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An interactive data tool for ecosystem service value assessment in the Great Barrier Reef

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A R T I C L E I N F O

Dataset link: SYNTHESEAS: Datasets supporting the cultural Ecosystem Service Value Chain of research to institutions (Reference data)

Keywords:
Ecosystem services
Environmental decision-making
Social-ecological systems
Data integration
Marine resource management
Ecosystem service valuation

A B S T R A C T

SYNTHESEAS (System for iNTegrating Human dimensions, Ecosystem Services and Economic Assessment for Sustainability) is an interactive R Shiny application developed by Commonwealth Scientific Industrial Research Organisation (CSIRO) to catalogue and share metadata on datasets related to ecosystem service values in the Australian Great Barrier Reef (GBR) region. Designed primarily for environmental managers, policy-makers, and researchers, the platform supports more informed decision-making by providing a structured overview of data describing the uses, benefits, and values associated with GBR ecosystems. SYNTHESEAS users can explore and filter datasets by ecosystem service category (Provisioning, Regulating, Cultural), specific service types (e.g. recreational fishing), and major beneficiary groups (Government, Households, Industry, and First Nations Peoples). The tool also enables filtering along key components of the Ecosystem Service Value Chain (ESVC), including types of use, methods of quantification or qualification, economic multipliers, and derived values. By integrating diverse data sources and making them accessible through an intuitive interface, SYNTHESEAS facilitates transparent, inclusive, and spatially nuanced assessments of ecosystem service values that pertain to marine social-ecological systems.

1. Introduction

With global anthropogenic changes posing escalating threats to natural ecosystems, better understanding the complex interdependencies between humans and the environment is becoming an urgent global imperative (IPBES, 2019). To address these threats, particularly in the coastal/marine context, environmental managers seek long-term, high-quality datasets that incorporate diverse socio-economic data for practical decision-making. However, research has shown that there is a deep imbalance in available data, with biophysical data being predominantly collected (Chan et al., 2020; Howie, 2021; Rendón et al., 2019; Saunders et al., 2024; Shi et al., 2022). While most socio-economic data products are openly accessible and discoverable, few (if any) adequately align with the specific needs of end users (Jetz et al., 2019). Although a wealth of free data is available, it remains highly fragmented, dispersed across numerous institutions and platforms, hindering integrated analysis and effective application (Hardisty et al., 2019). This persistent lack of socio-economic and cultural data in marine ecosystem studies undermines effective management in conservation and policy-making and constrains our understanding of how people interact with marine environments (Hicks et al., 2016).

Research on Ecosystem Services (ES) has grown over the past two decades, offering one avenue for bridging the knowledge gap between human societies and the natural capital they rely on for their survival. ES encompass the many goods and services provided by natural ecosystems, that contribute to human well-being in numerous ways

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(Millennium Ecosystem Assessment, 2003). While ecosystem services (ES) research has historically been dominated by terrestrial systems (Barceló, 2023; Campagne, 2023; Carrasco De La Cruz, 2021; Liquete et al., 2013; Martin et al., 2016; Müller et al., 2020; Rodrigues, 2017), a growing body of work has examined ES in coastal and marine environments (e.g. Arkema et al., 2015; Barbier et al., 2011; Guerry et al., 2015; Liquete et al., 2013). However, these studies remain comparatively limited in their translation into spatially explicit, decision-ready tools for coastal and marine planning, leaving practitioners with constrained ES-based guidance for operational decision-making.

This is certainly the case for the Australian Great Barrier Reef (GBR), the world's largest coral reef ecosystem and a UNESCO Word Heritage site since 1981. Despite the GBR being an iconic coastal system of immense importance to the Australian economy ($9 billion/year) and the livelihoods of thousands of people (77,000 jobs) (Ibrahim et al., 2025), there is dramatic scarcity of socio-economic data about it that is readily available to support GBR managers. In 2015 the Great Barrier Reef Management Authority (hereafter "The Reef Authority") guided the Reef 2050 Integrated Monitoring and Reporting Program (Australian Government and Queensland Government, 2023) (RIMReP) highlighting the overarching need to address critical data gaps to support effective monitoring and decision-making. Attempts to address these gaps have resulted in over 200 datasets being identified by Gooch et al. (2019) as relevant to people's uses and benefits from the Reef, but they did not connect these to ecosystems nor created a central repository collection of these to be accessible by others. User requirements for socio-economic data relating to the GBR are diverse and dynamic, evolving in response to changing management priorities and environmental conditions. Since then, a RIMReP Data Management System (DMS) has been built by Integrated Marine Observation Systems (IMOS) Reef Data Services and Infrastructure to help deliver datasets related to the Reef to help address this critical need. Unfortunately, such tools are still limited due to various issues or constraints, including legal voids, lack of skills needed to extract data, lack of information about data quality and usability, unidentified levels of ES uses and users, Indigenous Cultural and Intellectual Property (ICIP) protocols, data ownership issues, lack of consistent terminology and datasets not being systematically linked to ES.

These limitations have prompted numerous studies and discussions examining Great Barrier Reef (GBR) data user needs, available services and products, data-sharing practices, and the application of FAIR (Findable, Accessible, Interoperability, and Reusable) and CARE (Collective benefit, Authority to control, Responsibility, Ethics) principles for Indigenous data (Carroll et al., 2020; European Commission Directorate-General for Research and Innovation, 2018; Wilkinson et al., 2016). Despite these efforts, relatively little attention has been given to developing systematic solutions and strategies aimed at improving data products for a wider community of users. Sound decision-making regarding the trade-offs inherent in ecosystem management, land-use change, and activities impacting ecosystems and biodiversity relies on the availability of improved and more comprehensive information about the many contributions of ecosystems to our well-being, as well as a repository to access relevant datasets.

This paper details the interactive data tool called SYNTHESEAS (SYstem for iNTegrating Human dimensions, Ecosystem Services and Economic Assessment for Sustainability), designed in collaboration with the Reef Authority. SYNTHESEAS is supported by a new framework we designed and applied, called *Ecosystem Services Value Chain* (hereafter ESVC) (De Valck et al., 2023). The ESVC contributes a novel approach to organising and evaluating the extent, quality, and usability of existing ES-related socio-economic data associated with various types of stakeholders in the GBR area.

The primary objective of SYNTHESEAS is to provide information on economic welfare values related to ES measured primarily in monetary units. By communicating such values in monetary terms, we provide recognisable and comparable information that can be used to internalise the importance of nature in decision-making. It delivers reliable and readily accessible information on the economic benefits generated by ecosystems and biodiversity, as well as the costs associated with their loss/degradation, thereby supporting decision-making related to nature conservation, ecosystem restoration, and sustainable management of the GBR. This study contributes to indicator science by developing and demonstrating an interoperable indicator architecture that integrates environmental, social, governance, and stewardship indicators within a unified social–ecological decision-support platform.

2. Methods

2.1. Application to the Great Barrier Reef case study

Extending more than 2300 km along Australia's northeastern coastline and encompassing an area of approximately 344,400 km^2, the GBR represents the largest coral reef ecosystem on Earth(Great Barrier Reef Marine Park Authority, 2019). The ESVC framework (Coggan et al., 2026) was developed to support tracking socio-economic objectives towards the Reef 2050 Plan (Australian Government and Queensland Government, 2023), especially to understand: 1. who uses the Reef, 2. for what purposes; and 3. how do these natural resource users benefit (ES values). The ESVC emerged to reconcile the objectives of making socio-economic data both decision-maker friendly and ecosystem-relevant, with the SYNTHESEAS tool developed to provide easy access to relevant ESVC datasets. In consultation with the Reef Authority, the statutory legislative Authority for the Great Barrier Reef Marine Park (the Marine Park), two spatial areas were selected for the study: the Cairns Area Plan of Management zone (CAPOM) and the Keppels Capricorn Bunkers (KCB) (see Fig. 1). These areas were chosen due to the complexity and often contested interactions between multiple local ES beneficiaries, and the need to turn data into actionable information to enable re-evaluation of current policies for ongoing improvements to Reef management.

