific threatened salmon stocks. Most practical local (e.g., single river stock) Atlantic salmon management activity is restricted to local estuarine/riverine fishery management or other freshwater actions aimed to maximise annual production and safeguard recruitment (e.g., Thorstad et al., 2021). These activities largely rely upon the provision and use of locally available data (Fig. 1) and the integration of data from a limited number of audit points (such as counts of smolts leaving or adults returning to monitored river systems) to underpin modelling of abundance.

Atlantic salmon management should benefit from the extensive research and monitoring investment over recent decades, with integration of rich and well-mobilised data resources. Instead, much of the applicable data resources that could provide valuable insights into the factors responsible for salmon population declines are widely dispersed across a diverse community, aggregated at varying biological and geographical scales, and present challenges for harmonisation and further collective synthesis (ICES, 2020a). This situation currently limits the ability to consider wider marine data resources alongside local rich data sources when planning local management actions and undertaking informed scenario-testing. To achieve the scale of advance required to address the challenges facing Atlantic salmon, and develop more focused management actions based on better predictions, we require considerable interdisciplinary efforts and a shift towards improved data integration and wider ecosystem-based approaches (Curtin and Prellezo, 2010; Link, 2010) in how salmon stocks are being assessed and managed (Bull et al., 2022; Crozier et al., 2017; Watz et al., 2022; Woodward et al., 2021). Lessons on utilising these resources could be learnt from Pacific salmon management where data driven models are routinely integrated into management programmes to improve knowledge across management levels (Crozier et al., 2019, 2021; Hare et al., 2016; Hyatt et al., 2017; Scheuerell et al., 2006, 2021; Walsh et al., 2020).

Focusing attention towards improving understanding of the processes driving the reduced marine survival of Atlantic salmon, data acquisition and data mobilisation play key roles in linking surveillance networks (e.g., GBIF, GOOS, OTN) to research and the development of adaptive management strategies. Several wide-scale physical environmental data sets that are applicable for describing certain ocean conditions are easily accessed and well mobilised (e.g., sea surface temperature, salinity, colour and currents, derived from remote sensing and delivered through platforms such as Copernicus and ERDDAP). However, challenges remain for accessing, re-purposing and re-evaluating their relevance alongside other resources to assist salmon management in light of recent additions or new knowledge (ICES, 2020a). The hierarchical nature of possible environmental drivers of salmon marine survival (Olmos et al., 2019; Vollset et al., 2022) focuses attention on the relevance and descriptive power of available data resources for use in directing future management challenges. Application of space and time data filters, guided by recent salmon migration studies (Almodóvar et al., 2020; Gilbey et al., 2021; Olmos et al., 2019; Rikardsen et al., 2021; Strøm et al., 2019) may help better refine and describe the applicability of available marine datasets, and improve their use.

3. Harnessing data to assist future Atlantic salmon management

One current advance that demonstrates the power of harnessing and synthesising data from multiple jurisdictions is in the development of a life cycle model for Atlantic salmon at the scale of the North Atlantic Ocean (ICES, 2021b). The dynamics of all stock units considered by ICES (Northern Europe, Southern Europe and North America) are jointly analysed within a singular unified model, developed in a Bayesian framework. It allows for analysing (hindcasting) historical time-series of

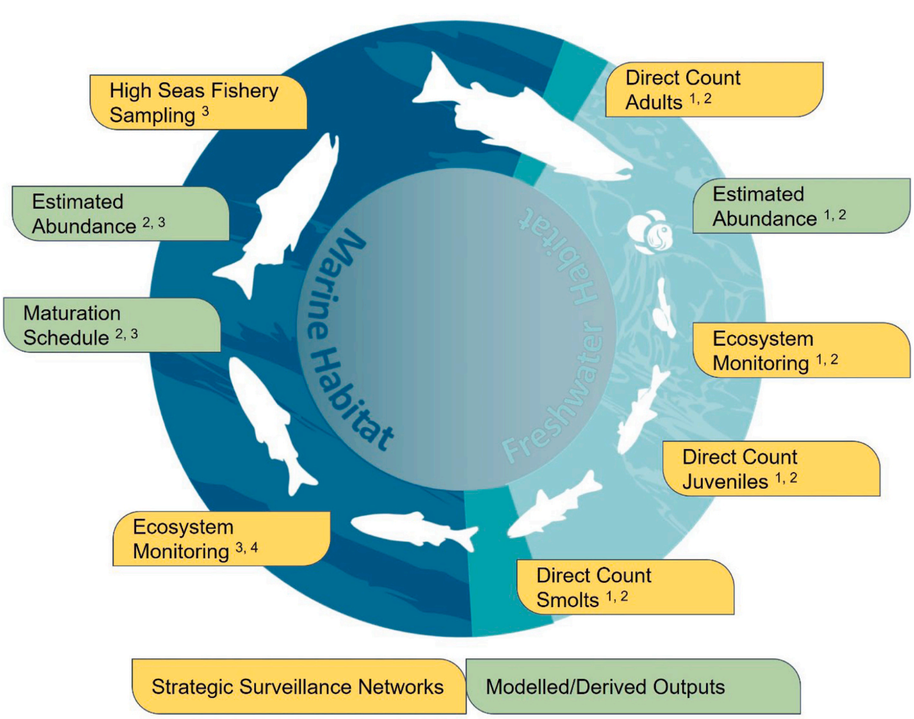


Fig. 1. Examples of potential data sources and indicative positions across the Atlantic salmon life cycle. These range from direct observations (Strategic surveillance networks) through to data underpinning guidance associated with stock assessment and management (Modelled/derived outputs). Superscript relates to the organisations associated with the data sources: 1. River and Fishery Management, 2. National Governmental Regulatory and Advisory, 3. International Cooperative Stock Assessment and Guidance, 4. International Cooperative Oceanographic Monitoring. Lifecycle graphic developed by Natascia Tamburello at ESSA Technologies (www.essa.com).

data to infer changes in the marine survival and maturation schedule over the last five decades. Formulating the dynamics of all stock units in a single model using a harmonised demographic scheme provides a tool for modelling covariation in key life history transitions among different populations that may share part of their migration routes at sea and may be exploited by the same marine fisheries (Olmos et al., 2019). Results were used to quantify the amount of temporal variation in those key life history traits that is accounted for by changes in sea surface temperature and primary productivity (Olmos et al., 2019). The life cycle modelling framework hence constitutes an important tool for future improvement of our understanding of the drivers and mechanisms that shape the dynamic of Atlantic salmon populations. The modelling framework is easily expandable and provides an opportunity to assimilate new sources of information when they become available (e.g., better proxies for salmon growth and survival). This new framework comes with an online database and a suite of R programs, including an R Shiny application for web interface, offering a mechanism to harmonise data from multiple sources into a format used directly by the model. This approach strengthens the robustness of the workflow from data processing (export/update) to hindcasting and the production of outputs (catch advice) (Hernvann et al., 2021; Rivot et al., 2021).

