Towards a unified ontology for monitoring ecosystem services

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Abstract

The concept of ecosystem services (ES) has greatly evolved since it was first proposed and, as it gained popularity, has been used in diverse applications. Today, ES are an important part of global and national environmental policies. In this context, there is a call for the monitoring of ES to support their management. The proliferation of terms used with the concept of ES may be a barrier to systematic monitoring. Monitoring ES requires knowing exactly what variables to measure and how they relate to change in the states of ES. It further requires interoperability between methodologies used by the information systems used to operationalise data flows. As such, there is a need to systematise the language used to define ES and the terminology used in their monitoring in a way that is unambiguous and both human and computer readable. Building on advances in other biological fields, we develop an ontology for monitoring ES. Ontologies are tools that operationalise concepts and the relationships among terms used to define them. An ontology further allows people and machines to use the terms consistently. The ES monitoring ontology aligns the language of ES with other ontologies in the biological sciences. We test the ES monitoring ontology with data from three ES in British Columbia, Canada, to highlight how it can enable information sharing and monitoring. We invite members of the ES community to join the effort of developing this ontology for ES so that can it contribute to the challenge of systematically monitoring change in social-ecological systems.

Keywords

Ecosystem services monitoring, interoperability, ontology, semantics, ecosystem service conceptualisation

Highlights

- Operationalising the language of ecosystem services remains a barrier to progress.
- A formal ontology to organise terms and data is needed to support interoperability.
- We propose a formal ontology for monitoring ecosystem services.
- Conceptual clarity enables data integration and automation.
- Efforts are required for a community of practice to develop this tool further.

1. Introduction

Ecosystems worldwide are undergoing large scale change, modifying social-ecological dynamics in ways that are difficult to predict and manage (Richardson *et al.*, 2023). Nations worldwide are making efforts to conserve ecosystems and the services they provide to society (CBD, 2022a). Ecosystem services in particular are now integral to policy at the global and national levels (Peterson *et al.*, 2018; CBD, 2022a). However, our understanding of how ecosystem services are changing remains limited (Vaz *et al.*, 2021). Efforts are being made to develop systematic monitoring systems to track ecosystem service change (Tallis *et al.*, 2012; Balvanera *et al.*, 2022; Gonzalez *et al.*, 2023; Schwantes *et al.*, 2024) but these face several challenges. One such challenge is the operationalisation of the concepts used in ecosystem service science to define and describe the variables to be monitored (de Groot, Wilson and Boumans, 2002; Bennett *et al.*, 2015; Polasky, Tallis and Reyers, 2015; Bull *et al.*, 2016). Ecosystem service monitoring requires a common use of terms that allow findings from different monitoring systems to be comparable. One way to move towards this goal is to develop a common ontology for the field of ecosystem services monitoring, which we propose and motivate in this article.

The use of the term "ecosystem services" has grown exponentially since its first use in 1981 (Ehrlich and Ehrlich, 1981; Chaudhary *et al.*, 2015). Popularised by two seminal publications (Costanza *et al.*, 1997; Daily, 1997) and later the Millenium Ecosystem Assessment (MA, 2005), ecosystem services have since been used in resource management, economic accounting, policymaking, academic research and more. The broad sense of the term (also known as "nature's benefits to people") has made it well suited to multiple applications (Abson *et al.*, 2014). However, this has come with the cost of inconsistent use (Heink and Kowarik, 2010). Indeed, due to the decades of work and hundreds of contributors to the field, much of the terminology of ecosystem service science is being used and understood in different, sometimes contradictory, ways (Ainscough *et al.*, 2019). The inconsistent use of terminology has been highlighted as a major barrier to the operationalisation and applicability of the concept of ecosystem services (Bennett *et al.*, 2015; Polasky, Tallis and Reyers, 2015; Bull *et al.*, 2016; Jax *et al.*, 2018; Palomo *et al.*, 2018).

There have been efforts to remedy the ambiguous definitions and use of terms by proposing typologies and classification systems that operationalise concepts (Haines-Young and Potschin, 2012; United States Environmental Protection Agency, 2015). These efforts have typically been led by governmental bodies in Europe and the United States who sought to categorise and systematise the terms for statistical accounts. Classification systems can be understood as hierarchical structures that organise information (e.g. Linnean taxonomy) complete with mutually exclusive definitions. The major classification systems in use today focus on the contributions of nature to the economy, following the ecosystem service cascade framework, a logic chain that connects ecosystems to the benefits enjoyed by people via ecosystem functions and services (Haines-Young and Potschin, 2010; Potschin-Young *et al.*, 2018). These classification systems have improved the comparability and usability of research (Finisdore *et al.*, 2020) by clearly differentiating between categories of ecosystem services (Haines-Young and Potschin, 2012), environments and users (Newcomer-Johnson *et al.*, 2020). However, distinct statistical categories, whilst useful for national reporting, fall short of what is needed to systematise the monitoring of ecosystem services. To fully operationalise ecosystem services monitoring, terms must be defined and related to each by an ontology.