2.2. Data and metadata collection stages

2.2.1. User needs assessment

Understanding user requirements is essential because the usefulness of data products is ultimately determined by the needs of their users, which can vary widely. User requirements are closely linked to the FAIR data principles—Findable, Accessible, Interoperable and Reusable (European Commission Directorate-General for Research and Innovation, 2018; Wilkinson et al., 2016)—as well as broader considerations such as data quality, ethics and latency. Among these principles, *findability* is often regarded as both the most critical and one of the most difficult to achieve (Wilkinson et al., 2016). In practice, users typically rely on search engines to locate datasets. However, the proliferation of data repositories worldwide makes discovery challenging, highlighting the need for standardised data catalogues supported by cross-organisational and international collaboration.

A major challenge lies in developing standardised data products accompanied by FAIR-compliant metadata. Achieving this can require substantial resources, including the reprocessing of existing datasets and additional effort for documentation and metadata development. These requirements can also create cultural and institutional barriers, as they increase the workload and costs associated with data product development. Consequently, users are often limited to the data products that are currently available and must frequently adapt them to meet their specific needs.

Ideally, user requirements should be identified early to inform strategies for data collection, product development and dissemination. In practice, however, many data products are generated within the scope of individual projects led by specific research teams. When such projects conclude, ongoing development and maintenance often cease. Without sustained support and long-term planning, the value and usability of

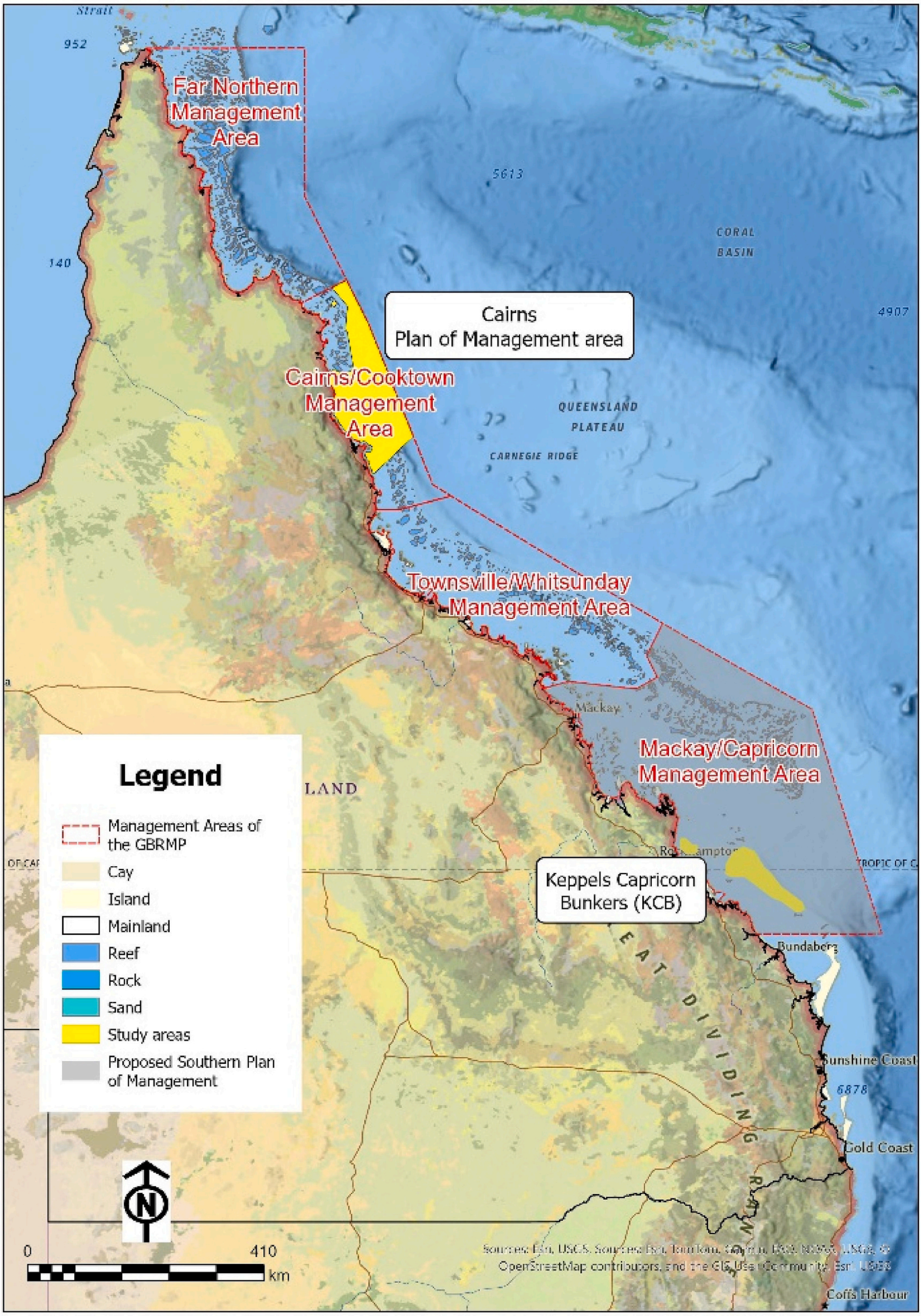

Fig. 1. Map of the Great Barrier Reef and location of the two case study regions used to demonstrate the Environmental and Social Value Chain (ESVC) framework and SYNTHESEAS platform. The Cairns Area Plan of Management (CAPOM) zone represents a northern Great Barrier Reef management region, while the Keppels Capricorn Bunkers (KCB) region represents a southern reef system, enabling comparison across different environmental, social, and management contexts.

these products may decline. For example, if updates are discontinued, activities and services dependent on those data products may also be affected. In our study, user needs were identified through via consultation with Reef Authority planners and social scientists. These inputs informed the selection of case study areas, ecosystem service indicators, as well as ecosystem types to focus on. While formal iterative co-design was not undertaken, the tool was developed with consideration of end-user requirements and intended decision-making contexts.

2.2.2. Data discovery

We undertook a structured data discovery process to identify all potentially relevant datasets, spanning environmental, ecological, spatial, and observational domains within the study area. Based on the ES categories identified in the hybrid framework searches were conducted across major government data portals (e.g., Australian Government open data hubs, state-based spatial repositories, and Reef Authority information services) as well as discipline-specific catalogues and previously documented datasets identified by Gooch et al. (2019) and referenced in technical reports and prior studies. All sources were screened for relevance, accessibility, licensing, spatial and temporal coverage, and alignment with the information requirements of this study (i.e., the data and outputs needed to address the research objectives), rather than an explicit evaluation of end-user needs.

2.2.3. Data inventory and prioritisation

A preliminary data inventory was compiled to organise and evaluate all candidate datasets identified during data discovery, mapping each dataset to the hybrid framework by ecosystem service (ES) category, associated values, and ecosystem service beneficiaries (natural resource users) across rows. Each dataset was systematically recorded in a structured spreadsheet that captured key attributes, including dataset title, spatial and temporal coverage, data custodians, licensing conditions, access mechanisms, update frequency, and known data-quality statements. Additional fields were used to document each dataset's relevance to the objectives of this study (i.e., its suitability for supporting ecosystem service classification, spatial analysis, and decision-support outputs), as well as anticipated preprocessing requirements and potential constraints such as incomplete metadata or restricted access.

This inventory enabled consistent comparison across heterogeneous datasets by applying a standardised metadata coding scheme, ensuring that each dataset was evaluated using the same predefined attributes and classification rules, and supported prioritisation for downloading, further processing, and potential integration into the database tool. Prioritisation was based on a qualitative ranking of dataset suitability across key attributes, including relevance to ecosystem service categories, spatial and temporal resolution (i.e. found within our study areas), data quality, metadata completeness, and accessibility, with higher-ranked datasets progressing to data cleaning, standardisation, and formatting for database integration. This spreadsheet was then used to feed into the PostgreSQL backend database for the R Shiny application.