Future development of this modelling framework would benefit from improved data mobilisation, enabling model refinement to better represent the mechanisms that shape the response of salmon populations to ecosystem changes. Building a suitable universal mechanism for data mobilisation that spans the range of potentially relevant knowledge sources across the different scales would solve some of the limitations being placed on the potential for advancing collective analysis (such as the life cycle model) and for wider knowledge exchange to promote advances through the tiers of management.

One collective approach aiming to address this and disconnections among the areas of current Atlantic salmon management was jointly developed by Pacific and Atlantic salmon scientists in response to declines in populations in recent decades (Crozier et al., 2017). The Likely Suspects Framework approach focuses collective attention on providing a wider life cycle view of salmon survival processes for management, and promoting improved understanding of the driving processes (Bull et al., 2022). In the UK, for Atlantic salmon, the approach is being advanced by the Missing Salmon Alliance (www.missingsalmonalliance.org). Phase one of the implementation of the approach in the Northeast Pacific began in 2020 via the Salmonscape Workshop Series, which was hosted by the North Pacific Anadromous Fish Commission (NPAFC) and partners as part of International Year of the Salmon (https://yearofthesalmon.org/) activities (Siegle et al., 2021).

Underpinning the approach is the requirement for the collective identification and testing of specific mortality hypotheses that span the life cycle, the development of new ecosystem indicators and their use in directing management activities (e.g., Large et al., 2015; Sobocinski et al., 2021). Hypotheses testing plays a role in the development of understanding proximate drivers of recent population change, utilising hindcast analysis, where sufficient data resources are available. It also forces thinking towards knowledge gaps and prioritisation of future research and monitoring needs. It contributes knowledge to the important discovery process that could suggest potential new focus areas for salmon management actions, and highlights ways in which established and emerging surveillance networks can be mobilised and integrated to provide better forecasting and understanding of early warnings of state changes (Litzow and Hunsicker, 2016). This could highlight new environmental and biological indicators (e.g., Harvey et al., 2020), where greater management emphasis will be required in response to future changes, or where redundancies may lie in the light of predictions. Unrestricted access to data is a prerequisite for any collective hypothesis testing process that advances our understanding of the potential mechanisms that shape population dynamics and productivity, like those behind recent changes in marine growth (Todd et al., 2021; Vollset et al., 2022) and early maturation of salmon (Tréhin et al., 2021). This needs to be supported by improved data mobilisation efforts pooled across disciplines and spatio-temporal scales.

In response we present the Salmon Ecosystem Data Hub (SalHub) as a mobilisation platform for Atlantic salmon-focused activities. This online tool offers the salmon research and management communities the opportunity to be jointly involved in efforts to mobilise data to progress our current understanding of factors affecting survival, and assist with implementing new adaptive management strategies. It creates the basis for organising a rich and growing collection of datasets that will guide researchers to sources to enable collective hypothesis testing.

In its current form SalHub is a metadata cataloguing tool for a designated community (Baker et al., 2015), where already mobilised knowledge and data can be indexed and more opaque resources can begin to be transitioned towards FAIR without exposing users to the full complexities of metadata authoring. It is a place where stakeholders in Atlantic salmon conservation and management may begin to describe and index data resources into a context specific structure, derived from the salmon's life cycle. To promote user confidence initially SalHub is accessible only to registered users. Going forward, the aim is to establish this tool as a publicly accessible presence, promoting open data whilst still maintaining a layer of restriction for opt-out resources, e.g., embargoed information or data identified as potentially sensitive. Users agree to encourage resource sharing and academic collaboration through a Memorandum of Understanding.

The Missing Salmon Alliance Likely Suspects Framework team has launched the application as a Minimum Viable Product as part of an Agile (http://agilemanifesto.org/) development plan. The application is ready to develop further functionality and as the user base grows it is anticipated that the research and management communities will provide guidance for subsequent development opportunities. This system is built upon a range of modern and open-source technologies (Fig. 2). The core data structures of the web application are a graph database (NEO4J), an extension of the mathematical graph (Trudeau, 2013) and more commonly referred to as a Labelled Property Graph (LPG). This is coupled to two primary data storage locations, a simple cloud-based file store (AWS S3) providing unstructured data capacity, and an SQL database (PostgreSQL) providing structured data capacity. Alongside these technologies the scientific programming language R (R Core Team, 2022) provides the programmatic tools for interacting with these storage structures (read, write, report and visualise), as well as enabling the presentation of the resource to a community of web-based users via the R Shiny package (Chang et al., 2022). Github provides a mechanism for community engagement in the development process (https://github.com/Missing-Salmon-Alliance/).

The initial metadata entries in the SalHub database were harvested from a review of existing data resources of relevance to Atlantic salmon carried out during the NASCO-ICES WKSALMON workshop on salmon mortality at sea (ICES, 2020a). Around 100 data sources were identified and described in SalHub to provide a new organisational tool for future cooperative workshops. The number of described resources in SalHub has since increased to over 250. Of these, around one third are open data and include a URL to the data itself. The remaining entries are a combination of resources identified via publications or targeted searches for specific data sources. Whilst this approach has proven useful in painting the knowledge landscape with a broad brush to begin the process, much of the finer detail of the data representations remain absent. This will require input from data creators to enable resources to be fully utilised in future hypothesis-testing frameworks.

