Maritimes Ecosystem Approach (marea) R package to support an Ecosystem Approach to Fisheries Management

Emily O'Grady, Jamie C. Tam, Andrew M. Edwards, Benoit Casault, Stephanie Clay, Adam M. Cook, Rémi M. Daigle, David Keith, Jaimie Harbin, Cornelia den Heyer, Brad Hubley, Mike McMahon

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ABSTRACT

O'Grady, E., Tam, J.C., Edwards, A.M., Casault, B., Clay, S., Cook, A.M., Daigle, R.M., Keith, D., Harbin, J., den Heyer, C., Hubley, B., McMahon, M. 2026. Maritimes Ecosystem Approach (marea) R package to support an Ecosystem Approach to Fisheries Management. Can. Tech. Rep. Fish. Aquat. Sci. 3755: v + 25 p. https://doi.org/10.60825/cbsa-tx29

Operationalizing Ecosystem Approaches requires access to robust data and information from a variety of sources to integrate ecosystem information into science advice. The marea package provides a stable, metadata-rich data structure and workflow for ecosystem data in Fisheries and Oceans Canada's Maritimes Region. It standardizes how time-series and spatio-temporal datasets are represented, inspected, plotted, and exchanged, using S4 class objects that ensure consistent behavior across data products. This report documents the rationale, design, and core methods of marea, focusing on package architecture and workflows that will remain stable over time. Dynamic content (e.g., specific datasets and values) is intentionally de-emphasized and referenced through a single runtime function that retrieves the current catalog. The package supports transparent metadata, reproducible analysis, and interoperability with related regional tools. This report provides clear background context for potential users and supplements the package vignettes to aid in developing a robust understanding of the data ecosystem.

RÉSUMÉ

O'Grady, E., Tam, J.C., Edwards, A.M., Casault, B., Clay, S., Cook, A.M., Daigle, R.M., Keith, D., Harbin, J., den Heyer, C., Hubley, B., McMahon, M. 2026. Maritimes Ecosystem Approach (marea) R package to support an Ecosystem Approach to Fisheries Management. Can. Tech. Rep. Fish. Aquat. Sci. 3755: v + 25 p. https://doi.org/10.60825/cbsa-tx29

Opérationnaliser les approches écosystémiques nécessite un accès à des données robustes provenant de diverses sources afin d'intégrer l'information écosystémique dans les avis scientifiques. Le R package marea fournit une structure de données stable, riche en métadonnées, ainsi qu'un flux de travail pour les données écosystémiques dans la région des Maritimes du Canada. Il normalise la manière dont les séries chronologiques et les ensembles de données spatio-temporels sont représentés, inspectés, visualisés et échangés, en utilisant des objets de classe S4 qui assurent un comportement cohérent entre les produits de données. Ce rapport documente la logique, la conception et les méthodes fondamentales de marea, en mettant l'accent sur l'architecture du paquet et les flux de travail qui resteront stables dans le temps. Le contenu dynamique (e.g. ensembles de données et valeurs spécifiques) est volontairement mis en retrait et référencé par une seule fonction d'exécution qui récupère le catalogue. Le R package favorise la transparence des métadonnées, l'analyse reproductible et l'interopérabilité avec les outils régionaux. Le présent rapport fournit un contexte de base clair aux utilisateurs potentiels et complète les vignettes du progiciel afin de faciliter l'acquisition d'une compréhension approfondie de l'écosystème de données.

1. Introduction

Ecosystem Based Management (EBM) encompasses a continuum of ecosystem considerations depending on the scope of a particular management focus that ranges from single-stock to multi-sectoral (Tam et al. 2024; Bundy et al. 2025). Along the continuum, Ecosystem Based Fisheries Management (EBFM) utilizes scientific and management methods that examine multispecies fisheries alongside ecosystem information considerations. Ecosystem Approaches to Fisheries Management (EAFM) in Canada is considered an enhancement of single-stock/species fisheries management whereby ecosystem information is incorporated and considered in existing fisheries science and management processes (Fisheries and Oceans Canada, 2025). Currently, only some stocks (~48-55%; Kulka et al. 2022, Oceana 2025) within Canada consider ecosystem information in stock assessments and subsequent science advice documents (e.g. Fisheries Science Advisory Reports), indicating that the department is only partially operationalizing EAFM and not able to provide science advice at the EBFM level (Pepin et al. 2024, Kulka et al. 2022).

At the national level, there is commitment to fully operationalizing EAFM in part to support Fish Stock Provisions (Lafrance & Nguyen, 2018), and to advance fisheries assessment and management processes in light of changing ecosystems for fish stocks (e.g. climate change). In the Maritimes Region, barriers in achieving EAFM for many stocks revolve around data availability, as is the case in the United States (Marshall et al 2019; Bastille et al. 2020). While a great deal of ecosystem information is collected in the region (primarily environmental and ecological, with some economic), the access to such information can be limited by disparate storage methods (e.g. data stored in multiple databases with regulated access, or stored privately by individual researchers), metadata formatting (e.g. multiple units, or context separated from data), and update protocols and timelines. These issues can prevent direct inclusion of ecosystem information into a stock assessment or management process that is required for EAFM in Canada.