An ontology is "a set of concepts and categories in a subject area or domain that shows their properties and relations between them" ('ontology, n.', 2023). In other words, an ontology includes the definitions of key terms and the way in which these are to be understood in relation to each other. In science, ontologies are tools to represent knowledge and, more specifically, data (Arp, Smith and Spear, 2015). A formal ontology is a digital tool that formalises terms and their relationships according to best available science and understanding of the domain to which it is applied (Guarino, Oberle and Staab, 2009). Ontologies are behind the development of the semantic web (Gomez-Perez and Corcho, 2002), making the internet navigable, and are at the forefront of the development of artificial intelligence. In public health and medicine, where similar terms often represent different concepts (especially due to acronyms), domain-specific ontologies are essential to research as they allow the identification of causal relationships between concepts linked to health outcomes (Gawich *et al.*, 2012). Other applications include geographic information systems that bring data together from a wide variety of sources and rely on ontological metadata to link and connect the data in relevant ways (Fonseca *et al.*, 2002). The biological sciences have a rich history of ontology use with notable examples including the gene ontology (Gene Ontology Consortium, 2006), the environment ontology (Buttigieg *et al.*, 2013, 2016) and the biological collections ontology (Walls *et al.*, 2014). These ontologies support data discoverability, reuse and model interoperability. A key to the success of biological sciences in developing ontologies is in their commitment to a common approach that relies on the Basic Formal Ontology (BFO) (The OBI Consortium *et al.*, 2007), an upper-level ontology, i.e. one that is domain-independent and defines the core terms to organise domain-specific terminology (Arp, Smith and Spear, 2015). BFO already provides the philosophical underpinnings necessary to develop ontologies and makes them interoperable with each other (Jackson *et al.*, 2021). Relying on BFO to develop an ontology for the purpose of monitoring ecosystem services provides an opportunity to move the field forward, tackling two major challenges in its development – conceptual clarity and data integration – whilst building on successful parallel efforts.

The lack of an ontology for ecosystem services limits interoperability (Bagstad *et al.*, In review) and hinders progress towards systematic monitoring to support the detection and attribution of change (Gonzalez, Chase and O'Connor, 2023). Developing a formal ontology with a clear and motivated logic that can integrate data and reason across concepts is a significant step towards tackling this challenge (Balbi *et al.*, 2022). A well-defined ontology will promote a systematic and comparable understanding of variables used for ecosystem service monitoring across widely different social-ecological contexts and systems (Guerrero *et al.*, 2018). An ontology will support the development of tools and analytical pipelines to assess ecosystem services and model trend change (Galaz García *et al.*, 2023; Griffith *et al.*, 2024). Here, we use BFO in conjunction with the most widely used and recognised conceptual frameworks for ecosystem services to develop a first ontology for monitoring ecosystem services (hereafter the ESM ontology). We motivate the reasoning for our choices in the sections below, present the formal ontology, test it with data from three ecosystem services and discuss its role in the advancement of interoperability and systematic ecosystem services monitoring.

2. Material and methods

2.1 Building the ESM ontology

Ontology building is a time-consuming and resource intensive task (Mateiu and Groza, 2023). Research into automation processes is ongoing (Al-Aswadi, Chan and Gan, 2020; Kommineni, König-Ries and Samuel, 2024) but it is unlikely that the need for human involvement will disappear in the future (Neuhaus and Hastings, 2022). Best practices and principles of manual ontology building have evolved little since their early development and mostly centre around general recommendations and heuristics to follow (Gruninger and Fox, 1995; Uschold and Gruninger, 1996; Fernández-López and Gómez-Pérez, 2002; Bravo Contreras, Hoyos Reyes and Reyes Ortiz, 2019).

There are four steps to building an ontology (Figure 1).

First, it is essential to bound the ontology by specifying its domain of application. Here, we focus on terms relevant and necessary to organise and use data collected in social-ecological systems to monitor ecosystem services.

Second, the focus is on extracting knowledge from the literature to produce a taxonomy of terms and their hierarchical relationships (Supplementary Table 1).

Third, the design of the ontology is an iterative process guided by the upper-level ontology (here BFO) and the conceptual frameworks of the domain (here the cascade model (Potschin-Young *et al.*, 2018), the social-ecological system (McGinnis and Ostrom, 2014), NESCS Plus (Newcomer-Johnson *et al.*, 2020), the Intergovernmental Panel on Biodiversity and Ecosystem Services conceptual framework (Diaz *et al.*, 2019) and the nature futures framework (IPBES, 2023), Supplementary Figure 1). The focus in this step is to produce an internally consistent ontology that reflects reality, aligns with BFO and represents domain knowledge through its taxonomy and relationships. Terms are hierarchically organised in **classes** (e.g. "fish" is a **class** and "salmon" is its **subclass** – bolded hereafter) with *relationships* (e.g. **fish** *participates in* **fishing** – italicised hereafter). During this step, it is good practice to collaborate with other domain experts to validate the budding ontology and to reassign terms as necessary. The ontology can then be formalised by coding it using a semantically defined language (here the Web Ontology Language – OWL (Bechhofer *et al.*, 2009)). At this step, data can be uploaded into the ontology to produce instances of a class: realisations of the class for which we have data (e.g. an instance of **fish** may be the salmon population of 2008, which has a year and abundance value). It is these data, related via the ontology, that realise the potential of an ontology in enabling interoperability and subsequent modelling efforts.

Fourth and final, the ontology is evaluated by using a reasoner then queried. The reasoner checks the internal logic of the ontology and verifies that no illogical relationships or class assignments are inferred from the specification in the third step. Then, two types of queries can be made (i) general queries about the classes and relationships in the ontology and (ii) specific queries about data that has been uploaded to the classes in the ontology. Querying an ontology enables the designer to (i) test the internal consistency of the ontology to make sure there are no spurious connections between terms nor missing links and (ii) that data can be retrieved correctly. Querying an ontology relies on competency questions (questions the domain ontology should be able to answer if built well) and is a common method of evaluation (Gruninger and Fox, 1995; Bravo Contreras, Hoyos Reyes and Reyes Ortiz, 2019). Questions and/or their answers can be reviewed by domain experts to improve the validation process.