Users intending to submit/register data resources may do so via a form designed as an intuitive and quick method to capture the level of detail required for findability and attribution. There is a minimum required fields restriction, set at a very low level of detail (title, natural language description and contact details) to encourage engagement and enable communication between data providers and the user community. Additional and optional fields invite further description of a resource's availability, geographic coverage and temporal range. A set of user

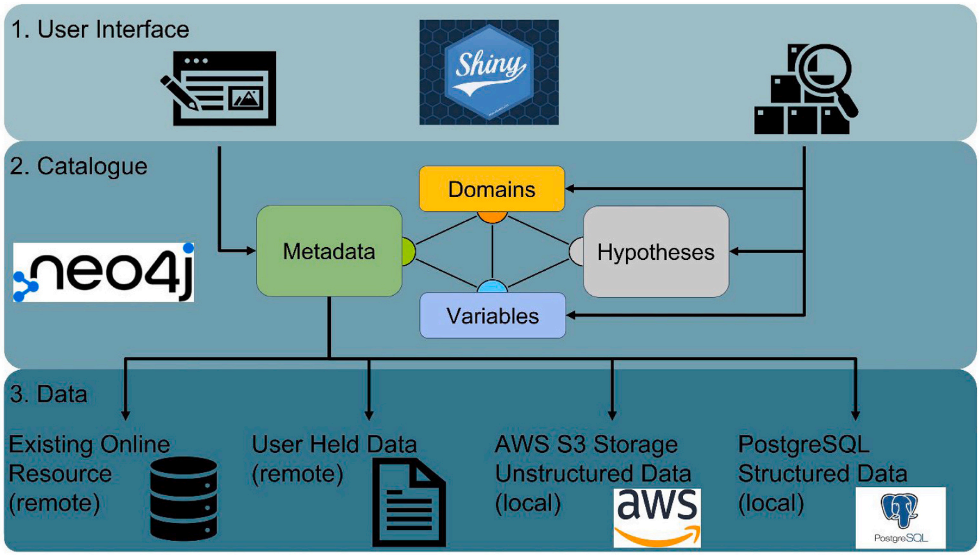


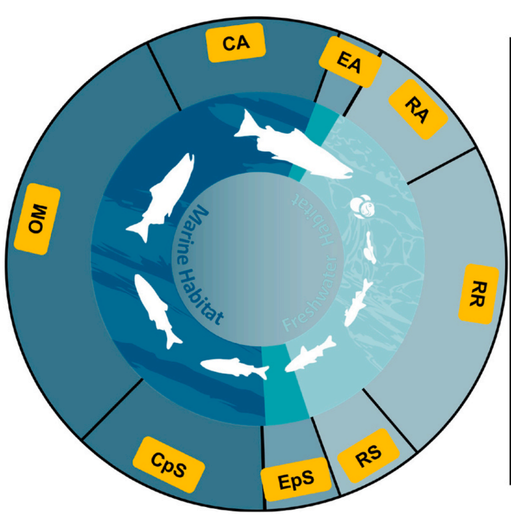
Fig. 2. The organisational structure and technology currently in use to operate the Salmon Ecosystem Data Hub. (1.) The R Shiny package provides the User Interface. (2.) Labelled property graph (NEO4J) provides the metadata catalogue. (3.) A combination of local and remote data storage solutions are provided by multiple technologies. Arrows represent catalogue indexing pathways.

guide videos have been created to assist users with this process and links are available via the application itself.

The fields found in the data submission process are derived from an existing metadata standard, Ecological Metadata Language (EML) (Jones et al., 2019), a strict and structured syntax for documenting research data, which is recognised as a leading metadata standard for ecological sciences. EML is already used by many metadata catalogues, such as the KNB, ensuring every effort put into describing a knowledge resource via SalHub is interoperable with the KNB and other online data portals. The use of EML also opens up pathways for development of SalHub that include implementing data federation capabilities (efficient mirroring of resources across repositories) and more easily leveraging technological advances made across large federated data repository networks (e.g., the Data Observation Network for Earth (DataONE), https://www.dataone.org/). This means that tools for more advanced annotations, version tracking and provenance representation will be available to data resources within SalHub with only minor developer input. SalHub already mirrors metadata to the KNB, albeit with restricted access, as part of this potential development track.

In addition to creating a simple metadata catalogue, a key outcome of SalHub is to implement a data network within which described resources may be indexed, and in turn utilised, in the context of addressing core questions facing Atlantic salmon research and management. The conditions and factors influencing salmon key life history traits (e.g., survival, growth, maturation) will vary continuously and be expressed singly, cumulatively, or in more complex (i.e., additive or synergistic) ways. Understanding and agreeing on the extent of these functional domains and associated data sources provides opportunities to link up valuable data resources and extend the reach of freshwater-based fisheries science to assist with providing a more holistic life cycle view (Bull et al., 2022).

We propose an organisational structure into which salmon-related



Variable Class		Life-Stage Domain: RR	RS	EpS	CpS	OM	CA	EA	RA
Biological Processes	Competitors	X	X	X	X	X			
	Predators	X	X	X	X	X	X	X	X
	Prey	X	X	X	X	X			
Physical Conditions	Water Quality	X	X	X	X	X	X	X	X
	Hydrology	X	X	X				X	X
	Salinity			X	X	X	X	X	
Salmon Traits	Migration Timings		X						X
	Abundance	X	X			X			X
	Condition	X	X	X	X	X	X	X	X

Fig. 3. The Atlantic salmon life cycle and representation of the main Life-Stage Domains used to organise knowledge resources within SalHub (left). Life-Stage Domains: RR - River Rearing, RS - River Migration Smolt, EpS - Estuary Migration Post-smolt, CpS - Coastal Migration Post-smolt, OM - Ocean Migration, CA - Coastal Migration Adult, EA - Estuary Migration Adult, RA - River Migration Adult. The relationship between Life-Stage Domains and an illustrative subset of Variable Classes is expanded in the table (right), giving an index within which data resources are related. Lifecycle graphic developed by Natascia Tamburello at ESSA Technologies (www.essa.com).

knowledge can be classified in this context. This structure incorporates eight classes representing a range of space-time domains occupied by salmon during successive life stages and as they transition between them (Olmos et al., 2019), and 60 subclasses (Variable Classes) based on what we have identified as descriptors for the range of variables that may influence salmon growth and survival (Fig. 3). These life-stage domains and subclasses are presented to the user through a tick box driven interface following on from the initial metadata forms, offering the opportunity to index any knowledge resource within this basic organisational structure.

Variable Classes provide further granularity to the structure of the database indexing network. They are authored with existing definitions in mind, such as the Essential Ocean Variables proposed by GOOS (https://www.goosocean.org/) and the Biodiversity Observation Network's Essential Biodiversity Variables (https://geobon.org/ebvs/), and are either set deliberately narrow, for well-defined observable metrics (e.g., Sea Surface Temperature) or wider to capture sets of observable events (e.g., Pathogens/disease status). Variable classes are grouped into three categories:

- **Physical conditions**: physical metrics that are relevant to salmon at one or more of the main life-stage domains (e.g., estimated wetted accessible area for egg deposition, or daily Sea Surface Temperature time series)
- **Biological processes**: other species that may be relevant (as competitors, prey, predators) to salmon at one or more of the main life-stage domains (e.g., the biomass of sandeels, one of their main prey along marine migration routes, or population trends in known predator species)
- **Salmon traits**: metrics from the salmon themselves, from individual or population measurement or assessment (e.g., data on distribution, abundance or body condition).