The Maritimes Region has been working to enhance collaborations within and across divisions/branches at Fisheries and Oceans Canada (DFO). There are a number of multidisciplinary working groups that aim to describe and solve issues surrounding data and varying levels of EBM, including the R & Git Working Group (Atlantic R WG, 2025), EBM Initiative (EBM Initiative, 2025) and EBFM Working Group (EBFM WG, 2025). Membership in these groups includes computer scientists, oceanographers, fisheries scientists, ecosystem scientists, assessment scientists, and resource managers. These groups can create familiarity among subject matter experts around workflows, issues, and data usages. These groups allow for the exchange of practical information about the implementation of new workflows, provide a forum for discussion of barriers, and to share the efficient development of new solutions.

2. Materials & Methods

Marea R package

Data requirements for fisheries management in the Maritimes Region include ecological and climate data which are distributed across multiple sources, vary in structure and metadata conventions, and differ in temporal and spatial resolution (Galbraith et al. 2025; DFO 2025; Layton et al. 2025). The same is true for products derived from models, such as from population dynamics models and oceanographic models; in this manuscript data is assumed to encompass both observational and modelled data products. This heterogeneity of data and metadata complicates integration and hinders reproducible use in assessments and advisory processes, impeding transparency, reproducibility, and timely synthesis, even though a variety of data products and analyses are available (Cogliati et al. 2025)

To address some of these issues in other regions, products have been developed including Gulf of St. Lawrence Ecosystem Approach R package (`gslea`; Duplisea et al, 2020), and Pacific Ecosystem Approach R package (`pacea`; Edwards et al, 2024). Inspired by this work, the Maritimes Region began developing a sibling R package compatible with other regional Ecosystem Approach (EA) packages. The foundations of this package called, naturally, the Maritimes Ecosystem Approaches (`marea`), was initially developed through a regional workshop led by Dr. Andrew Edwards (lead developer of `pacea`) and a group of Maritimes experts (authors) in oceanography, population ecology, and ecosystem science with R coding and package development experience (see Supplementary 1 for details). The marea R package was developed to meet the specific needs of Maritimes stock assessment teams to support EAFM to reduce identified barriers to incorporation of environmental data including data accessibility and formatting.

Figure 1. Photo of the original marea development meeting, where experts gathered at Bedford Institute of Oceanography to prototype the package with Andrew Edwards of the Pacific region (lead developer of pacea). These early development days allowed for the rapid development of solutions with input from end users and a variety of perspectives including oceanographers, fisheries scientists and technical experts in data management.

The objective of the `marea` package is to provide a predictable data interface, with self-contained, transportable metadata, for curated time-series and spatial datasets which could be used for EBM/EBFM/EAFM in the Maritimes Region (Tam et al. 2025a). By standardizing data representation and access, the package supports consistent analytical workflows and the integration of diverse data products. This package is not intended to act as a data repository or archive, and the products contained in `marea` represent processed data which is ready to be directly integrated into reports and assessments. The package is not intended to house raw data and metadata should always include reference to original archive location of a particular product.

The anticipated outcomes are threefold. First, `marea` promotes consistency in how datasets are stored, summarized, plotted, and shared. Second, it improves reproducibility and transparency in stock assessments, ecosystem status reporting, and management planning by ensuring that metadata accompanies data through all stages of analysis. Third, it establishes a platform for ongoing data curation, provenance tracking, and quality assurance/quality control, without disrupting existing user workflows.

To achieve these outcomes, marea implements standardized S4 classes that define object behavior (`plot`) while ensuring that metadata travels alongside data. Custom functions such as `ea.summary()` and `ea.subset()` also help with data manipulation, and maintenance of self-contained metadata. Constructor functions (`ea_data` and `ea_spatial`) enforce structural requirements and require a minimum metadata standard at object creation. Plotting methods return ggplot2 objects with sensible defaults and style presets, enabling rapid visualization and straightforward customization for publication-quality outputs. Interoperability functions convert objects from external sources (e.g., `pacea`) into marea classes without loss of information, facilitating integration across regional EA packages. It is anticipated that ideas from `marea` and `pacea` will continue to be shared between the packages, even though their structures (e.g. classes) are different, because marea was developed to more closely align with the `oce` package than with `pacea`. Finally, Ecosystem Summary Reports (Tam et al. 2025b) and a Maritimes Ecosystem Indicator Catalogue (Lawlor et al. 2026) uses currently available datasets in marea as a communication interface (e.g. github pages) , thereby avoiding hard-coded inventories in static documents that would quickly become outdated.