2.2.4. Data collection

Following data inventory and prioritisation, the identified datasets were systematically downloaded and catalogued in the data inventory spreadsheet and further examined to determine their suitability for further processing and integration into the database tool by detailed examination of attributes and associated values coded. These datasets varied widely in structure, format, resolution, and intended purpose. Because observational gaps are common across the study region, particularly in remote coastal and marine environments, we assembled complementary datasets from multiple secondary sources—including spatial datasets, observational records, and published data tables in reports and scientific literature—to maximise spatial and temporal coverage while maintaining clear provenance and traceability. Gaps like these can affect data quality and, consequently, limit the resolution and reliability of derived environmental indicators.

2.2.5. Data assessment

To ensure comparability across datasets, we evaluated data quality using the Commonwealth Scientific Industrial Research Organisation (CSIRO) 5-star Data Rating Tool (Yu & Cox, 2017), assessing consistency, continuity, uncertainty, bias, latency, and spatial and temporal resolution (Fig. 2). Dataset preparation effort was also considered, including relevance, accessibility, conversion requirements, processing needs, software dependencies, and data gaps. The CSIRO 5-star framework provides a structured maturity assessment rather than an automated scoring algorithm. Datasets were assessed against published social, technical, and informational criteria and assigned ratings using the standard five-star maturity scale. Social attributes considered governance, ownership, and accessibility; technical attributes considered interoperability, standards compliance, and machine-readability; and informational attributes considered metadata completeness, documentation, fitness-for-purpose, and data quality. No additional weighting was applied beyond the framework's prescribed assessment approach.

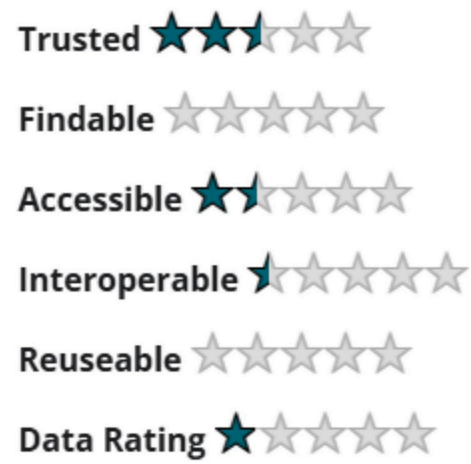

Fig. 2. Example application of the CSIRO 5-star Data Rating Tool used in this study to assess dataset quality and maturity. Datasets were evaluated against social, technical, and informational criteria, including governance, accessibility, interoperability, metadata completeness, and fitness-for-purpose. The resulting ratings provide a standardised basis for comparing datasets and determining their suitability for integration within the ESVC and SYNTHESEAS platform.

Uncertainty was evaluated through documented confidence measures, known biases, error estimates, and identified limitations. Resulting quality metrics were retained as dataset-level metadata to support transparent interpretation and reuse of integrated data products. The framework also supports assessment of attributes aligned with FAIR data management principles (Wilkinson et al., 2016)."

2.2.6. Data processing

Datasets were standardised prior to integration through a series of preprocessing steps, including spatial clipping from broader extents (e.g., Great Barrier Reef–wide datasets) to the defined study areas (see Section 2.1), and format conversion (e.g., KML to shapefile) to ensure compatibility within the ArcGIS environment. Additional processing included projection alignment and minor data cleaning where required to support consistent spatial display. This step was used to assist with data reduction, data enhancement and classification of spatial and temporal patterns particular to our two study areas: Cairns Area Plan of Management zone (CAPOM) and the Keppels Capricorn Bunkers (KCB). Furthermore, economic values provided in existing data sets were adjusted to 2023 $AUD values using the Reserve Bank of Australia (RBA) calculator available online at Inflation Calculator | RBA.

2.2.7. Data integration workflow

Following acquisition, datasets entered a structured integration pipeline consisting of (1) ingestion, (2) metadata extraction, (3) quality assessment, (4) transformation and standardisation as required, (5) ESVC classification and mapping, (6) database loading, and (7) dissemination through the SYNTHESEAS application interface. During transformation, spatial reference systems, temporal formats, classification schemes, and metadata fields were harmonised to support interoperability across heterogeneous sources. Standardised records were then loaded into PostgreSQL and linked to ecosystem service, beneficiary, stewardship, and indicator entities within the underlying ESVC architecture.

3. ESVC framework development and system implementation

3.1. Marine ecosystems and ecosystem services framework

The Reef comprises 17 major ecosystems (Great Barrier Reef Marine Park Authority, 2019). Of these, ten coastal and marine ecosystems occurring within the CAPOM and KCB study areas were identified by the Reef Authority as management priorities. These included coral reefs, shoals, mangroves, lagoon floors, the water column, islands, seagrass meadows, coastlines, Halimeda banks, and the continental slope.

Through consultation with the Reef Authority and reference to the Common International Classification of Ecosystem Services (CICES) Version 5.2 (https://cices.eu), priority ecosystem services associated with these ecosystems were identified for inclusion within the study areas (see also de Valck et al., 2023). Services were classified according to the three major CICES categories: Provisioning, Regulating, and Cultural ecosystem services. Specific ecosystem services of management relevance to the Great Barrier Reef were then selected in consultation with stakeholders (see Graphical abstract in de Valck et al., 2023).

These ecosystems and ecosystem services form the ecological foundation of the Ecosystem Service Value Chain (ESVC) framework. Ecosystems represent the underlying ecological assets, while ecosystem services provide the conceptual link between ecological condition, human beneficiaries, and social, economic, and cultural values. As such, ecosystem service categories were used as a primary organising structure for classifying datasets and indicators within SYNTHESEAS and for linking them to beneficiary user groups, stewardship actions, and management objectives.

Within the platform, ecosystem service categories and individual ecosystem services are implemented as controlled lookup tables that support dataset discovery and filtering. Users can filter datasets according to ecosystem service category and service type (Fig. 3), enabling rapid identification of indicators and datasets relevant to specific management, planning, monitoring, and decision-support questions.

3.2. Beneficiary framework for the Great Barrier Reef

Beneficiaries of ecosystem services (hereafter referred to as 'GBR user types') were grouped into four categories: (i) Government, (ii) Industry, (iii) Household, and (iv) First Nations (Fig. 4). This classification was adapted from the United Nations System of Environmental-Economic Accounting Ecosystem Accounting (SEEA-EA) framework (United Nations et al., 2024) and refined through the Ecosystem Service Value Chain (ESVC) framework developed by Coggan et al. (2026). These beneficiary groups represent the principal actors that derive benefits from, manage, regulate, or depend upon Great Barrier Reef ecosystem services.

Within the ESVC framework, beneficiaries provide the critical social component linking ecosystem services to social, cultural, environmental, and economic outcomes. Consequently, beneficiary groups were incorporated as a core organising element within the indicator