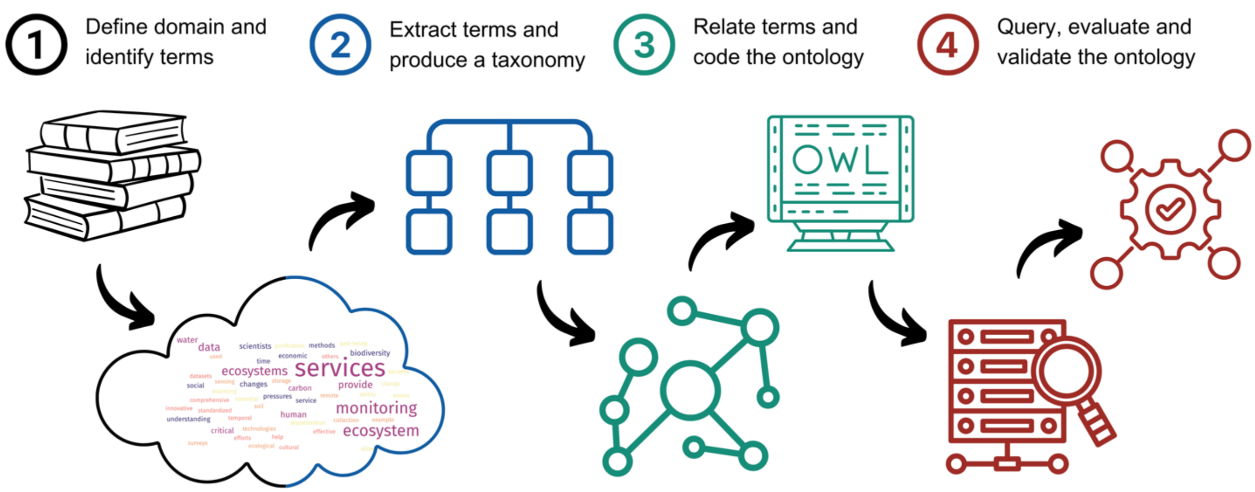

Figure 1. The four steps to building an ontology. 1. The domain of application is specified and a literature review conducted. 2. Terms identified as necessary are organised in a systematic taxonomy. 3. Relationships between terms are added to form an ontology that can be formally coded and to which data can be linked. 4. The formal ontology can be queried via a computer to validate its content and structure.

2.1.1 A taxonomy for ES monitoring

The taxonomy for ecosystem services monitoring was established from a literature review of foundational texts on ecosystem service science and more recent literature on ecosystem services monitoring. We followed a theoretical sampling approach where the concepts of interest (here terms relevant to monitoring ecosystem services) are continuously compared to extract meaning, until a point of saturation is reached when no new variation in meaning is found (Corbin and Strauss, 2015; Patton, 2015). The terms selected (Supplementary Table 1) form the basis of what an ontology for monitoring ecosystem services should cover but can be extended to include additional terms as needed.

2.1.2 Designing the ontology

Adopting BFO as upper-level ontology not only supports interoperability with other domain ontologies, but it also sets the philosophical foundations upon which to develop the ESM ontology. BFO is grounded in philosophical positivism and epistemological realism, adopting the view that an objective reality exists independent of human thought or perception and that it can be understood using the scientific method. In fact, BFO concerns itself mainly with making data, which can be measured, interoperable and discoverable. In the context of monitoring ecosystem services, we are also concerned with the measurable and observable. As such, adopting BFO's philosophical underpinnings is logical and appropriate. This position means that only objectively measurable entities can be part of a BFO ontology. Those entities are divided into **continuants** (that persist through time, like objects) and **occurrents** (that unfold over time, like processes). BFO also contains pre-existing relationships that follow defined rules and axioms (e.g. a **process** *occurs in* a **material entity** (Smith *et al.*, 2005)). The **continuants**, **occurrents** and *relationships* defined in BFO can be used to map and relate the terms needed for ecosystem services monitoring.

Assigning the terms in the taxonomy to the appropriate BFO entity was straightforward for most terms (e.g. "actor" and "ecosystem component" are **objects**, but "economic activity" is a **process**). In social-ecological systems there exist entities which persist through time and are made of matter, these are logically part of **material entities** and either **objects** (e.g. a fish) or **object aggregates** (e.g. a school of fish). Geographical location, essential information in ecosystem service monitoring, is a **spatial region** within **immaterial entities**. Values of any kind are **qualities**: **continuants** that depend on others (e.g. the monetary value of a fish). **Processes** are **occurrents** which have some material entity taking part in them (e.g. the reproduction of fish). In the ESM ontology, this includes ecosystem processes, human activity (economic and non-economic) and drivers of change.

The core of the ESM ontology was built to reflect the major conceptual frameworks in ecosystem service science (Supplementary Figure 1) whilst allowing for a systematic approach to measuring the different aspects of ecosystem services. There are two parts to the ontology that bring together the social and ecological dimensions of a system. On the ecological side (Figure 2), **ecosystems** are **object aggregates** that are made of **ecosystem components** (**biotic** and **abiotic**), they are *located in* some **ecosystem extent** and have some **ecosystem condition** and **intrinsic value**. **Ecosystem processes** *occur in* **ecosystems**. Some are **ecosystem functions** which *realise* an **ecosystem service** and *output* **ecosystem goods**. On the social side, **actors** (**economic** and **non-economic**) and **anthropogenic assets** *participate in* **human activity** which *realises* **ecosystem services**. **Actors** *benefit from* the **values** derived from **human activity** or the **commodities** it produces. **Human activity** and **commodities** can have different types of **values** (**instrumental** or **relational**). **Human activity** also produces **drivers of change**. Connecting both sides: **ecosystem goods** *participate in* **human activity** (e.g. fish population in commercial fishing or freshwater in swimming) and **drivers** are *causally related* to **ecosystem components** and/or **ecosystem processes** (e.g. pollution negatively affects growth).

The ESM ontology focuses on ecosystems and the **processes** and **objects** within them, allowing flexibility to the user to represent the observable and measurable reality of their social-ecological system. It further allows multiple ecosystem services to be realised by the same ecosystem process but by different human activities, highlighting the interdependencies among services.