Implementation

Marea is organized around a concise, extensible architecture that prioritizes predictable behavior and robust workflows. At its core are two R S4 classes that formalize how ecosystem data are represented and manipulated: `ea_data` for tabular or time-series datasets, and `ea_spatial` for spatial-temporal datasets. These S4 classes were inspired by the object architecture in the `oce` package (Kelley et al. 2025), which provides structures for a variety of oceanographic data and includes a custom metadata slot to encourage the documentation of various data products in reproducible workflows. The design of `marea` structures covers the principal data formats required for ecosystem analyses (tabular and spatial data objects) while keeping the package minimal, and generic for flexibility. The vignettes and Read Me documentation in `marea` on GitHub (Tam, et al., 2025) provide initial guidance on downloading the package and implementing it in existing workflows.

Each class contains two primary slots. The 'data' slot stores the observations themselves, as a data frame or tibble for `ea_data`, and as a spatial object for `ea_spatial` (supporting the packages sf, stars, or terra). The 'meta' slot holds a list of metadata fields that include standardized elements (for example, data_type, units, region, source_citation) as well as user-defined fields which can be extended as appropriate for individual datasets and applications (Figure 2). This structure ensures that metadata travels with the data through all supported operations.

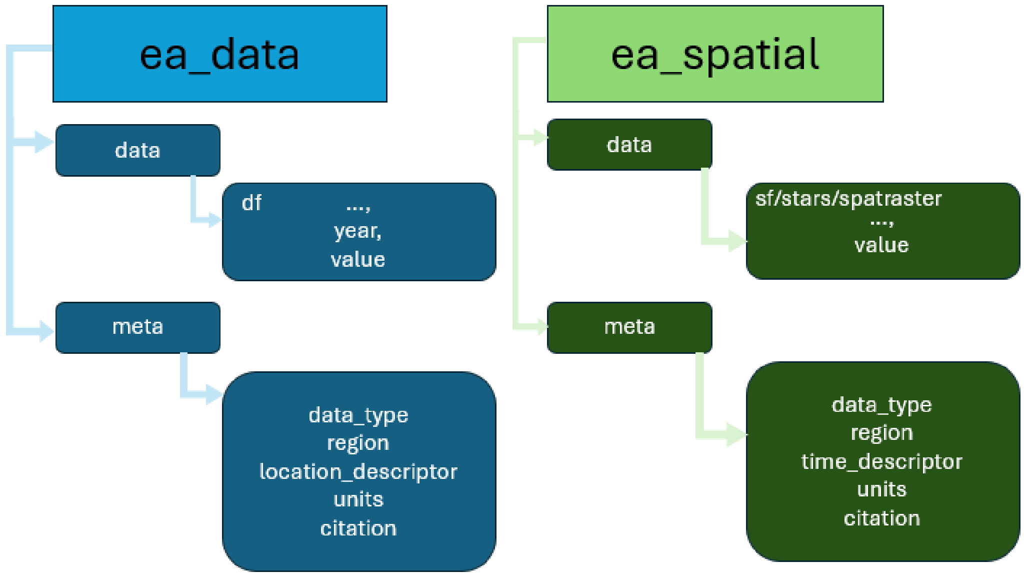

Figure 2 ea_data and ea_spatial object structure as formal R S4 classes. Each has a data and meta slot. The data slots contain values, in either dataframe format for timeseries data contained in ea_data objects, or sf/stars/spatraster spatial data format in ea_spatial. The meta slot contains some required metadata columns, but can be extended to include a user's custom defined metadata slots.

Access to object content is available through two complementary mechanisms. Advanced users may retrieve slots directly using the @ operator (for example, `x@data, x@meta`). For routine use, a custom double-bracket extractor (`[[`) provides a unified interface that first checks the "meta" slot then "data" slot. This ordered resolution enables concise and readable code for both metadata retrieval and data access without exposing slot syntax (Figure 3). This is the same syntax which is implemented in `oce` (Kelley et al. 2025).

```
library(marea)
data(“azmp_bottom_temperature”)
azmp_bottom_temperature@meta
# outputs meta slot as a list
azmp_bottom_temperature@meta$units
#output single metadata value
azmp_bottom_temperature[[‘year’]]
#outputs a vector of year values from the data slot
```

Figure 3. Example R code using different methods to access items within a marea ea_data object. Using the @…$ syntax allows direct selection, where the '[[' syntax will scan meta and data slots and return the first result

The package supplies a coherent set of methods that implement common analytical workflows. For inspection, `ea.print()` and `ea.summary()` provide structured object summaries, including metadata, variable previews, and basic diagnostics. For visualization, `plot()` methods are defined for both classes and return ggplot2 objects with sensible defaults and style presets. For `ea_data`, styles include default, ribbon, anomaly, and biomass and others; for `ea_spatial`, styles include fill, contour, and bubble and others (Figure 4). Plot details can be accessed through R with ``?`plot,ea_data-method` ``. Sub-setting functions (for example, `ea.subset()` and `ea.subset.spatial()` enable filtering by time, attributes, or spatial descriptors while preserving associated metadata, and standard indexing on the data slot remains available where appropriate.

```
# Load and plot North Atlantic Oscillation index
data(nao)
plot(nao)
```