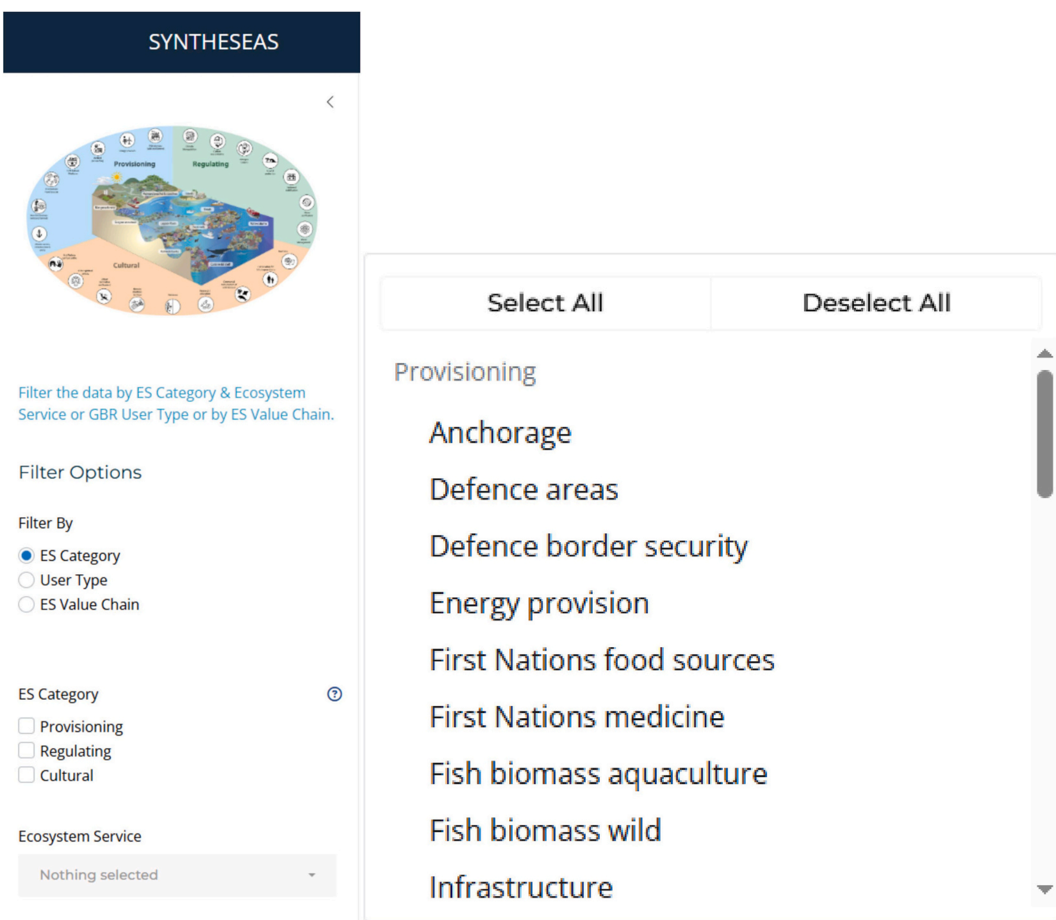

Fig. 3. User interface showing ecosystem service filtering options within SYNTHESEAS. The example illustrates selection of provisioning ecosystem services from a scrollable menu, enabling users to rapidly identify, filter, and access datasets associated with specific ecosystem service categories. This functionality supports efficient dataset discovery and exploration within the ESVC framework.

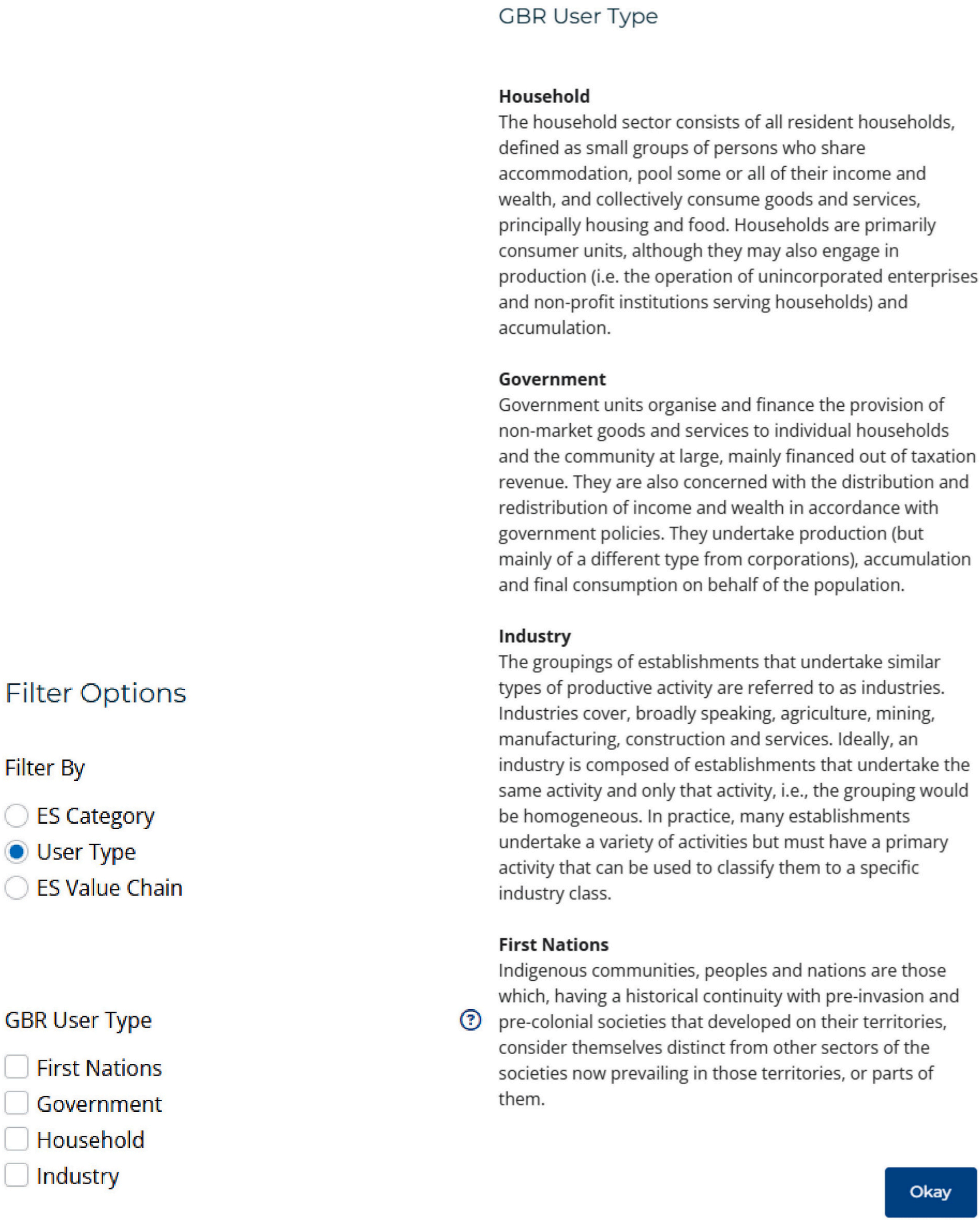

Fig. 4. Great Barrier Reef (GBR) user types and associated descriptions used within the ESVC framework. User types represent ecosystem service beneficiaries and are used to map datasets and indicators to specific stakeholder groups, enabling targeted data discovery, social–ecological analysis, and decision-support applications within the SYNTHESEAS platform.

architecture and database schema. Datasets and indicators were mapped to one or more beneficiary groups based on the primary users, recipients, or stakeholders represented within the dataset. This classification enables users to discover datasets relevant to specific stakeholder groups and facilitates analysis of how ecosystem service benefits, stewardship activities, and management outcomes are distributed across different sectors of society.

Within the SYNTHESEAS platform, users can filter datasets by beneficiary group through the "GBR User Type" interface option (Fig. 4). This functionality enables targeted exploration of datasets associated with particular stakeholder groups and supports management questions focused on equity, dependency, stewardship, and ecosystem service beneficiaries.

The inclusion of First Nations peoples as a distinct beneficiary group reflects an expanding body of literature recognising the unique relationships between Indigenous peoples and ecosystems (De Valck et al., 2023; Finau et al., 2023; Larson et al., 2023; Larson et al., 2025). These studies highlight the importance of acknowledging diverse conceptualisations of ecosystem service flows and the values attributed to them through Traditional Ecological Knowledge and cultural knowledge systems. Incorporating First Nations peoples as a distinct beneficiary group within the ESVC framework recognises that different worldviews generate distinct services, benefits, responsibilities, and value pathways that must be considered to fully represent social–ecological relationships associated with the Great Barrier Reef (De Valck et al., 2023; Larson et al., 2025; Stoeckl et al., 2021; Woodward et al., 2023).