This organisational structure also parallels a key aspect of data mobilisation, that of the annotation of data resources with highly defined (dereferenceable) terms describing observations or attributes within the resource. As the landscape of controlled vocabularies and ontologies is potentially confusing to the intended audience (data creators/providers), annotation addresses one of the barriers to user engagement described previously. SalHub's domain-variable class structure offers a discipline specific, and therefore familiar, mechanism to move data resources into a framework which has an emergent property similar to that of metadata annotation. Though currently lacking the formal definitions recommended by the FAIR principles, it provides a step towards more robust data description and annotations that may be deployed in future development, i.e., linking in with existing variable classes such as the Essential Ocean Variables (EOV), Essential Biodiversity Variables (EBV), or controlled vocabularies like the British Oceanographic Data Centre's Vocabulary Server (http://vocab.nerc.ac.uk/collection/).

The domain-variable class structure may also be utilised not only to describe data resources, but to frame research questions. It will assist in assessing the utility of multiple spatial and temporally scaled datasets for inclusion in the testing of hypothesized relationships between the declines in salmon survival and various environmental and ecosystem factors, and in considering their use as future indicators of change. Several key salmon mortality hypotheses have already been indexed within this structure so that data resources can be inherently linked to broad questions.

Fig. 4. The Salmon Ecosystem Data Hub map interface. Resources are automatically clustered by the map software based on proximity and will adjust with the zoom level. Single resource markers (blue), clusters representing 2–9 resources (green), clusters representing 10–99 resources (yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Browsing resources within SalHub is achieved through a set of predefined filters on separate pages. These filters are defined using a selection of mortality hypotheses, through the domain-variable class index directly, or by the spatial properties of the resources displayed on an atlas (Fig. 4) that also incorporates additional layers to enhance the context available to the user (e.g., ICES ecoregions (ICES, 2020b), NAFO Divisions (https://www.nafo.int/About-us/Maps), and/or the NASCO rivers database location data (https://nasco.int/about-nascos-rivers-database/)).

The LPG provides the technical capacity for storing this organisational structure and the metadata captured through the user interface. It is also a versatile starting point for future development opportunities such as linking in with existing knowledge graphing activities (e.g., Akenhead et al., 2021). The LPG itself is not an appropriate place to directly store data files: data and knowledge are ultimately held in digital formats and locations that depend on the nature of the entry and how the user has chosen to store them. There are four distinct possibilities for storing the resource: 1. If data are already available online a URL may be supplied within the metadata, 2. A file may be uploaded along with the metadata directly and stored within the SalHub file store, 3. Structured resources may then be passed on to the SQL database if appropriate, and 4. Data may remain with the metadata author in their own storage solution. Data availability is arranged via correspondence between the requester, the SalHub data administrator, and the owner.

Given the geographic range that salmon cover throughout their life cycle, and the breadth of jurisdictions, and potential knowledge holders, data resources are numerous and widespread. We suggest that SalHub offers novel support for future collaborative research and can contribute to the development of more effective salmon management. Benefits include:

- Centralising the search for information sources relevant to Atlantic salmon.
- Ready consideration of resources within multiple existing online repositories and databases, making it easier to visualise and interrogate the knowledge landscape of the Atlantic salmon, and encourage greater utilisation of valuable and hard-earned datasets.
- As data sources are gathered in a single location, it becomes more achievable to create and share associated workflows from source materials to synthesis and data products. This visibility may be of use to help improve and elaborate on formal data pipelines (e.g., formal data calls in support of cooperative stock assessment exercises (ICES, 2021a), and in assisting with bridging this activity to wider developments in ecosystem-based management.
- Early career scientists may also benefit by accessing a wider professional network of data providers, and later stage career scientists will benefit from the improved re-use and attribution of their outputs.

4. Discussion

Collaborative efforts calling for the development of suitable data mobilisation systems to assist future salmon management across their range are gaining momentum (e.g., Bull et al., 2022; ICES, 2020a; Siegle et al., 2021; Woodward et al., 2021). Ongoing data initiatives (such as the development of SalHub) begin to address these requirements and need to be supported. They provide guidance, and a direction of travel that can be emulated and used to promote effective management change. However, the development of data solutions faces multiple technical and operational challenges to promote widespread uptake of this, or similar, interoperable systems into current and future salmon research, stock assessment and management frameworks.

Whilst it is recognised that simply indexing every potential resource in a single location will not address all the challenges of data and model limitations when there is a requirement to forecast complex ecological systems, we believe it represents a step in the right direction for the future of Atlantic salmon management. Even in its early developmental stages it presents to the ecological sciences a unique tool to bridge the gap between ecoinformatics experts and discipline/species experts, promoting data mobilisation in a space where limited salmon-specific data tools exist. It already supports the development of the Likely Suspects Framework (Bull et al., 2022) by the Missing Salmon Alliance and offers a common platform for the re-synthesis and sharing of knowledge resources, and the promotion of cooperative analysis in support of hypothesis-testing.

As a general example of the database's utility, a researcher interested in processes influencing salmon growth or survival during a specific life stage may engage with SalHub by firstly selecting the appropriate filters (i.e., domains and/or variable classes). These will provide a list of potentially valuable source material to assess the opportunities for hypothesis development and testing. In time, further refinement of search tools will allow users to specify spatial or temporal extents. As a direct example of SalHub's current utility, research efforts to test hypotheses to determine the proximate drivers of changes in early marine survival in southern European Atlantic salmon stocks are underway using it to organise data resources synthesised from various sources. These include oceanographic models (Atlantic Margin Model 7. O'Dea et al., 2017; Scottish Shelf Model. Wolf et al., 2016), salmon marine survival data (ICES, 2021a), river conditions prior to emigration (Hannaford, 2004) and the abundance, composition and distribution of biota from various trophic levels e.g., Continuous Plankton Recorder (Johns, 2011), and pelagic fish species (ICES, 2021c).

Existing online data platforms aimed at salmon research and management tend to focus on visualisations of specific analysis, e.g., the Pacific Salmon Explorer (PSE) https://www.salmonexplorer.ca/ or the Spatial Hydro-Ecological Decision System (SHEDS) https://pitdata.ecosheds.org/fish-movements/). Others, e.g., the SalmoGlob Toolbox (https://sirs.agrocampus-ouest.fr/discardless_app/WGNAS-ToolBox/) (Hernvann et al., 2021), facilitate specific data (i.e., assessment model data input and outputs) synthesis. Collating data and communicating and disseminating trends through visualisations such as those found in the PSE and SHEDS are of the utmost importance to improve public engagement in science. Specific and live syntheses such as SalmoGlob demonstrate novel and critically important pathways to maintaining up-to-date sets of time series data and indirectly provide support for greater communication on the functioning and capabilities of assessment models, fostering the integration of new data in the latter. SalHub performs a unique function in this space, offering strategic enrichment of the knowledge base underpinning current and future salmon research, serving knowledge exchange and resourcing the research activities that these platforms (and others) may potentially draw benefits from.