To expand on the applicability of the ESM ontology, align it with current standard in ecosystem services monitoring and provide an example use case and extension, we added one module (a stand-alone section that connects to the ontology but does not affect its core functioning) that does not align with BFO. The concept of essential ecosystem service variable (EESV) was introduced by the Group on Earth Observation Biodiversity Observation Network (GEO BON) to support standardised monitoring of ecosystem services (Balvanera *et al.*, 2022; Schwantes *et al.*, 2024). EESVs are a concept and not an observable entity. Therefore, we add them to a new top class: **concept** (besides **occurrent** and **continuant**) and connect them to their relevant measures in the rest of the ontology (e.g. **anthropogenic asset** *measure of* **anthropogenic contribution** as defined by the EESV concept; see Schwantes et al., 2024). This extension allows the ontology to support the efforts of GEO BON in producing EESVs from social-ecological data to monitor ecosystem services without affecting the core ontology by relating the EESVs to the core ontology terms most relevant to each class (Supplementary Figure S2).

2.1.3 Resolving differences in language

Two terms warrant additional discussion: "ecosystem function" and "ecosystem service".

The distinction between an ecosystem process and an ecosystem function is not always clear. These terms have a history of being used interchangeably (Jax, 2005), prompting some to suggest avoiding the term "ecosystem function" entirely (Jax, 2016). Given its prominence in the ecosystem services literature, we choose to include the term in our ontology but define it specifically as a subclass of **ecosystem process**. Specifically, we consider ecosystem functions to be those ecosystem processes that have a specific purpose in relation to humans (e.g. water purification and primary production). As such, ecosystem functions are those ecosystem processes that underpin ecosystem services. This definition does not imply that each ecosystem function must be the result of a single ecosystem process. In fact, the ontology allows for some ecosystem functions to be the outcome of several ecosystem processes (e.g. biomass production as an outcome of reproduction and predation). Our definition aligns with others (MA, 2005; Wallace, 2007; Luck *et al.*, 2009) and enables us to operationalise the language of ecosystem services in the ontology.

Our approach to defining ecosystem functions allows us to specify ecosystem services as **dependent entities** of ecosystems that are *realised* by the ecosystem functions occurring in the ecosystem and some human activity. In fact, we assert that ecosystem services are not some objective measurable entity or process in the environment, but rather a perception, rooted in culture, of the role of ecosystems in contributing to human wellbeing. As such, ecosystem services are **roles** filled by specific ecosystems.

As academics and practitioners, we usually do not directly measure an ecosystem service but rather some dimension of it (e.g. supply, use or demand). Attempting to measure ecosystem services directly without being explicit about the entities being measured has led to the proliferation of definitions, approaches and classification systems (Fisher, Turner and Morling, 2009; Nahlik *et al.*, 2012; Polasky, Tallis and Reyers, 2015; Danley and Widmark, 2016; Finisdore *et al.*, 2020) .

Additionally, the attempt to measure all ecosystem services (regulating, provisioning and cultural) in the same way leads to an important category mistake (Wallace and Jago, 2017). Indeed, regulating services are typically understood as processes (e.g. erosion control) or properties (e.g. soil quality) whilst provisioning or cultural services are dependent on material entities (e.g. fish, a natural park). These are ontologically different categories of entities that should not be measured in the same way. However, one can measure the various parts of a social-ecological system that realise an ecosystem service (e.g. ecosystem processes and components, human activity and goods). Doing so also resolves the issue of assigning multiple ecosystem services to a single ecosystem component or good (another category mistake). In fact, it is the process in which the ecosystem component or good participates or is produced that realises the ecosystem service, not the component or good itself. This understanding of ecosystem services allows for systematic monitoring of all dimensions of an ecosystem service through the ESM ontology.

2.1.4 Formalising the ESM ontology

We formalised the ESM ontology described above using the free open-source ontology editor and knowledge management software Protégé (Musen, 2015) and coded it in OWL language (Bechhofer *et al.*, 2009). We first imported the latest version of BFO and specified our ontology within it. All classes, subclasses and relationships were defined according to the logic described above.

2.1.5 Uploading data to the ontology

To test our ontology and showcase its usefulness, we loaded the ontology in Python and added data about three ecosystem services using the rdflib package (Boettiger *et al.*, 2020). The ecosystem services – salmon provisioning, water quality regulation and whale watching in British Columbia, Canada – were selected based on previous work carried out to operationalise essential ecosystem service variables for monitoring (Schwantes *et al.*, 2024). We selected these examples to show how the ontology handles all three types of ecosystem services and associated data, making the work of systematic monitoring more straightforward. Additionally, in these examples, EESVs had already been identified, enabling us to connect the data to the corresponding terms in the ontology. The data contained phosphorus concentration in the Salmon River (water quality regulation), orca abundance, whale watching effort, boat collisions and awareness of regulations in the Southern Resident Killer Whale critical habitat (whale watching), Chinook salmon abundance, catch, fishing effort and wholesale value in coastal British Columbia waters (salmon provisioning) between the years 1984 and 2022 (although time series length varied between datasets, Table 1). We had data from Schwantes *et al.*, (2024) for 192 instances from 9 classes. Three of these time series (awareness of whale respecting guidelines, count of vessels accompanying orcas and count of incidents between orcas and whale watching vessels) are not publicly available and therefore not published with the ontology.

Table 1. Data included from (Schwantes *et al.*, 2024) to test the ecosystem services monitoring ontology and associated **class** and **super class** from the core ontology (Figure 2). To add data to the ESM ontology, an instance of the class is created and some data properties associated with it. For example, the freshwater supply in Salmon River in 2000 is an instance of **clean freshwater** to which we can associate the data of quality, volume, year and more (Figure 3).