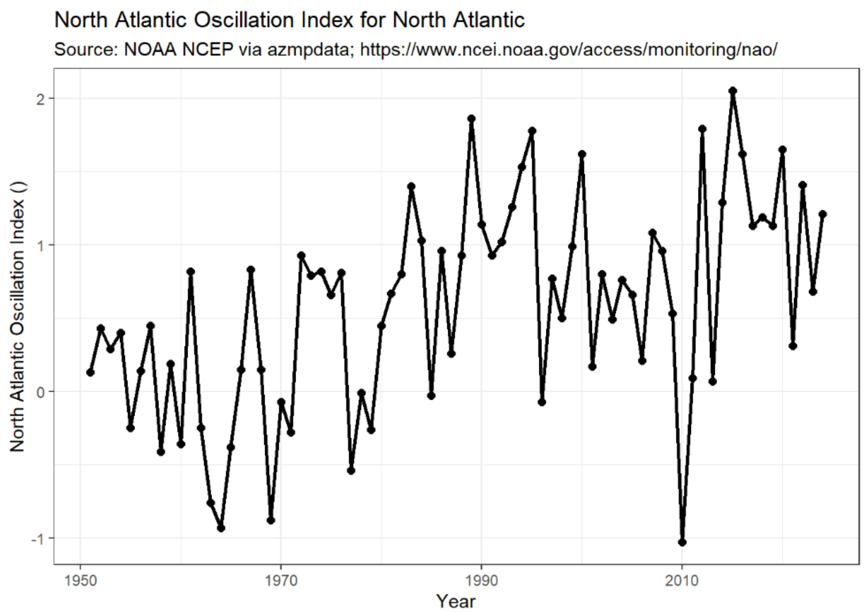

Figure 4. Example R code and resulting plot showing simple visualization of NAO (North Atlantic Oscillation) Index values over 1950-2020. This marea default plot has created a ggplot2 object which can be layered and adjusted based on user preferences, while the default still maintains value for data manipulation and early analysis. The marea defaults also encourage clear metadata including the citation as the subtitle, and clear axis labels (with units when applicable).

The package distributes a growing catalog of curated, analysis-ready indices and spatial fields, including climate indices, ecological indicators, and physical data products, with provenance, units, and regional descriptors embedded in object metadata (see Supplementary 2 for list). Automated continuous integration (R CMD check) and code coverage enforce stability of the user-facing package on GitHub and guard against errors, supporting reliable use in assessment, reporting, and research settings.

The `ea_data` class represents one-dimensional series or tabular datasets such as annual abundance estimates and climate indices. Its constructor requires the following arguments: a data frame or tibble supplied as data; the name of the primary measurement column(s) specified via value_col; and core metadata fields including data_type, region, units, and source_citation (Table 1). Optional metadata can be provided to refine context, for example, species, location_descriptor, and any additional key–value pairs such as assessment year. Upon construction, `ea_data` standardizes value columns by renaming them internally to the form originalname_value, and validates inputs for required fields and types.

The `ea_spatial` class represents gridded or spatial-temporal datasets and accepts inputs in widely used spatial formats (sf, stars, or terra). Its constructor requires a spatial object supplied as data; the value_col identifying the primary field; and the same core metadata fields as an ea_data object (data_type, region, units, source_citation), with the addition of a time_descriptor that records the temporal scope of the dataset (Table 1). The class stores spatial bounds and temporal descriptors in the metadata and supports plot styles appropriate to spatial data, including fill and contour, enabling consistent visualization across products.

Metadata

The marea package implements explicit principles for metadata to ensure provenance, consistency, and interpretability across datasets. At a minimum, each object records the data_type, region, units, and source_citation, and may include domain-relevant descriptors such as species or a time_descriptor that clarifies temporal scope. The constructor function supports extensibility: users may supply arbitrary named metadata fields that are embedded at creation and preserved through subsequent operations, enabling objects to carry context-specific information through standard workflows. Provenance is emphasized through the required source_citation and an optional details field that captures processing steps and automated conversion notes (for example, “Converted using marea::as_ea_data() YYYY-MM-DD”), thereby supporting traceability and auditability.

Data conventions are defined to promote internal consistency and reduce ambiguity. For time series, the data slot uses a canonical “year” field (with optional “month” or seasonal indicators where appropriate) and standardizes the primary measured or derived quantity to the column name “*originalname*_value.” Uncertainty information may be provided via companion columns such as “lower” and “upper,” which are recognized by downstream methods but remain optional. For spatial datasets, the coordinate reference system (CRS) is documented in the data slot as part of the spatial object, the primary field is standardized via value_col. In the meta slot, time_descriptor articulates temporal coverage (for example, “July 2023”). These conventions enable uniform plotting, summarization, and subsetting across heterogeneous sources.