Development of SalHub is still in its infancy, and several limitations need to be addressed moving forward. It has been launched with the understanding that its long-term success is reliant on the acceptance and use by the wider salmon research community. There is a requirement to consider expansion within the resource to capture valuable fisheries focused Indigenous Knowledge (e.g., Reid et al., 2021; Sethi et al., 2011), and it would be pertinent to explore what community driven solutions (such as SalHub or similar) could offer this effort. A critical approach to the usage, analysis and integration of the resources registered in SalHub by the scientific users will require maintenance, as would be expected regardless of data source. Building closer ties to existing data repository networks (e.g., DataONE) will enhance longevity and ensure that resources can remain sustainable by providing persistent metadata, whilst maintaining a degree of freedom to evolve capabilities that can emerge from community interaction in the development process.

5. Recommendations for improving data mobilisation for salmon management

The scale of progress required to address the challenges facing

Atlantic salmon will require considerable interdisciplinary efforts and a major shift towards improved data integration in order to develop wider ecosystem-based approaches in how salmon stocks are being assessed and managed. It is hoped that data owners populating new resources into SalHub will be encouraged by the opportunities presented to contribute to cooperative research initiatives in the pursuit of improved future salmon management. Further to this altruistic motivation, there are tangible benefits for data owners via increased co-authorship opportunities and direct data citations (Data Citation Synthesis Group, 2014).

For the full potential of SalHub to be realised, extensive cooperative efforts from within the salmon science and management communities will be required in populating knowledge resources and expanding them to include wider sources alongside newly synthesised products. Regular updates and reliable submissions of data from key sources will assist with the promotion, uptake and use of the resource in the science communities, whereas recognition and endorsement by statutory bodies such as NASCO, and established expert groups (e.g., ICES Working Group on North Atlantic Salmon (ICES, 2021a)) would help marshal resources towards addressing critical management needs.

By cooperatively building a data mobilisation network and a user-group that is truly multi-disciplinary, SalHub can provide a new space for innovative data pipelines to be developed and shared, ensuring widespread incorporation of high-quality synthesised products. Assisted and guided by these efforts the synthesis of a wide range of biotic and abiotic indicators for use in stock assessment (Harvey et al., 2020) could promote a greater mechanistic understanding of how and why salmon populations are declining (Woodward et al., 2021). Capitalising on this new knowledge could drive the design of robust, and adaptive, management support systems, providing forecasting capacity, and directing practical actions to address the salmon crisis.

Declaration of Competing Interest

None.

Data availability

Data and code are available on Github and linked to in the manuscript

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References

Akenhead, S.A., Batten, G., Bird, T., Doan, N., Irvine, J.R., Korol, O., Nessman, C., O'Blenis, P., 2021. The salmon of knowledge. In: North Pacific Anadromous Fish Commission (NPAFC) Technical Report No. 17, pp. 130–134.

Almodóvar, A., Nicola, G.G., Ayllón, D., Trueman, C.N., Davidson, I., Kennedy, R., Elvira, B., 2020. Stable isotopes suggest the location of marine feeding grounds of south European Atlantic salmon in Greenland. ICES J. Mar. Sci. 77 (2), 593–603. https://doi.org/10.1093/icesjms/fsz258.

Baker, K.S., Duerr, R.E., Parsons, M.A., 2015. Scientific knowledge mobilization: Co-evolution of data products and designated Communities. Int. J. Digit. Curation 10 (2). https://doi.org/10.2218/ijdc.v10i2.346.

Benson, A., LaScala-Gruenewald, D., McGuinn, R., Satterthwaite, E., Beaulieu, S., Biddle, M., et al., 2021. Biological Observation data standardization - a primer for data managers. Earth Sci. Inf. Partners. https://doi.org/10.6084/m9.figshare.16806712.v1.

Birnie-Gauvin, K., Thorstad, E.B., Aarestrup, K., 2019. Overlooked aspects of the Salmo salar and Salmo trutta lifecycles. Rev. Fish Biol. Fish. 29, 749–766. https://doi.org/10.1007/s11160-019-09575-x.

Bull, C.D., Gregory, S.D., Rivot, E., Sheehan, T.F., Ensing, D., Woodward, G., Crozier, W., 2022. The likely suspects framework: the need for a life cycle approach for managing Atlantic salmon (Salmo salar) stocks across multiple scales. ICES J. Mar. Sci. 79 (5), 1445–1456. https://doi.org/10.1093/icesjms/fsac099.

Chang, W., Cheng, J., Allaire, J.J., Sievert, C., Schloerke, B., Xie, Y., Allen, J., McPherson, J., Dipert, A., Borges, B., 2022. Shiny: web application framework for R. In: R Package Version 1.6.0.. https://shiny.rstudio.com/.

Chaput, G., 2012. Overview of the status of Atlantic salmon (Salmo salar) in the North Atlantic and trends in marine mortality. ICES J. Mar. Sci. 69 (9), 1538–1548. https://doi.org/10.1093/icesjms/fss013.

Coleman, D.C., 2010. Big Ecology. University of California Press.

Core Team, R., 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Crozier, W., Whelan, K., Buoro, M., Chaput, G., Daniels, J., Grant, S., Hyatt, K., Irvine, J., Ó'Maoiléidagh, N., Prévost, E., Rivot, E., et al., 2017. Atlantic salmon mortality at sea: developing an evidence based 'likely suspects' framework. In: Atlantic Salmon Trust report. https://atlanticsalmontrust.org/wp-content/uploads/2020/07/LSF-Blue-Book-June-2018-June-2018-copy-2-.pdf [accessed 10th march 2022].

Crozier, L.G., McClure, M.M., Beechie, T., Bograd, S.J., Boughton, D.A., Carr, M., Cooney, T.D., et al., 2019. Climate vulnerability assessment for Pacific salmon and steelhead in the California current Large marine ecosystem. PLoS One 14, e0217711. https://doi.org/10.1371/journal.pone.0217711.

Crozier, L.G., Burke, B.J., Chasco, B.E., Widener, D.L., Zabel, R.W., 2021. Climate change threatens Chinook salmon throughout their life cycle. Commun. Biol. 4, 1–14. https://doi.org/10.1038/s42003-021-01734-w, 222.