Super class	Class	Data	Time series
Ecosystem good	Clean freshwater	Total phosphorus concentration	1984-2020
Ecosystem good aggregate	Fish population	Chinook salmon abundance	1999-2018
Monetary instrumental value	Wholesale value	Wholesale value of Chinook salmon	1997-2021
Anthropogenic asset aggregate	Fishing fleet	Fishing vessel count	2005-2020
Commodity aggregate	Wild caught fish	Chinook salmon catch	1999-2019
Ecosystem good aggregate	Whale population	Southern resident orca abundance	1998-2021
Relational value	Cultural value	Awareness of whale respecting guidelines	2009-2021
Anthropogenic asset aggregate	Whale watching fleet	Count of vessels accompanying orcas	1998-2021
Direct driver	Vessel strike	Count of incidents between orcas and whale watching vessels	1998-2021

2.2 Testing and validating the ESM ontology

We tested and validated the ontology in three ways.

First, we solicitated informal feedback on the core ontology, in person, to attendees of the 3rd global conference of the Programme on Ecosystem Change and Society and, online, to members of the GEO BON ecosystem services working group (in total, 15 people shared their views on the ESM ontology between August and October 2024). During these discussions, the core ontology was reviewed. Specifically, we discussed the positioning of terms within BFO classes, the relationships connecting terms and whether all present terms were sufficient. These conversations led to the reassignment of several terms, especially the placing of **ecosystem function** as a subclass of **ecosystem process**.

Second, we built the ESM ontology and ran the HermiT 1.3.4 reasoner plugin in Protégé to check for errors or logical inconsistencies.

Finally, we queried the ontology and the data it contained using a set of competency questions with the owlready2 Python package (Lamy, 2017). We used a total of 25 questions (Supplementary Table 2) that we expect an ontology designed to monitor ecosystem services to be able to answer. We manually checked the answers returned from the queries to validate their accuracy (Supplementary Table 2).

3. Results

In this section, we first present the ESM ontology, and the results of the validation step (Figure 1), then outline how it enables information sharing and monitoring using an example case study for a specific ecosystem service in British Columbia, Canada.

3.1 The ESM ontology

3.1.1 The core ontology

The core classes and relationships are designed to be applicable to any social-ecological system and ecosystem service (Figure 2). In total, the ESM ontology contains 119 classes and 61 relationships, of which 93 and 2 respectively are new to the ESM ontology (i.e. were not already part of BFO). We purposefully reused as many pre-existing relationships as possible to improve the interoperability of our ontology with pre-existing BFO-based ontologies. A complete list of new (non-BFO) classes and relationships and their definitions is available in Supplementary Table 3. We only represent a subset of possible ecosystems, ecosystem processes and ecosystem services in the current version of the ontology. We focus on those terms relevant to our examples and as guidance for users looking to add their own terms.

The complete ontology is available at: https://github.com/FlavAff/ESMOntology.

3.1.2 Validating the ontology

We queried the ontology in two steps. First, we focused on the core ontology checking that classes were correctly linked to each other according to the logic specified above. Second, we queried the instances added to the ontology to check if the ontology was able to retrieve the correct data.

Of the 25 competency questions, 18 were focused on classes and 7 on instances (Supplementary Table 2). Overall, the ontology returned 21 correct answers, 2 partially correct and 2 incorrect answers. The ontology was able to retrieve the correct data for all queries on instances but made errors for some classes. We used partially correct and incorrect answers to edit the ontology and ensure that it would return all correct answers when queried again.

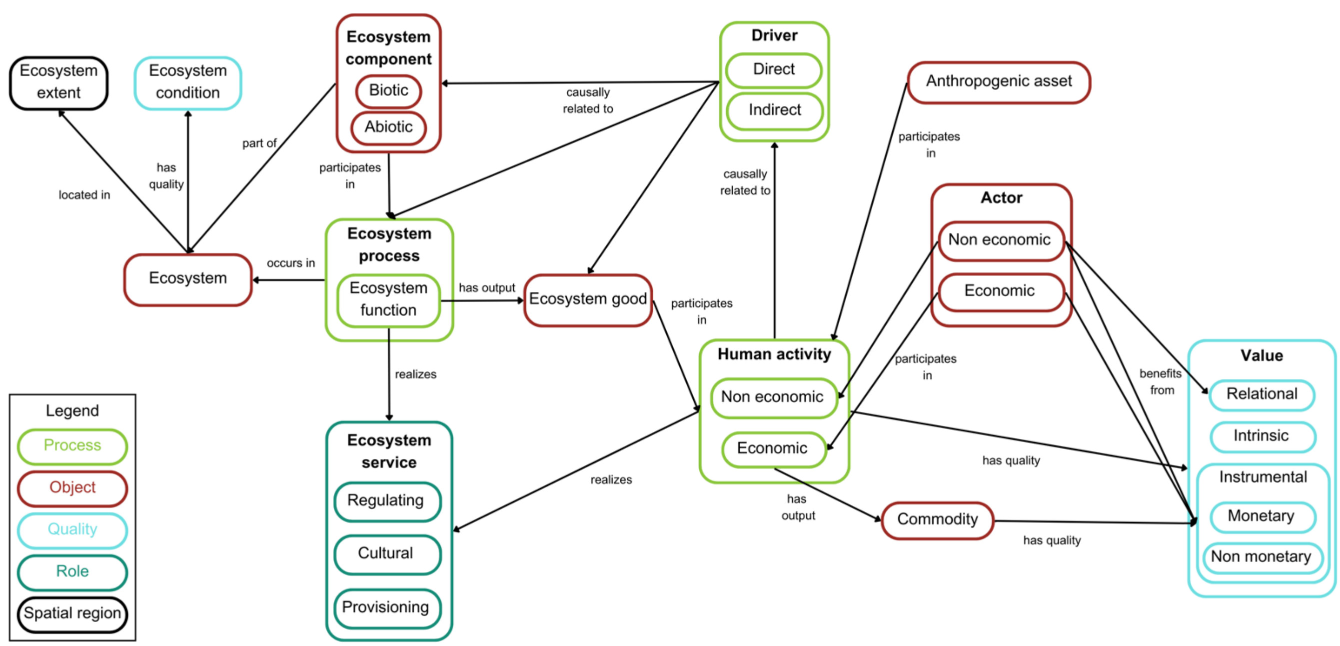

Figure 2. Core terms and relationships in the ecosystem services monitoring ontology. The core ontology contains all essential terms to the social-ecological representation of ecosystem services. Colours correspond to BFO specified classes. All terms represented here are classes in the ontology, terms within boxes are subclasses. Labels used here are simplified for graphical representation. Relationships are represented with directional

arrows and labeled. For clarity, not all relationships between terms are shown (e.g. *realizes* is represented but *realized by* is not, and the link from **Ecosystem** to **Intrinsic value** is not shown).