While `marea` does not mandate a single external metadata schema, the fields it maintains are readily mapped to widely used environmental metadata concepts, including units, geographic region, source, and temporal coverage. The minimum metadata standard for `marea` maps well to Ecological Metadata Language (EML) (Table 1) for exporting data to standardized international platforms. This approach balances rigor with flexibility: it preserves compatibility with common standards and facilitates future harmonization efforts, while allowing researchers to encode additional, project-specific descriptors needed for assessment, reporting, and synthesis.

Table 1 Metadata requirements for ea objects in marea

Marea field name	**Field description**	**Mapping to Ecological Metadata Language**
data_type	A character string defining the type of data contained in the EA object	title: Please use only alphanumeric characters, hyphens, or underscores.
region	The region in which data was collected, can be a DFO region, oceanographic region or NAFO area or Conservation area name	NA
location_descriptor	[ea_data] A more detailed description of the geographical range of the data product	geographicCoverage: a short text description of the area. E.g. the river mouth of the Scheldt Estuary.
time_descriptor	[ea_spatial] The temporal range of the data product	temporalCoverage : Use ISO 8601
units	A unit descriptor for the value(s) in the data product	units
source_citation	A citation or source for the data product presented	citation : A single citation for use when citing the dataset

Plotting

The `marea` package provides a consistent plotting interface for both time-series and spatial data, with style presets that produce informative defaults suitable for rapid exploration and report-ready figures. For time-series objects (`ea_data`), available styles include: default, which renders a line with points; ribbon, which overlays uncertainty bands; plain, which provides a line without points; anomaly, which displays positive and negative anomaly values as bars. For spatial objects (`ea_spatial`), the package supports fill maps for continuous fields, contour plots that depict isolines, and bubble plots where symbol size and/or color reflect point values.

All plotting methods return standard ggplot2 objects, enabling users to add additional layers (for example, smoothing curves or reference lines), adjust scales and legends, apply custom themes, and assemble multi-panel figures. These capabilities allow analysts to begin with sensible defaults and then incrementally tailor outputs for publication, assessment documents, or exploratory data analysis while maintaining familiar plotting functions across datasets.

Typical usage follows simple, readable patterns. A call to `plot(x)`, where `x` is an ea object, provides a quick diagnostic visualization of any ea object using context-appropriate defaults. When uncertainty bounds are available in time-series data, specifying `plot(x, style = "ribbon")` highlights interval information. For spatial fields, `plot(spatial_obj, style = "fill")` combined with appropriate color scales yields publication-ready maps. This approach balances speed and flexibility: defaults facilitate immediate insight, and the underlying ggplot2 structure supports precise, reproducible customization.

```
library(marea)
library(ggplot2)
library(ggtext)
data("grey_seals")
plot(grey_seals, style = 'ribbon') +
       labs(
             title = "Grey Seal Abundance on Sable Island") +
      theme_bw(
        # increase title and subtitle size
        base_size = 14)+
      theme(
        # wrap subtitle text
        plot.subtitle = ggtext::element_textbox_simple())
```