Curtin, R., Prellezo, R., 2010. Understanding marine ecosystem based management: a literature review. Mar. Policy 34 (5), 821–830. https://doi.org/10.1016/j.marpol.2010.01.003.

Cvitanovic, C., Hobday, A.J., van Kerkhoff, L., Wilson, S.K., Dobbs, K., Marshall, N.A., 2015. Improving knowledge exchange among scientists and decision-makers to facilitate the adaptive governance of marine resources: a review of knowledge and research needs. Ocean Coast. Manag. 112, 25–35. https://doi.org/10.1016/j.ocecoaman.2015.05.002.

Data Citation Synthesis Group, 2014. Joint declaration of data citation principles. In: Martone, M. (Ed.). FORCE11, San Diego, CA. https://doi.org/10.25490/a97f-egyk.

De Robertis, A., Levine, M., Lauffenburger, N., Honkalehto, T., Ianelli, J., Monnahan, C. C., Towler, R., Jones, D., Stienessen, S., McKelvey, D., 2021. Uncrewed surface vehicle (USV) survey of walleye Pollock, Gadus chalcogrammus, in response to the cancellation of ship-based surveys. ICES J. Mar. Sci. 78 (8), 2797–2808. https://doi.org/10.1093/icesjms/fsab155.

Dexter, P., Summerhayes, C.P., 2010. Ocean observations - the Global Ocean observing system (GOOS). Chapter 11. In: Pugh, D., Holland, G. (Eds.), Troubled Waters: Ocean Science and Governance, 161-178. CUP, Cambridge.

Fleming, I.A., 2011. Reproductive ecology: a tale of two sexes. In: Aas, Ø., Einum, S., Klemetsen, A., Skurdal, J. (Eds.), Atlantic Salmon Ecology, pp. 33–65.

Forseth, T., Letcher, B.H., Johansen, M., 2011. The behavioural flexibility of salmon growth. In: Aas, Ø., Einum, S., Klemetsen, A., Skurdal, J. (Eds.), Atlantic Salmon Ecology. Wiley-Blackwell, Oxford, pp. 145–161.

Geijzendorffer, I.R., Regan, E.C., Pereira, H.M., Brotons, L., Brummitt, N., Gavish, Y., Haase, P., Martin, C.S., Mihoub, J.B., Secades, C., Schmeller, D.S., 2016. Bridging the gap between biodiversity data and policy reporting needs: an essential biodiversity variables perspective. J. Appl. Ecol. 53 (5), 1341–1350. https://doi.org/10.1111/1365-2664.12417.

Gilbey, J., Utne, K.R., Wennevik, V., Beck, A.C., Kausrud, K., Hindar, K., Garcia de Leaniz, C., Cherbonnel, C., Coughlan, J., Cross, T.F., Dillane, E., 2021. The early marine distribution of Atlantic salmon in the north-East Atlantic: A genetically informed stock-specific synthesis. Fish Fish. 22 (6), 1274–1306. https://doi.org/10.1111/faf.12587.

Gorospe, K.D., Michaels, W., Pomeroy, R., Elvidge, C., Lynch, P., Wongbusarakum, S., Brainard, R.E., 2016. The mobilization of science and technology fisheries innovations towards an ecosystem approach to fisheries management in the coral triangle and Southeast Asia. Mar. Policy 74, 143–152. https://doi.org/10.1016/j.marpol.2016.09.014.

Hannaford, J., 2004. Development of a strategic data management system for a national hydrological database, the Uk national river flow archive. In: Hydroinformatics: (in 2 volumes, with CD-ROM). World Scientific Publishing, pp. 637–644. available from: https://doi.org/10.1142/9789812702838_0078.

Hare, J.A., Morrison, W.E., Nelson, M.W., Stachura, M.M., Teeters, E.J., Griffis, R.B., Alexander, M.A., Scott, J.D., Alade, L., Bell, R.J., Chute, A.S., 2016. A vulnerability assessment of fish and invertebrates to climate change on the northeast US continental shelf. PLoS One 11 (2), e0146756. https://doi.org/10.1371/journal.pone.0146756.

Harvey, C., Garfield, N.T., Williams, G., Tolimieri, N., Andrews, K., Barnas, K., Bjorkstedt, E., Bograd, S., Borchert, J., Braby, C., Brodeur, R., 2020. Ecosystem status report of the California current for 2019-20: A summary of ecosystem indicators compiled by the California current integrated ecosystem assessment Team (CCIEA). In: NOAA technical memorandum NMFS-NWFSC, 160. https://doi.org/10.25923/e5rb-9f55 available from:

Hernvann, P.-Y., Patin, R., Guitton, J., Olmos, M., Etienne, M.-P., Labouyrie, M., Bezier, L., Rivot, E., 2021. WGNAS-SalmoGlob ToolBox: A Web Application for Supporting Atlantic Salmon Stock Assessment at the Scale of the North Atlantic Basin Scale.

Hvenegaard, G.T., Halpenny, E.A., Bueddefeld, J.N.H., 2021. Towards mobilizing knowledge for effective decision-making in parks and protected areas. Land 10, 254. https://doi.org/10.3390/land10030254.

Hyatt, K., Pearsall, L., Luedke, W., 2017. A Risk Assessment Methodology for Salmon (RAMS) Population Conservation and Management within an Ecosystem Context. Department of Fisheries and Oceans. Science Branch, Pacific Biological Station, Nanaimo, British Columbia.