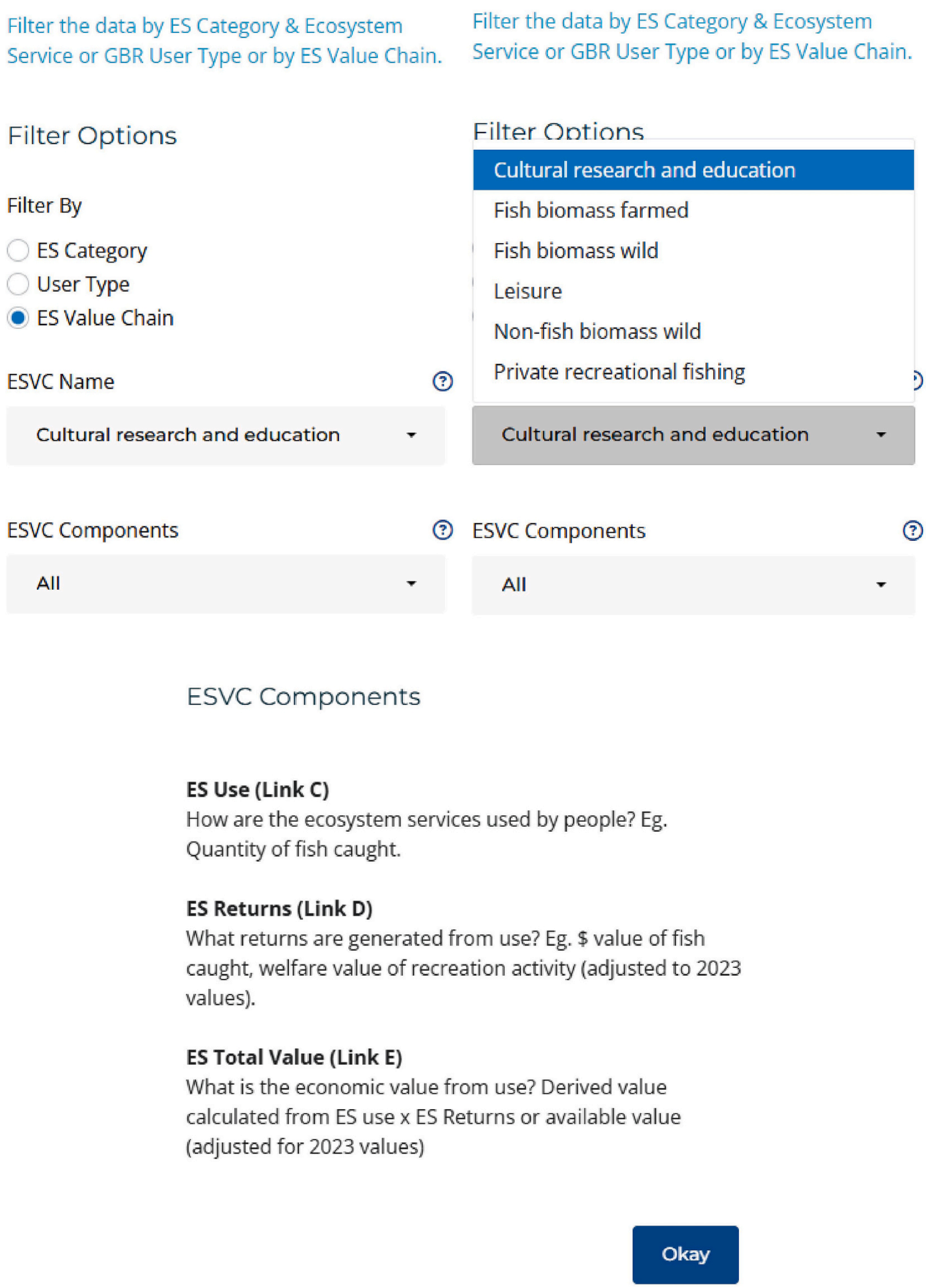

Fig. 5. Ecosystem Service Value Chain (ESVC) framework and its core components. The ESVC architecture illustrates the pathways through which ecosystem assets and functions generate ecosystem services that are accessed by beneficiary groups and translated into social, cultural, environmental, and economic values. Within SYNTHESEAS, these relationships provide the foundation for linking datasets, indicators, ecosystem services, beneficiaries, and management contexts within a unified social–ecological indicator system.

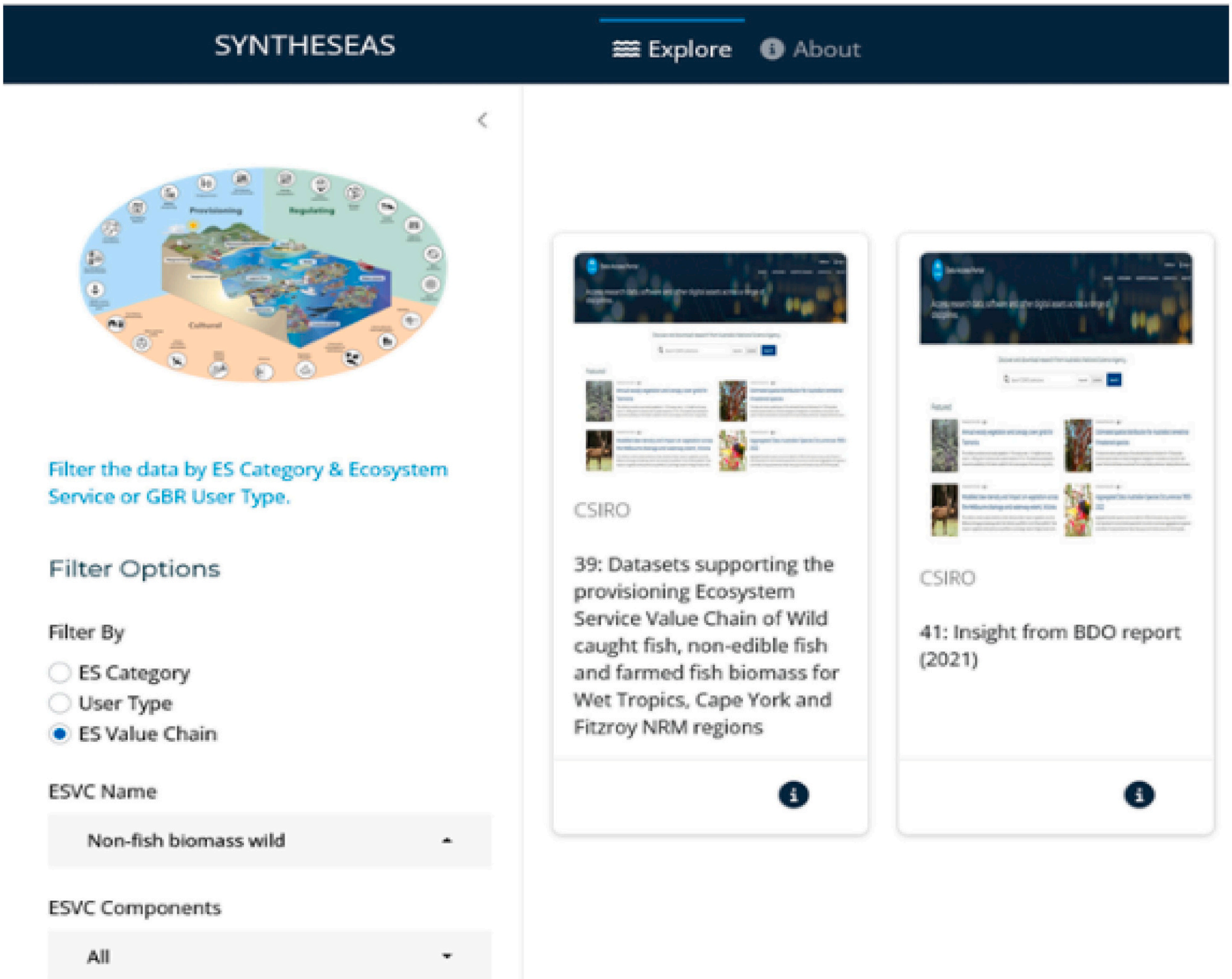

Fig. 5. (*continued*).

3.3. Ecosystem Service Value Chains (ESVC) indicator architecture

Drawing on the ecosystem services concept, the Ecosystem Service Value Chain (ESVC) framework was developed and applied to structure and synthesise the large body of available data. By clicking on the "Filter by ESVC" this enables a visualisation of how an ES is used, who uses it, and what constitutes benefit from this use.