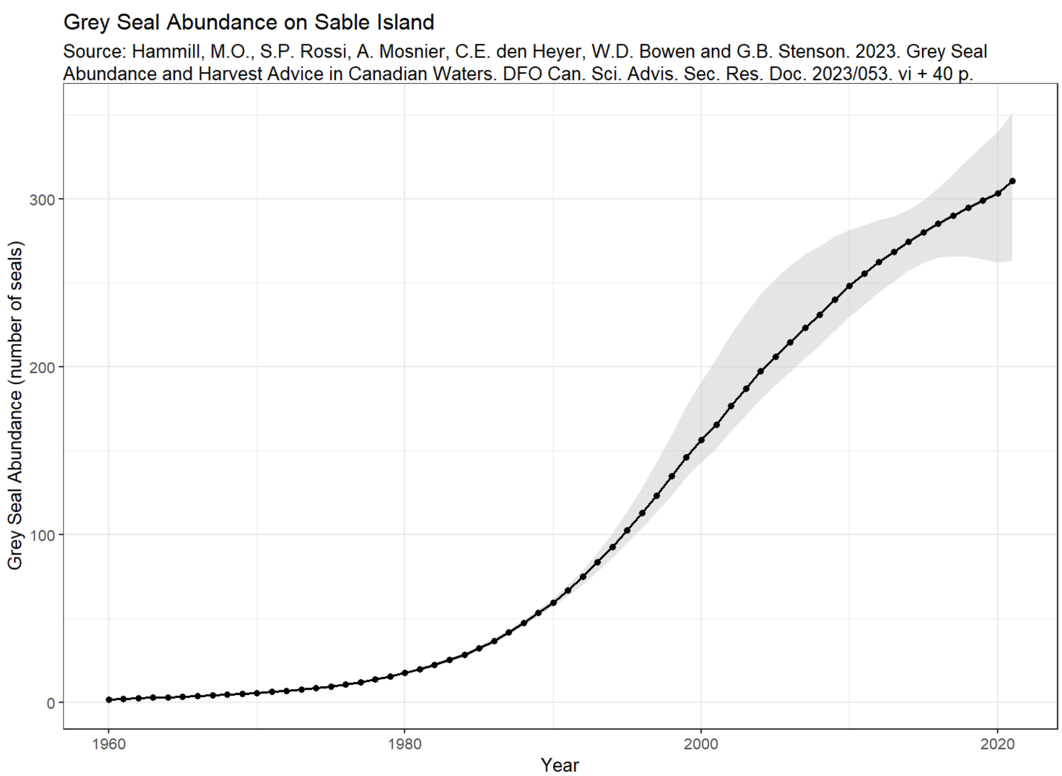

Figure 5. ggplot2 code to produce the bottom custom plot, which shows integrated population model ensemble estimates of total abundance for the Scotian Shelf herd (Hammill et al. 2023). Points represent posterior medians while lines represent the 95% uncertainty intervals.

Interoperability and extensibility

The `marea` package is designed to be extensible to new data products and institutional needs. To facilitate integration of external sources, the package provides a conversion pathway via `as_ea_data()`, which transforms compatible datasets (including products from `pacea`) into `ea_data` objects. During conversion, the primary measurement column is carried over using value_col, and essential metadata such as source and temporal descriptors are added or harmonized into the meta slot from attributes and user provided values. This approach preserves information content, enabling cross-package workflows without data loss or ad hoc restructuring. It is anticipated that ideas from `marea` and `pacea` will continue to be shared between the packages, even though their structures (e.g. classes) are different.

Interoperability extends to visualization and spatial analysis. Because all plotting methods return `ggplot2` objects, users can employ the extensive "grammar of graphics" to adapt figures for exploration, reporting, and publication. For spatial data, `ea_spatial` accepts widely used formats (`sf`, `stars`, and `terra`), ensuring compatibility with established geospatial operations, including projection, subsetting, and raster–vector transformations. This design choice allows marea objects to participate directly in existing analytical pipelines and to benefit from ongoing advances in the broader R geospatial community. The simplicity of the plotting defaults is intended for fast data visualization during data manipulation and cleaning stages, but the `ggplot2` objects can be used as a starting point for existing publication figure code. In this way we are not attempting to replace or improve upon existing visualization code, especially for formal assessments and publications, but to encourage data exploration during early analysis.

The package is also intentionally extensible with respect to metadata. Users can embed additional, domain-specific context in object creation without breaking methods or altering core behavior. These custom fields are preserved through standard operations and can be queried alongside standardized metadata, thereby supporting richer documentation and downstream interpretation while maintaining a stable, predictable interface.

Reproducibility, QA/QC, and governance

`Marea` promotes reproducibility and good governance through explicit versioning, automated testing, and transparent provenance. The package provides data publicly and validates that all data submissions meet necessary standards for publication including unclassified data classification. The package is versioned and developed openly; code and dataset updates are tracked in the GitHub repository, and an archival DOI (10.5281/zenodo.15706086) is issued via Zenodo to support citation and long-term reference. The package and DOI are updated annually in concurrence with the annual data cycle, new products are released typically in March and subsequently loaded into `marea`. This combination provides clear identifiers for releases and facilitates traceability across assessment cycles and publications.

Quality assurance and control of the code are enforced through continuous integration and unit testing in the `testthat` framework. Routine R-CMD-check workflows verify build integrity across platforms, and code coverage (via `codecov`) monitors the extent to which constructors, methods, and plotting routines are exercised by tests. These safeguards reduce the risk of regressions, ensure stability of the user-facing code, and provide early detection of issues introduced by any changes.

Data assurance is anchored in constructor validation and explicit metadata. Required fields and types are checked at object creation, and plotting methods verify the presence of needed columns before rendering. Provenance and measurement units are recorded in metadata to prevent misinterpretation and to enable consistent reuse. Comprehensive documentation, including vignettes on class behavior, plotting, and object construction from user data, supports correct application of the package. Dynamic inventories of available datasets are exposed via the `marea_metadata()` function, ensuring that users can retrieve an up-to-date catalog without relying on static, easily outdated listings. Together, these measures foster transparent, reproducible workflows suitable for assessment, advisory, and research contexts.

This R package was developed in R v.4.4.3 (R Core Team 2025) using many supporting packages, we are grateful to all of the continued efforts of the R development community (for full list of package dependencies, see Supplementary 3).