ICES, 2020a. NASCO workshop for North Atlantic Salmon At-Sea mortality (WKSalmon, output from 2019 meeting). In: ICES scientific reports. 2, 69, p. 175 doi: 10.17895/ices.pub.5979.
ICES, 2020b. Definition and rationale for ICES ecoregions (Version 1). Ices Technical Guidelines. https://doi.org/10.17895/ices.advice.6014.
ICES, 2021a. Working group on North Atlantic Salmon (WGNAS). ICES scientific reports. 3, 29, p. 407 doi: 10.17895/ices.pub.7923.
ICES, 2021b. Workshop for Salmon life cycle modelling (WKSalModel). ICES scientific reports. 3, 24, p. 20 doi: 10.17895/ices.pub.7921.
ICES, 2021c. Working group on widely distributed stocks (WGWIDE). ICES scientific reports. 3, p. 95 doi: 10.17895/ices.pub.8298.
Johns, D., 2011. Continuous plankton recorder dataset (SAHFOS) - phytoplankton. v4.1. Sir Alister hardy Foundation for Ocean Science (SAHFOS). Dataset/occurrence. Marine Biological Association. https://doi.org/10.7487/ysaz8e.
Jones, M.B., O'Brien, M., Mecum, B., Boettiger, C., Schildhauer, M., Maier, M., Whiteaker, T., Earl, S., Chong, S., 2019. In: Jones, M.B., et al. (Eds.), Ecological Metadata Language (EML). NCEAS. https://doi.org/10.5063/F11834T2.
Large, S.I., Fay, G., Friedland, K.D., Link, J.S., 2015. Quantifying patterns of change in marine ecosystem response to multiple pressures. PLoS One 10 (3), e0119922. https://doi.org/10.1371/journal.pone.0119922.
Link, J.S., 2010. Ecosystem-Based Fisheries Management: Confronting Tradeoffs. Cambridge University Press, Cambridge, UK.
Litzow, M.A., Hunsicker, M.E., 2016. Early warning signals, nonlinearity, and signs of hysteresis in real ecosystems. Ecosphere 7, 1923–1928. https://doi.org/10.1002/ecs2.1614.
Melero, R., Navarro-Molina, C., 2020. Researchers' attitudes and perceptions towards data sharing and data reuse in the field of food science and technology. Learned publishing 33 (2), 163–179. https://doi.org/10.1002/leap.1287.
Michener, W.K., 2015. Ecological data sharing. Ecolog. Informat. 29, 33–44. https://doi.org/10.1016/j.ecoinf.2015.06.010.
Nguyen, V.M., Young, N., Corriveau, M., Hinch, S.G., Cooke, S.J., 2018. What is "usable" knowledge? Perceived barriers for integrating new knowledge into management of an iconic Canadian fishery. Can. J. Fish. Aquat. Sci. 76 (3), 463–474. https://doi.org/10.1139/cjfas-2017-0305.
O'Dea, E., Furner, R., Wakelin, S., Siddorn, J., While, J., Sykes, P., King, R., Holt, J., Hewitt, H., 2017. The CO5 configuration of the 7 km Atlantic margin model: large-scale biases and sensitivity to forcing, physics options and vertical resolution. Geosci. Model Dev. 10 (8), 2947–2969. https://doi.org/10.5194/gmd-10-2947-2017.
Ohman, M.D., Davis, R.E., Sherman, J.T., Grindley, K.R., Whitmore, B.M., Nickels, C.F., Ellen, J.S., 2019. Zooglider: an autonomous vehicle for optical and acoustic sensing of zooplankton. Limnol. Oceanogr. Methods 17 (1), 69–86. https://doi.org/10.1002/lom3.10301.
Olmos, M., Payne, M.R., Nevoux, M., Prévost, E., Chaput, G., Du Pontavice, H., Guitton, J., et al., 2019. Spatial synchrony in the response of a long range migratory species (Salmo salar) to climate change in the North Atlantic Ocean. Glob. Chang. Biol. 26, 1319–1337. https://doi.org/10.1111/gcb.14913.
Parrish, D.L., Behnke, R.J., Gephard, S.R., McCormick, S.D., Reeves, G.H., 1998. Why aren't there more Atlantic salmon (*Salmo salar*)? Can. J. Fish. Aquat. Sci. 55 (Suppl. 1), 281–287. https://doi.org/10.1139/d98-012.
Reichman, O.J., Jones, M.B., Schildhauer, M.P., 2011. Challenges and opportunities of open data in ecology. Science 331 (6018), 703–705. https://doi.org/10.1126/science.1197962.
Reid, A.J., Eckert, L.E., Lane, J.F., Young, N., Hinch, S.G., Darimont, C.T., Cooke, S.J., Ban, N.C., Marshall, A., 2021. "Two-eyed seeing": an indigenous framework to transform fisheries research and management. Fish Fish. 22 (2), 243–261. https://doi.org/10.1111/faf.12516.
Rikardsen, A.H., Righton, D., Strøm, J.F., Thorstad, E.B., Gargan, P., Sheehan, T., Økland, F., Chittenden, C.M., Hedger, R.D., Næsje, T.F., Renkawitz, M., 2021. Redefining the oceanic distribution of Atlantic salmon. Sci. Rep. 11 (1), 1–12. https://doi.org/10.1038/s41598-021-91137-y.
Rivot, E., Patin, R., Olmos, M., Chaput, G., Hernvann, P.-Y., 2021. A hierarchical Bayesian life cycle model for Atlantic salmon stock assessment at the North Atlantic basin scale. In: ICES WGNAS working paper 2021/26, 22th march - 1st April 2021, p. 99.
Scheuerell, M.D., Hilborn, R., Ruckelshaus, M.H., Bartz, K.K., Lagueux, K.M., Haas, A.D., Rawson, K., 2006. The shiraz model: a tool for incorporating anthropogenic effects and fish–habitat relationships in conservation planning. Can. J. Fish. Aquat. Sci. 63, 1596–1607. https://doi.org/10.1139/f06-056.
Scheuerell, M.D., Ruff, C.P., Anderson, J.H., Beamer, E.M., 2021. An integrated population model for estimating the relative effects of natural and anthropogenic factors on a threatened population of steelhead trout. J. Appl. Ecol. 58, 114–124. https://doi.org/10.1111/1365-2664.13789.
Schulman, L., Lahti, K., Piirainen, E., et al., 2021. The Finnish biodiversity information facility as a best-practice model for biodiversity data infrastructures. Sci. Data 8, 137. https://doi.org/10.1038/s41597-021-00919-6.
Science, Digital, Simons, N., Goodey, G., Hardeman, M., Clare, C., Gonzales, S., Strange, D., Smith, G., Kipnis, D., Iida, K., Miyairi, N., Tshetsha, V., Ramokgola, R., Makhera, P., Barbour, G., 2021. The State of Open Data 2021. https://doi.org/10.6084/m9.figshare.17061347.v1.
Sethi, S.N., Sundarav, J.K., Panigrahi, A., Chand, S., 2011. Prediction and management of natural disasters through indigenous technical knowledge, with special reference to fisheries. Indian J. Tradit. Knowl. 10 (1), 167–172, available from: http://krishi.icar.gov.in/jspui/handle/123456789/42904.