3.2 How does the ontology enable information sharing and monitoring?

The ecosystem services ontology enables users to systematically study the change in multiple dimensions of an ecosystem service (e.g. use, supply, value). Scientists or practitioners collecting data in the field can use the ontology to assign the variables they measure to the appropriate classes, relate them to each other and upload quantitative data (Figure 3). The data associated with these classes can then be readily integrated into models that can be used to study the dynamics of an ecosystem service and predict future trends (Figure 4).

For example, take the case of a team of scientists tasked with inferring the future of whale watching as an ecosystem service in British Columbia, Canada. Southern resident killer whales in British Columbia are listed as endangered (COSEWIC, 2008) but they are an important part of the local culture and support a valuable whale-watching industry out of Vancouver and other cities in Southern British Columbia and Washington state. Therefore, understanding how this ecosystem service is changing is highly relevant to the local economy and culture. Monitoring efforts in the region have been ongoing and data on the social-ecological system is available from various sources (non-governmental organisations, academic institutions and the government). However, these data had not been used together to analyse the ecosystem service prior to Schwantes *et al.*, (2024).

Without an ontology, it is up to the team to inform themselves on the literature of ecosystem services, choose an applicable framework (e.g. GEO BON's essential ecosystem service variables), and rely on their interpretation of the terms to formalize a model to analyse the data. This limits the replicability of their approach by only organising the data according to this application of the EESV framework. Furthermore, in this case, it is impossible for computers to understand how the data relates to the ecosystem service therefore limiting interoperability should another team wish to extend the work or apply it in a different system. With the ESM ontology, however, the team could organise the data and information about the ecosystem service in a systematic way that can be reused across applications or analytical pipelines.

Therefore, we revisited the work of Schwantes *et al.*, (2024) to include the terms and data they used in the ESM ontology (Figure 3). This organises the data and information in a systematic way that simplifies analysis and highlights what kind of data is available or needed, making it possible to infer change in the ecosystem service using GEO BON's EESVs or any alternative approach.

In this system, Chinook salmon populations (**biotic ecosystem component**) in the epipelagic ocean waters (**ecosystem**) are prey in the Southern resident killer whale's critical habitat (**ecosystem extent**) which sustains the whale population (**ecosystem good**) through predation (**ecosystem process**). This provides habitat (**ecosystem function**) for the whales in an area that can sustain a whale watching industry (**human activity**) to realise the cultural ecosystem service of wildlife viewing (**ecosystem service**). Tourists then benefit from the experience of partaking in the activity (**non-monetary instrumental value**) and tour operators benefit from the income generated by whale watching (**monetary instrumental value**) and the cultural importance of the species to the area (**relational value**). Additionally, whale watching vessels (**anthropogenic assets**) can be involved in ship strikes (**direct driver**) that affect population growth. Alongside this information, any data (e.g. abundance, count, year) is associated with each corresponding variable.

The qualitative information about the relationships in the social-ecological system is essential to understanding how and why the ecosystem service may be changing, even though some variables are currently lacking quantitative data. Additionally, data from other related social-ecological systems (e.g. Pacific salmon fisheries) present in the ontology and can be used to understand the decline in killer whale abundance from reduced food availability through a decline in habitat quality.