Available data types

Enumerating specific datasets in a static technical report is inherently fragile, as inventories evolve with ongoing curation and releases. Data available at the time of publication is available in Supplementary 2. To provide a durable access pattern, users are directed to query the package directly. The function `marea_metadata()` returns the current catalog of packaged datasets together with their metadata, including titles, regions, units, and brief descriptions. Any listed dataset can then be loaded using `data("<name>")` and examined with `ea.print()` and `ea.summary()` to verify structure and provenance before analysis. For authoritative and up-to-date information on contents, versioning, and data notes, users should consult the project repository (https://github.com/MarEcosystemApproaches/marea) and the archival DOI landing page (https://doi.org/10.5281/zenodo.15706086). This approach decouples long-lived documentation from a dynamic catalog, ensuring that workflows remain reproducible as the package grows.

Uses of AI

AI tools have been used selectively to accelerate development tasks that benefit from drafting, templating, or refactoring without compromising scientific integrity. In this project, effective uses include preparing and editing documentation outlines, README sections, and code comments; generating unit testing structures to maintain consistent useability of the package and reproducible examples for documentation. All use-cases are subsequently validated by development team members.

Use is constrained by explicit guardrails and follows best practices as outlined for the federal public service (Government of Canada, 2025). No AI-derived data transformations are accepted. All AI-assisted code and text are reviewed by domain experts, and correctness is enforced through unit tests and continuous integration. Sensitive or unpublished data are not shared with external services; when AI assistance is employed, offline or enterprise tools are preferred where applicable.

The net effect of this approach is faster iteration on documentation and examples while maintaining robust human oversight. This balance improves productivity and consistency, reduces the likelihood of errors, and preserves the rigor expected of scientific software used in assessment, advisory, and research contexts.

3. Results

EA Data science support across fisheries management cycles

The package supports multiple components of Fisheries and Oceans science and advice including stock assessment and ecosystem context, enablement of rapid retrieval and standardized visualization of climate indices, environmental variables, and ecological indicators, which thereby streamlines inclusion of contextual information in assessment documents. For ecosystem status reporting and advisory processes, consistent time-series graphics and metadata-rich objects facilitate efficient report production and transparent peer review. In management strategy evaluation and risk assessment, the availability of ready-to-use covariates, with supporting metadata, supports reproducible conditioning of scenarios and sensitivity analyses. For research and synthesis, the standardized classes simplify comparative analyses across indices and regions and integrate readily into programming workflows such as R Markdown. Finally, for spatial planning and monitoring, harmonized spatial fields allow consistent mapping of environmental conditions to support survey design, area-based management, and related applications.

Continued Product Development

Development will proceed along clearly defined near- and medium-term (approx. three year) paths to strengthen reliability, usability, and interoperability. In the near term, priorities include expanding unit test coverage. The package will also extend its repertoire of plotting styles and introduce theming utilities aligned with common report formats to streamline production of consistent graphics.

Medium-term work will focus on additional data including optional connectors to remote catalogs where governance and data-sharing policies permit. The project will also provide enhanced guidance for metadata harmonization, with recommendations to facilitate mapping `marea's` fields to external standards and institutional schemas.

Community engagement is central to sustained quality and relevance. Issues and pull requests are welcomed through the GitHub repository, and contribution guidelines included in the repository outline coding standards, review processes, and documentation expectations. Users and contributors can access resources and submit feedback at https://github.com/MarEcosystemApproaches/marea.

The package will be continuously maintained by the core marea development team through quarterly development meetings. Data products will be updated annually in sync with the `azmpdata` package updates and AZMP reporting publication in late March (Casault et al. 2025).

4. Discussion

The `marea` package contributes to a growing ecosystem of tools which encourage transparent and reproducible science workflows, including other R packages managing ecosystem approaches in other regions (`pacea` and `gslea`), an R package which supports reproducible reporting for Canadian Science Advisory Secretariat meetings (`csasdown`, Anderson, 2026) and departmental efforts to move towards reproducible workflows (Gomez et al., 2020). The package, which improves data accessibility and provides tools for data manipulation, will facilitate the use of ecosystem and environmental data products in reproducible workflows across fisheries science. The self-contained metadata standard and clear data provenance supports the use of environmental data in fisheries science, aligned with FAIR principles (Wilkinson et al., 2016). The package specifically targets interoperability which is a principle that is not often fully implemented in marine sciences, creating barriers to data usage. The package is designed for immediate implementation in ecosystem based fisheries management, stock assessments and ecosystem reporting products in the Maritimes region. This package also assists data users and providers in moving toward implementation of CARE principles (Carroll, 2020), prioritizing accessibility for collective benefit and data provenance supporting authority to control.

`The marea package` contributes to both fisheries science through the improved accessibility to environmental data, and also to environmental monitoring programs, such as the Atlantic Zone Monitoring Program (AZMP). AZMP benefits from improved data accessibility and clear provenance which can support monitoring programs by elucidating the national impacts and use cases for the valuable datasets collected. This has been a goal since early in the program (Ouellet, 2003).