Sharma, L.K., Gupta, R., Pandey, P.C., 2021. Future aspects and potential of the remote sensing technology to meet the natural resource needs. Adv. Remote Sens. Nat. Resour. Monit. 445–464. https://doi.org/10.1002/9781119616016.ch22.
Siegle, M., Litt, A., Saunders, M., Graham, C., Schubert, A., Jasinski, C., Akenhead, S., Erhardt, R., Wells, B., Michielsens, C., Porter, M., Bull, C., and Grant., S. 2021. Roadmap to develop the likely suspects framework: Salmonscape workshop series. North Pacific Anadromous Fish Commission Technical Report No. 16. available from: https://npafc.org/technical-report/.
Simons, R.A., Mendelssohn, R., 2012, December. ERDDAP-a Brokering Data Server For Gridded and Tabular Datasets. Agu Fall Meeting Abstracts (Vol. 2012, IN21B-1473).
Sobocinski, K.L., Greene, C.M., Anderson, J.H., Kendall, N.W., Schmidt, M.W., Zimmerman, M.S., Kemp, I.M., Kim, S., Ruff, C.P., 2021. A hypothesis-driven statistical approach for identifying ecosystem indicators of coho and Chinook salmon marine survival. Ecol. Indic. 124, 107403. https://doi.org/10.1016/j.ecolind.2021.107403.
Strøm, J.F., Rikardsen, A.H., Campana, S.E., Righton, D., Carr, J., Aarestrup, K., Stokesbury, M.J., Gargan, P., Javierre, P.C., Thorstad, E.B., 2019. Ocean predation and mortality of adult Atlantic salmon. Sci. Rep. 9 (1), 1–11. https://doi.org/10.1038/s41598-019-44041-5.
Tenopir, C., Allard, S., Douglass, K., Aydinoglu, A.U., Wu, L., Read, E., Manoff, M., Frame, M., 2011. Data sharing by scientists: practices and perceptions. PLoS One 6 (6), e21101. https://doi.org/10.1371/journal.pone.0021101.
Tenopir, C., Dalton, E.D., Allard, S., Frame, M., Pjesivac, I., Birch, B., Pollock, D., Dorsett, K., 2015. Changes in data sharing and data reuse practices and perceptions among scientists worldwide. PLoS One 10 (8), e0134826. https://doi.org/10.1371/journal.pone.0134826.
Teperek, M., Sansone, S.-A., Dunning, A., 2019. The layered cake of FAIR coordination: how many is too many? Available from. http://blogs.nature.com/scientificdata/2019/10/22/the-layered-cake/.
Thorpe, J.E., 1994. Performance thresholds and life-history flexibility in salmonids. Conserv. Biol. 8 (3), 877–879, available from: https://www.jstor.org/stable/2386536.
Thorstad, E.B., Whoriskey, F.G., Rikardsen, A.H., Aarestrup, K., Aas, Ø., 2011. Aquatic nomads: The life and migrations of the Atlantic salmon. In: Einum, S., Klemetsen, A., Skurdal, J. (Eds.), Atlantic Salmon ecology. Oxford: Wiley-Blackwell, pp. 1–32.
Thorstad, E.B., Bliss, D., Breau, C., Damon-Randall, K., Sundt-Hansen, L.E., Hatfield, E. M., Horsburgh, G., et al., 2021. Atlantic salmon in a rapidly changing environment—facing the challenges of reduced marine survival and climate change. Aquat. Conserv. Mar. Freshwat. Ecosyst. 31, 2654–2665. https://doi.org/10.1002/aqc.3624.
Todd, C.D., Hanson, N.N., Boehme, L., Revie, C.W., Marques, A.R., 2021. Variation in the post-smolt growth pattern of wild one sea-winter salmon (Salmo salar L.), and its linkage to surface warming in the eastern North Atlantic Ocean. J. Fish Biol. 98, 6–16. https://doi.org/10.1111/jfb.14552.
Tréhin, C., Rivot, E., Lamireau, L., Meslier, L., Besnard, A.-L., Gregory, S.D., Nevoux, M., 2021. Growth during the first summer at sea modulates sex-specific maturation schedule in Atlantic salmon. Can. J. Fish. Aquat. Sci. 78, 659–669. https://doi.org/10.1139/cjfas-2020-0236.
Trudeau, R.J., 2013. Introduction to Graph Theory. Courier Corporation.
Vollset, K.W., Urdal, K., Utne, K., Thorstad, E.B., Sægrov Raunsgard, A., Skagseth, Ø., Cooper, R.J., Østborg, G.M., Ugedal, O., Jensen, A.J., Bolstad, G.H., Fiske, P., 2022. Ecological regime shift in the Northeast Atlantic Ocean revealed from the unprecedented reduction in marine growth of Atlantic salmon. Sci. Adv. 8 (9), eabk2542. https://doi.org/10.1126/sciadv.abk2542.
Walsh, J.C., Connors, K., Hertz, E., Kehoe, L., Martin, T.G., Connors, B., Bradford, M.J., Freshwater, C., Frid, A., Halverson, J., Moore, J.W., 2020. Prioritizing conservation actions for Pacific salmon in Canada. J. Appl. Ecol. 57 (9), 1688–1699. https://doi.org/10.1111/1365-2664.13646.
Watz, J., Aldvén, D., Andreasson, P., Aziz, K., Blixt, M., Calles, O., Piccolo, J.J., 2022. Atlantic salmon in regulated rivers: Understanding river management through the ecosystem services lens. Fish Fish. 23 (2), 478–491. https://doi.org/10.1111/faf.12628.
Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.W., da Silva Santos, L.B., Bourne, P.E., Bouwman, J., Brookes, A.J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.T., Finkers, R., Gonzalez-Beltran, A., Gray, A.J.G., Groth, P., Goble, C., Grethe, J.S., Heringa, J., 't Hoen, P.A.C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S.J., Martone, M.E., Mons, A., Packer, A.L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M. A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., Mons, B., 2016. The FAIR guiding principles for scientific data management and stewardship. Sci. Data 3, 160018. https://doi.org/10.1038/sdata.2016.18.
Wolf, J., Yates, N., Brereton, A., Buckland, H., De Dominicis, M., Gallego, A., O'Hara Murray, R., 2016. In: The Scottish Shelf Model. Part 1: Shelf-Wide Domain. Scottish Marine and Freshwater Science, available from: https://doi.org/10.7489/1692-1.
Woodward, G., Morris, O., Barquin, J., Belgrano, A., Bull, C., de Eyto, E., Friberg, N., Layer-Dobra, K., Lauridsen, R.B., Guðbergsson, G., Lewis, H.M., 2021. Using food webs and metabolic theory to monitor, model, and manage Atlantic Salmon-A keystone species under threat. Front. Ecol. Evol. 9 https://doi.org/10.3389/fevo.2021.675261.
Young, N., Gingras, I., Nguyen, V.M., Cooke, S.J., Hinch, S.G., 2013. Mobilizing new science into management practice: the challenge of biotelemetry for fisheries management, a case study of Canada's Fraser River. J. Internat. Wildlife law & Pol. 16 (4), 331–351. https://doi.org/10.1080/13880292.2013.805074.