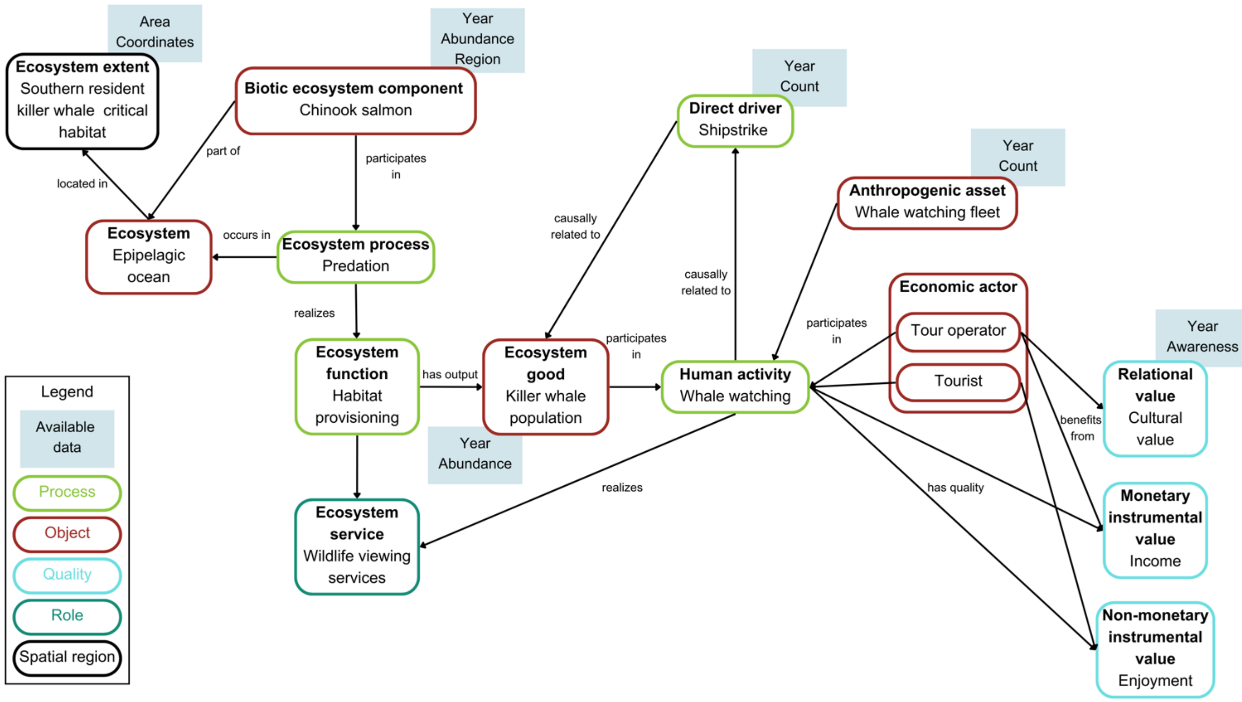

Figure 3. Example application of the ecosystem services ontology to the ecosystems service of wildlife viewing for British Columbia Southern resident killer whales. The social-ecological system can be represented explicitly using the core ontology to organise variables and the relationships between them (e.g. whale watching is a **human activity** that can *cause* ship strikes, a **direct driver** that is *causally related to* the killer whale population, an **ecosystem good**). All terms relevant to the social-ecological system are therefore placed within the core ontology to understand the dynamics of the system and organise data. The data that is measured for each variable is loaded into the ontology to create instances of each class. In this case, data were available from Schwantes *et al.* (2024) for six relevant classes (e.g. killer whale population had abundance and year data). Quantitative information about each variable (the data contained in each instance) can be retrieved from the ontology alongside qualitative information about how variables relate to each other to help produce models and analytical pipelines that support monitoring (Figure 4).

With the ESM ontology, the work from Schwantes *et al.,* (2024) becomes reusable, allowing additional analysis of the whale watching ecosystem service. For example, the authors did not compare the effects of food availability and ship strikes on the whale population and the whale watching industry it supports. Declining Chinook salmon populations have been cited as a leading cause for a decline in the Southern resident killer whale population (Williams *et al.*, 2011; Hanson *et al.*, 2021) but policy action has focused on limiting the distance between orcas and boats (Frayne, 2020; Kassakian and Flight, 2020). Using the ESM ontology, a user can explore what processes are driving the dynamics of the social-ecological system and extract the data available to analyse the quantitative relationships between them. Here, one could explore the relative effect of food availability and ship strikes by querying the data on killer whale abundance, count of vessels following them, number of ship strikes, and Chinook salmon abundance from 1998-2021. Those data can then be used in a process model of the variables and their relationships to explain how the whale population has been changing and may be expected to change within the current policy regime (Figure 4). Additionally, the ESM ontology highlights what additional data on related variables may be missing (e.g. income generated) and could be collected and included to allow further analysis and causal understanding of long-term outcomes (e.g. is the ecosystem service economically sustainable?).

The ESM ontology therefore allows a user to understand the complex dynamics of a specific social-ecological system, to identify the important relationships to study, extract and analyse data as well as to identify which additional data would be required for complete monitoring of the ecosystem service.