Throughout the course of the SEABORNE project (https://research.csiro.au/seaborne/), six ESVCs were developed and populated with existing data for:

- Provisioning service of fish and other biomass (wild caught and farmed) to commercial service users.
- Cultural service of recreation and leisure (recreational and non-recreational fishing) to households.
- Cultural service of education and research to Government.

These six ESVCs were populated as a prototype and appear in the dropdown list as follows: 1) Cultural research and education, 2) Fish biomass farmed, 3) Fish biomass wild, 4) Leisure, 5) Non-fish biomass wild, and 6) Private recreational fishing (Fig. 5). When the user clicks the radio button "ES Value Chain", a dropdown menu of the 6 ESVCs is displayed, allowing the user to investigate the datasets used to populate that chain. As a default all ESVC components are selected, however users can also select from the second dropdown list to investigate further ESVC components such as: Links c (ES Use) and d (ES Returns), which are the links that connect the ecosystems to the economic value of the benefits derived from these ecosystems. Link c (ES Use) demonstrates datasets we found that represent returns or benefits that are generated from the use of ES, and link d (ES Returns) demonstrates datasets we found about the economic value of the benefit that is generated from the use of the ES. Link e (ES Total Value) contains datasets that were combined to generate a new data point of total value (Fig. 5).

3.3.1. Dataset-to-ESVC mapping

Each dataset was assigned to one or more ESVC components through a structured classification process. Datasets were first classified according to the ecosystem services they measured or informed. Subsequently, links were established to beneficiary groups and stewardship themes based on the conceptual relationships represented within the ESVC framework. For example, coral cover monitoring datasets were linked to habitat provision services, tourism beneficiaries, and reef stewardship outcomes, while social survey datasets were linked to stewardship, wellbeing, and community resilience components. For more information on individual ESVCs mapped see Coggan et al. (2026).

3.4. Platform implementation: the SYNTHESEAS application

3.4.1. Database architecture

The SYNTHESEAS platform was implemented using a PostgreSQL relational database designed to support the storage, discovery, and integration of heterogeneous social–ecological datasets. The database architecture was developed around six principal entities: Datasets, Indicators, Ecosystem Services, Beneficiaries, Stewardship Actions, and Metadata Records. Each entity was assigned a unique identifier and linked through primary and foreign key relationships to enable many-to-many associations while maintaining data provenance and traceability.

The Datasets entity forms the core of the schema and stores descriptive information for each dataset identified through the discovery and assessment process. Associated Metadata Records contain information on dataset ownership, provenance, spatial and temporal coverage, accessibility, licensing conditions, and quality assessment results. Ecosystem Service, Beneficiary, and Stewardship entities provide the conceptual links required to operationalise the Ecosystem Service Value Chain (ESVC) framework, enabling datasets to be associated with specific ecosystem services, user groups, management contexts, and social–ecological outcomes.

This relational structure enables users to identify datasets relevant to particular ecosystem services, beneficiary groups, stewardship themes, or management questions while preserving links to underlying metadata and quality assessments. The architecture also supports future expansion through the addition of new ecosystem services, indicators, beneficiary categories, and geographic regions without requiring modification of the underlying schema.

3.4.2. Metadata standardisation and harmonisation

To support interoperability across heterogeneous data sources, all datasets were subjected to a metadata standardisation and harmonisation process prior to integration. Standardised metadata fields were developed to capture dataset identification, spatial and temporal characteristics, quality information, accessibility, and provenance (Table 1).

Datasets originated from multiple organisations and disciplines and therefore exhibited substantial variation in terminology, formats, classifications, coordinate systems, and temporal structures. Harmonisation procedures included standardisation of spatial reference systems, temporal formats, metadata fields, and classification schemes. Controlled vocabularies were developed for ecosystem service categories, beneficiary groups, stewardship themes, and indicator classifications to improve consistency across datasets. Duplicate metadata fields were consolidated, and indicator terminology was normalised where equivalent concepts were represented using different nomenclature.

These procedures improved comparability among datasets and facilitated integration within the ESVC framework. Standardised metadata records also enhanced discoverability, transparency, and reuse by enabling users to assess dataset provenance, quality, coverage, and suitability for specific management applications.

3.4.3. Application architecture and user interface

The user-facing component of SYNTHESEAS was developed using the R Shiny framework (Chang et al., 2025), which enables the development of interactive web applications within the R programming environment (R Core Team, 2024). The application was implemented using the bslib package (Sievert et al., 2025) to provide a responsive user interface and communicates directly with the underlying PostgreSQL database to support dynamic retrieval, filtering, and exploration of dataset metadata.

The interface was designed around common dataset discovery workflows identified during stakeholder engagement. By default, users access the Explore tab, which enables datasets to be searched using keywords and filtered according to ecosystem service category, ecosystem service type, GBR beneficiary group (user type), and Ecosystem Service Value Chain (ESVC) component (Fig. 6). These filtering functions allow users to progressively refine search results and identify datasets relevant to specific management, planning, monitoring, and research questions.

Dataset records are presented through interactive summary cards that provide rapid access to key metadata attributes, including dataset provenance, accessibility, spatial and temporal coverage, and CSIRO 5-star quality assessment results. This functionality enables users to evaluate dataset suitability and compare alternative information sources before undertaking further analysis.

In addition to the public interface, a restricted administrative module supports the addition, modification, and maintenance of metadata records within the PostgreSQL database using the RPostgres package (Wickham et al., 2025). This functionality supports ongoing database curation and future expansion of the platform.

Table 1
Metadata categories and representative attributes used to standardise heterogeneous datasets prior to integration within the SYNTHESEAS PostgreSQL database. The metadata schema supports dataset harmonisation, quality assessment, provenance documentation, and information retrieval across environmental, social, economic, governance, and stewardship datasets.

Metadata Category	Example Attributes
Identification	Dataset title, owner, description
Spatial	Geographic extent, coordinate system, resolution
Temporal	Collection period, update frequency
Quality	CSIRO 5-star rating, uncertainty information
Access	Licence conditions, availability
Provenance	Source organisation, citation

3.5. Product dissemination

SYNTHESEAS was developed as a unified platform enabling access to ecosystem service datasets and related information for the Great Barrier Reef, supporting a wide range of users including stakeholders, decision-makers, policy-makers, and the broader public. Effective dissemination is critical to maximising research impact; without appropriate strategies, even high-quality products may fail to reach intended users. The application is publicly accessible via the SEABORNE website and was communicated directly to project stakeholders. However, dissemination remains challenging, particularly in ensuring that data are FAIR and openly accessible (Tenopir et al., 2020; Wilkinson et al., 2016). The application is available https://shiny.csiro.au/syntheseas/.

4. System demonstration and applications

4.1. Great Barrier Reef demonstration

The Great Barrier Reef (GBR) case study demonstrates how heterogeneous environmental, social, economic, governance, and stewardship datasets can be organised within the Ecosystem Service Value Chain (ESVC) framework and accessed through the SYNTHESEAS platform. Datasets incorporated into the system include ecological monitoring data, ecosystem service valuation studies, social survey datasets, stewardship indicators, economic statistics, and cultural information relevant to Reef management.

Each dataset was classified according to its ecosystem service category, beneficiary group, and position within the ESVC architecture. For example, coral condition monitoring datasets were linked to regulating and cultural ecosystem services, while tourism expenditure datasets were linked to beneficiary groups associated with reef-based recreation and commercial tourism. Social survey datasets describing stewardship attitudes, wellbeing, and community perceptions were similarly linked to beneficiary groups and stewardship outcomes.

This classification process enables users to move beyond individual datasets and explore relationships between ecosystem condition, ecosystem services, beneficiaries, and management outcomes. By integrating datasets within a common social–ecological framework, SYNTHESEAS provides a transparent mechanism for identifying available evidence, assessing data quality, and understanding how diverse indicators contribute to ecosystem service assessments and decision-support activities.