The `marea` package enables reproducible, ecosystem-informed advice by implementing a simple, stable, and metadata-rich object system that serves both time-series and spatial data. Its core value lies in predictable behavior: users can load, inspect, plot, subset, and analyze diverse datasets using a common interface, with metadata preserved at every step to maintain provenance and interpretability.

By focusing this project on architecture and workflow, and delegating dynamic inventories to the package catalogue, the documentation remains durable even as the data catalogue evolves. The package is production-oriented, tested, versioned, and well documented, and interoperates with widely used R tools for analysis and visualization. Adoption is encouraged across assessments, ecosystem status reporting, and research. Feedback and contributions from the community are welcome to further expand and refine the ecosystem data foundation for the Maritimes Region. The `marea` package will continue to evolve within the ecosystem assessment environment nationally at DFO and collaboration with `pacea` and `gslea` will continue to inform priorities and increase efficiencies across national workflows.

5. Conclusion

Overall, the `marea` package strengthens the foundation for transparent, reproducible, and ecosystem-informed fisheries science by improving access to ecosystem data and standardizing its use within analytical workflows. The stable, metadata-rich class system and focus on interoperability helps to enable and encourage integration of ecosystem information into stock assessments and fisheries management (i.e. implementing EAFM). By engaging a broad community of users throughout its development, `marea` is positioned for adoption across Divisions and Branches of DFO, supporting more consistent, efficient, and ecosystem-informed approach to fisheries science advice provision.

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Supplementary 1. List of participants, affiliations, and expertise

Participant	Role	Affiliation	Expertise
Jamie C. Tam	Organizer	MAR OESD	Ecosystem Science
Andrew Edwards	Lead Developer	PAC PBS	Fisheries Ecology
Emily O'Grady	Developer	MAR OESD	Oceanography, data science
Benoit Casault	Data provider	MAR OESD	Biological Oceanography
Stephanie Clay	Data provider	MAR OESD	Biological Oceanography
Adam M. Cook	Assessment lead	MAR PESD	Population Ecology, lobster
Rémi M. Daigle	Developer	MAR SSPPI	Oceanography, tool development
David Keith	Assessment lead	MAR PESD	Population Ecology
Jaimie Harbin	Developer	MAR SSPPI	Oceanography, tool development
Nell den Heyer	Assessment lead	MAR OESD	Population Ecology, Seals
Brad Hubley	Assessment lead	MAR PESD	Population Ecology
Mike McMahon	Developer	MAR PESD	Data manager
Alida Bundy	Data provider	MAR OESD	Ecosystem-Based Management
Emmanuel Devred	Data provider	MAR OESD	Oceanography

Supplementary 2: List of products available in the marea package as of March 4, 2026.

Dataset
Atlantic Multidecadal Oscillation index (AMO)
Arctic Oscillation Index (AO)
Bottom temperature
Salinity
Surface temperature from satellite
Stratification
Surface temperature
Ecological indicators
Bottom temperature from GLORYS model
Grey seals
North Atlantic Oscillation index (NAO)
Satellite Ocean Colour
North Pacific Gyre Oscillation (NPGO)
Oceanic Niño Index (ONI)
Pacific Decadal Oscillation (PDO)
Southern Oscillation Index (SOI)

Supplementary 3. List of dependent packages

Packages included, akima v. 0.6.3.6 (Akima and Gebhardt 2025), azmpdata v. 0.2019.0.9100 (Casault et al. 2025), devtools v. 2.4.5 (Wickham et al. 2022), here v. 1.0.2 (Müller 2025), knitr v. 1.50 (Xie 2014, 2015, 2025), maps v. 3.4.3 (Becker et al. 2025), marea v. 1.0.0 (Tam et al., n.d.), mockery v. 0.4.4 (Finkelstein et al. 2023), pacea v. 1.0.0 (Edwards et al. 2024), pals v. 1.10 (Wright 2025), patchwork v. 1.3.2 (Pedersen 2025), remotes v. 2.5.0 (Csárdi et al. 2024), rerddap v. 1.2.1 (Chamberlain 2025), reticulate v. 1.42.0 (Ushey et al. 2025), rmarkdown v. 2.29 (Xie et al. 2018, 2020; Allaire et al. 2024), rnaturalearth v. 1.1.0 (Massicotte and South 2025), sf v. 1.0.21 (Pebesma 2018; Pebesma and Bivand 2023a), sinew v. 0.4.0 (Sidi 2022), stars v. 0.6.8 (Pebesma and Bivand 2023b), terra v. 1.8.60 (Hijmans 2025), testthat v. 3.2.3 (Wickham 2011), tidyterra v. 0.7.2 (Hernangómez 2023), tidyverse v. 2.0.0 (Wickham et al. 2019), units v. 0.8.7 (Pebesma et al. 2016), usethis v. 3.1.0 (Wickham et al. 2024).

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