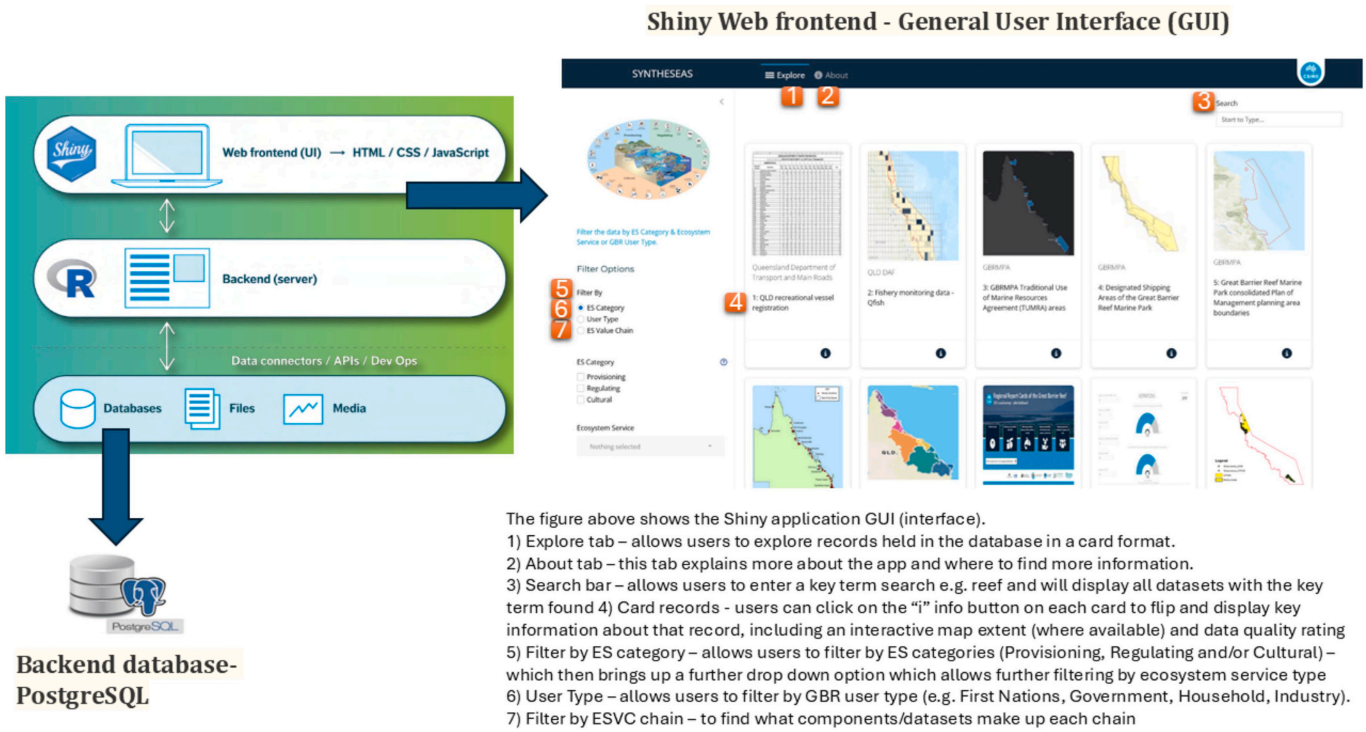

Fig. 6. Final SYNTHESEAS user interface for external users (https://shiny.csiro.au/syntheseas/) with key components annotated. The numbered callouts illustrate the primary user workflow: (1) explore ecosystem service datasets and indicators, (2) view platform information and guidance, (3) search datasets using keywords, (4) examine dataset records and metadata summaries, (5) filter by ecosystem service category, (6) filter by beneficiary (user) type, and (7) filter by Ecosystem Service Value Chain (ESVC) component. This functionality enables users to efficiently discover, assess, and access datasets within the ESVC indicator architecture.

4.2. *Indicator discovery and explanation*

A core function of SYNTHESEAS is to support efficient discovery and interpretation of indicators relevant to specific management questions. Users can search datasets using keywords, browse ecosystem service categories, filter by beneficiary group, and explore datasets associated with particular components of the ESVC framework.

Each dataset record contains standardised metadata describing dataset provenance, spatial and temporal coverage, accessibility, quality characteristics, and links to ecosystem services and beneficiary groups. Users can interrogate metadata to assess whether a dataset is appropriate for a particular application and examine CSIRO 5-star quality ratings to better understand data maturity, interoperability, documentation quality, and fitness-for-purpose.

For example, a user interested in reef tourism may filter the database to identify datasets describing visitor numbers, tourism expenditure, recreational use, stewardship participation, or ecosystem condition. Metadata and quality information allow datasets to be compared and evaluated before being incorporated into subsequent analysis, planning, or reporting activities.

4.3. *Decision-support applications*

The primary users of SYNTHESEAS include environmental managers, policy-makers, planners, researchers, Traditional Owners, industry stakeholders, and community organisations involved in Great Barrier Reef management. These users frequently require access to diverse environmental, social, economic, and stewardship indicators to support planning, monitoring, reporting, prioritisation, and adaptive management activities. However, such information is often fragmented across organisations, disciplines, and data repositories. SYNTHESEAS was developed to address this challenge by providing an application for discovering, assessing, and contextualising social–ecological datasets within an ecosystem service value chain framework.

The ESVC architecture enables datasets to be explored within management-relevant contexts rather than as isolated information products. For example, environmental managers may use the platform to identify indicators for evaluating stewardship programs, researchers may locate datasets suitable for ecosystem service assessments, and planners may examine economic and social indicators associated with reef-dependent industries.

Table 2 presents illustrative examples of management questions that can be supported through the platform. These examples demonstrate how users can identify relevant datasets, evaluate data quality and suitability, and link indicators to ecosystem services, beneficiary groups, and decision-making objectives. While the present study does not formally evaluate management outcomes, these examples illustrate the practical pathways through which integrated social–ecological information can support evidence-informed planning, monitoring, prioritisation, and adaptive management.

Table 2
Example applications of the SYNTHESEAS platform showing how environmental, social, economic, and stewardship datasets can be discovered, integrated, and interpreted to address practical Great Barrier Reef management questions. The table demonstrates the operational value of the ESVC framework by linking management needs to relevant indicators, datasets, and decision-support applications.

Management question	Dataset type	Example indicator	Potential application
Is reef stewardship improving?	Social survey data	Stewardship index	Program evaluation
Which communities depend most on reef tourism?	Economic datasets	Tourism expenditure	Regional planning
Where are monitoring gaps?	Metadata records	Spatial coverage	Monitoring prioritisation
Which services benefit local communities?	ESVC-linked datasets	Recreational use indicators	Policy development

5. Discussion

5.1. Contribution to indicator science

While many indicator studies focus on the development, validation, or application of individual indicators, a persistent challenge remains the integration of diverse indicators into coherent assessment systems capable of supporting environmental management. ESVC contributes to indicator science by providing an interoperable indicator architecture that enables environmental, social, economic, governance, and stewardship indicators to be discovered, assessed, integrated, and analysed within a common social–ecological framework.

The SYNTHESEAS platform advances indicator practice in several ways. First, it establishes a standardised framework for indicator metadata, quality assessment, and documentation, improving transparency and reproducibility. Second, it facilitates interoperability among indicators derived from disparate monitoring programs, institutions, and disciplines. Third, it supports multi-scale assessment by harmonising indicators across spatial and temporal dimensions. Finally, it enables indicator synthesis and exploration within decision-support workflows, helping bridge the gap between indicator production and practical application.

Viewed in this context, ESVC represents an indicator architecture that supports the operationalisation of social–ecological indicators rather than a repository of individual metrics. Its contribution lies in enabling integrated indicator systems capable of supporting adaptive management, monitoring, and evidence-based decision-making in complex environmental settings.

5.2. Advancing social-ecological indicator integration

Furthermore, the SYNTHESEAS R Shiny application introduces an integrated, value-chain–oriented approach that enables policy-makers, environmental managers and spatial planners to rapidly identify, filter, and compare ecosystem service datasets relevant to management questions in the Great Barrier Reef. By consolidating fragmented socio-economic and ecosystem service information into a single, queryable interface, the tool is designed to address long-standing accessibility barriers and provide a transparent basis for evidence-informed decision-making. Its structured filtering by ecosystem service type, beneficiary group, and value-chain component supports spatial planning workflows, enabling users to trace how ecosystem uses translate into measurable economic and social benefits. This capacity to link datasets to specific management contexts makes SYNTHESEAS an innovative decision-support resource for Reef governance, policy development, and scenario planning. While existing decision-support tools such as InVEST and ARIES provide sophisticated spatial modelling and scenario analysis of ecosystem services, they primarily focus on biophysical outputs rather than systematic discovery, integration, and policy contextualisation of heterogeneous datasets (Natural Capital Alliance, 2026; Villa et al., 2014). A key distinction is that InVEST and ARIES primarily generate ecosystem service estimates through modelling workflows, whereas SYNTHESEAS focuses on the organisation, discovery, quality assessment, interoperability, and contextual interpretation of existing datasets and indicators. Consequently, SYNTHESEAS addresses an earlier but often overlooked stage of the decision-support pipeline: enabling users to identify what data exist, assess their suitability, understand their quality and provenance, and trace their relevance to ecosystem service value chains, beneficiary groups, and management objectives. In this regard, SYNTHESEAS complements rather than replaces model-based ecosystem service assessment tools. Furthermore, SYNTHESEAS addresses this gap by operating as a data-centric decision-support layer that links ecosystem service datasets to beneficiary groups, value-chain components, and governance contexts, complementing model-based approaches and enhancing evidence-informed Reef management (Willcock et al., 2018).

For example, a regional planner seeking information on reef-dependent tourism could use SYNTHESEAS to identify datasets describing visitor use, tourism expenditure, employment, stewardship participation, and ecosystem condition. Through ESVC-linked filtering, these datasets can be connected to beneficiary groups, ecosystem services, and management objectives, enabling a more comprehensive understanding of how ecological change may affect social and economic outcomes. Similarly, environmental managers can identify stewardship indicators, community survey datasets, and monitoring records relevant to evaluating program effectiveness or identifying spatial and thematic data gaps.

5.3. Strengths and limitations

A key strength of the ESVC framework and SYNTHESEAS platform is its ability to integrate diverse environmental, social, economic, governance, and stewardship datasets within a common social–ecological architecture. By combining standardised metadata, quality assessment procedures, and ESVC-based classification, the platform improves dataset discoverability, transparency, and interoperability across disciplines and institutions. This provides users with a structured mechanism for identifying available evidence and assessing its suitability for specific management and research applications.

Despite substantial efforts to collect primary data from reliable sources, observational gaps persist, particularly across large oceanic regions and remote coastal and marine environments. These gaps can affect data quality and limit applications such as long-term environmental monitoring and the analysis of climate and hazard-related events. An additional challenge is that while biophysical scientists typically establish long-term monitoring programs with clear and consistent protocols, social scientists often collect data on a more ad hoc basis, with looser terminology for describing what is measured or reported. This creates inconsistencies that hinder the development of coherent datasets across spatial and temporal scales. In the absence of sufficient observation networks, data gaps are frequently addressed using integrated datasets of varying quality, making interpretation and comparison of integrated datasets challenging in some applications. The current implementation is also constrained by the availability and quality of source datasets. As a metadata-driven platform, SYNTHESEAS does not resolve underlying deficiencies in data coverage, consistency, or methodological design. Consequently, the quality and utility of information available through the platform remain dependent on the datasets contributed by monitoring programs, government agencies, research institutions, and other data providers.

5.4. Future development and evaluation

The focus of this study was the design and implementation of an integrated social–ecological information platform rather than formal evaluation of user performance or management outcomes. Although the Great Barrier Reef case study demonstrates the platform's capacity to integrate and visualise diverse environmental and social indicators, further validation is required to assess operational effectiveness. Future work should include structured usability testing with end-users, stakeholder workshops, task-completion assessments, user satisfaction surveys, and longitudinal evaluation of decision-support outcomes. Comparative benchmarking against existing environmental information systems would also provide valuable insights into relative performance, efficiency, and user value. Such evaluations will be essential for determining the platform's effectiveness in supporting evidence-based environmental management and adaptive decision-making.

Further development of SYNTHESEAS offers several opportunities to strengthen its utility for environmental managers, policy-makers, and researchers. A key priority is expanding the breadth and quality of the underlying datasets, particularly socio-economic and cultural indicators that remain sparse or inconsistently collected across the Great Barrier

Reef region. Integrating automated data-harvesting pipelines and APIs would improve update frequency and reduce reliance on manual curation, while embedding standardised quality-assessment workflows (e.g., FAIR and CARE evaluation modules) could support more transparent reporting of data provenance and uncertainty. Future versions could also incorporate spatial analytics, scenario-modelling tools, and interoperability with external decision-support platforms such as the RIMReP Data Management System, enabling end-to-end workflows from data discovery to policy evaluation. Enhancing First Nations data governance features—such as ICIP-aligned access controls and community-defined metadata fields—would strengthen cultural appropriateness and ensure alignment with emerging Indigenous data sovereignty frameworks. Over time, expanding the ESVC logic to additional ecosystem services, industries, and bioregions, as well as enabling user-contributed datasets through moderated submission pathways, would transform SYNTHESEAS into a living, co-produced repository that continually adapts to the evolving needs of GBR decision-making and marine social-ecological research.

6. Conclusion

This study presents SYNTHESEAS, an interactive decision-support tool developed by the Commonwealth Scientific and Industrial Research Organisation to enhance the discoverability, integration, and application of ecosystem service valuation datasets in the Great Barrier Reef region. By operationalising the Ecosystem Service Value Chain framework within a structured and user-oriented interface, SYNTHESEAS addresses persistent fragmentation in socio-economic data and responds directly to the needs of environmental managers, policymakers, and researchers engaged in Reef governance.

The tool advances ecosystem service assessment by systematically linking ecosystems, beneficiary groups, and value components, thereby improving transparency in how ecological functions translate into measurable social and economic benefits. In doing so, it contributes to a more coherent evidence base for evaluating trade-offs, informing spatial planning, and supporting adaptive management under the Reef 2050 framework. Importantly, the explicit inclusion of First Nations beneficiaries and alignment with emerging data governance principles strengthens the cultural relevance and inclusivity of ecosystem accounting in complex marine social–ecological systems.

While SYNTHESEAS does not replace biophysical modelling or scenario-analysis platforms, it fills a critical gap by functioning as a data-centric integration layer that enhances the accessibility and contextualisation of heterogeneous datasets. Remaining challenges—including uneven socio-economic data coverage, variable data quality, and the need for sustained institutional support—underscore the importance of continued investment in interoperable infrastructure, standardised metadata, and collaborative governance arrangements.

Future development should prioritise expansion of cultural and social indicators, integration with complementary monitoring and reporting systems, and the incorporation of enhanced quality-assessment and Indigenous data sovereignty mechanisms. Through iterative refinement and co-production with stakeholders, SYNTHESEAS has the potential to evolve into a living repository that strengthens ecosystem service assessment and supports more transparent, equitable, and evidence-informed management of the Great Barrier Reef and other coastal regions.

CRediT authorship contribution statement

Petina L. Pert: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Lauren Stevens:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Anthea Coggan:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Jeremy De Valck:** Writing – review & editing, Writing – original draft, Validation, Methodology. **Diane Jarvis:** Writing – review & editing, Writing – original draft, Validation. **Victoria Graham:** Writing – review & editing, Writing – original draft, Validation, Data curation. **Cindy Huchery:** Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Michelle Dyer:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Akshat Sehgal:** Validation, Software, Resources, Methodology, Formal analysis, Data curation. **Eduardo Klein Salas:** Writing – review & editing, Resources, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Corresponding author Petina Lesley Pert is currently an Associate Editor for the journal. Given her role as Associate Editor, she will have no involvement in the peer review of this article and had no access to information regarding its peer review. Full responsibility for the editorial process for this article was (will be) delegated to another journal editor. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Research Link Provided

SYNTHESEAS: Datasets supporting the cultural Ecosystem Service Value Chain of research to institutions (Reference data) (CSIRO Data Access Portal)

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