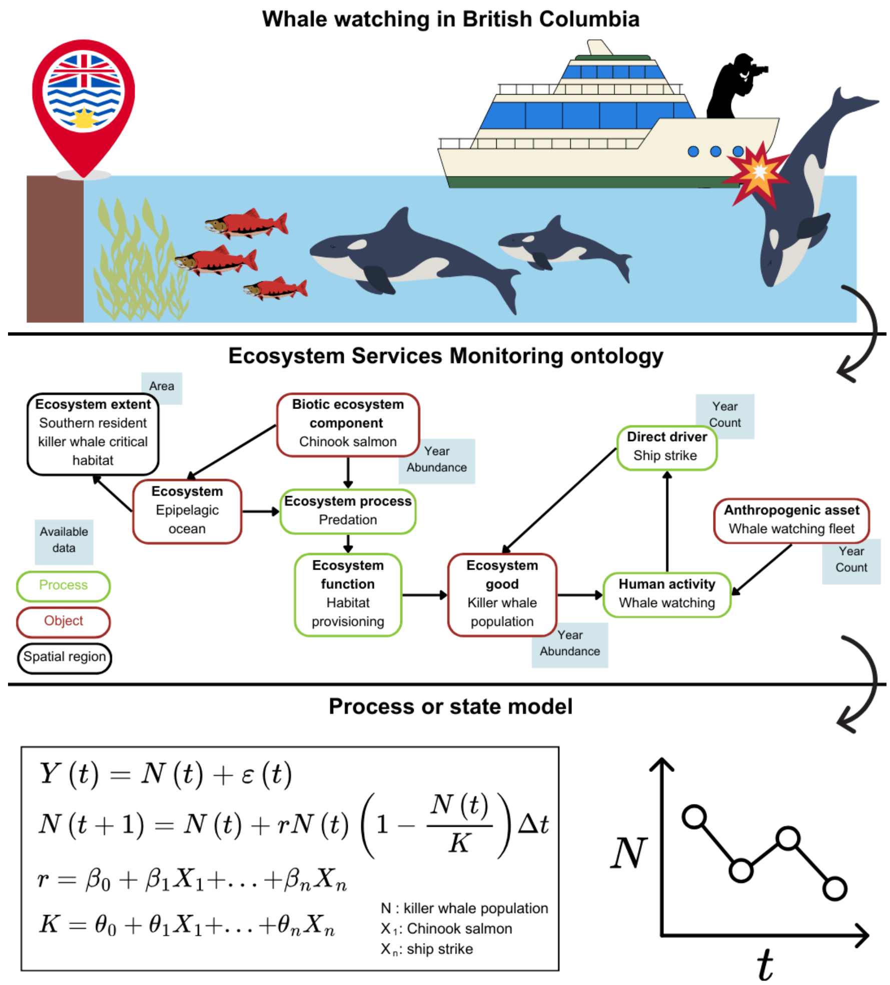

Figure 4. The role of the ESM ontology in understanding and inferring change in ecosystem services. Systematic use of terms (middle) helps relate the observable reality (top) to models (bottom) in a coherent and shareable way. Data collected in the field is organised and related according to the ontology (middle), making it possible to model ecosystem services dynamics (bottom). The variables organised in the ontology directly relate to models that can represent the causal reality of the system (bottom). Here, the Lotka-Volterra model for killer-whale population growth relies on variables and data available in, and organised according to, the ESM ontology and allows for the modelling of ecosystem service supply. Additional economic models to represent the growth in whale watching fleet size and its impact on ship strikes could be a logical extension to understand ecosystem service dynamics supported by the ontology. The ESM ontology makes consistent the use of data and language helping both reusability and comparability of models. Use of the ontology when monitoring ecosystem services therefore allows for the development of tools to assess and predict ecosystem service change.

4. Discussion

This paper had two aims (i) to propose an ontology for the terms used in the field of ecosystem services and (ii) to provide a tool that can enable systematic and consistent monitoring of the variables used to measure ecosystem service change. We discuss each, in turn, reflecting on what we have proposed, then focus on opportunities for further work and development, automation and the need to operationalize use and uptake by a broad community of researchers and decision-makers.

4.1 A tool to improve monitoring

Monitoring ecosystems and the services they provide is required to assess progress towards international sustainable development and conservation goals (Diaz *et al.*, 2019; CBD, 2022a). The tools currently available to enable rapid data integration, sharing and reuse are insufficient (Adamo and Willis, 2023; Bagstad *et al.*, In review) and much work remains to be done before ecosystem services monitoring can support reliable automated ecosystem service assessments (Galaz García *et al.*, 2023). Here, we take one small yet crucial step towards enabling consistent and systematic monitoring of ecosystem services. Having focused on one significant barrier to interoperability – the terms of ecosystem services and their use in language and science – we propose a novel ontology for monitoring ecosystem services.

The ecosystem services monitoring ontology provides a clear and systematic representation of the language needed to understand and monitor ecosystem services. Currently, it focuses on a set of core terms and how they relate, including three real-world examples. The ESM ontology can retrieve information on all three types of ecosystem services and provide the relevant data to assess and report on trends. Its structure is set up to guide users on how to represent their social-ecological system and share their data so that it can be accessed and used systematically. The addition of GEO BON's essential ecosystem service variable (EESV) classes as a module makes it possible to connect local data collection to global standards of monitoring (Geijzendorffer *et al.*, 2016; Proença *et al.*, 2017; Turak *et al.*, 2017).

The ESM ontology builds on decades of work to conceptualise how ecosystems contribute to human wellbeing, combined with BFO, a widely used and globally recognised statistical classification standard (ISO, 2021), to provide a structure that should be familiar to users whilst requiring them to be explicit about the data they are reporting and what it corresponds to. This strict approach limits the risk of category mistakes being made (Wallace and Jago, 2017) and prevents the simple yet error-inducing idea of "measuring an ecosystem service" by requiring that data be specifically assigned to some measurable aspect of reality that is related to an ecosystem service (e.g. abundance of whales, fishing effort, wholesale value). This further encourages users to be holistic in their efforts to quantify ecosystem services by measuring all relevant aspects of the social-ecological system. With data organised systematically in this way, two things become possible (i) misunderstandings about what exactly is being measured and understood as an ecosystem service are avoided and (ii) how and why the social-ecological system is changing is measurable.

4.2 Clarifying and operationalising the concept

By using BFO as its upper-level ontology, the ecosystem services monitoring ontology adopts a positivist view of the world that aims to represent real entities that can be observed and measured, not concepts or ideas that are context dependent (Schulz *et al.*, 2013; Arp, Smith and Spear, 2015). This helps to operationalise the language of ecosystem services in a way that enables measuring, and therefore monitoring, in a consistent manner, independent of the data's ultimate end use (e.g. accounting, valuation, …). It forces the difference between goods and processes to be made explicit so that measures of value, supply, *etc.* can be appropriately ascribed to what is used by humans (the good, e.g. water) rather than a step in its production (the process, e.g. water purification). This view aligns well with efforts to quantify what is actually contributed to humans through ecosystem functions and processes whether for accounting (Boyd and Banzhaf, 2007) or from a systems ecology perspective (La Notte *et al.*, 2017).

The ESM ontology further highlights the difference between provisioning, cultural and regulating services in how they contribute to human wellbeing. Provisioning services are realised by ecosystem functions that produce ecosystem goods that are, in turn, used (consumptive use) to produce economic goods (commodities). Cultural services are also realised by ecosystem functions that produce ecosystem goods, but these are not consumed (non-consumptive use). In the former case, value is derived from the commodity produced from the ecosystem good, for the latter, value is derived from the human activity, the experience that depends on the ecosystem good (Chan *et al.*, 2012). For regulating services, the ecosystem service is realised by the ecosystem function itself, but value is derived down the line from the ecosystem good that is produced. This view is supported by the stock-flow and stock-fund perspective on ecosystem services (Raffaelli and White, 2013) and the idea that, in ecosystem accounting, intermediate services are relevant only insofar as they contribute to a final service (SEEA, 2021). The ontology explicitly supports all these conceptualisations by focusing exclusively on what is measurable and organising it relative to the ecosystem service of interest.

Note that this ontological approach means the ecosystem service itself, by virtue of being the role of an ecosystem function, is never measurable. Only the associated ecosystem goods, functions, human activities, commodities, anthropogenic assets and their monetary or non-monetary values are measurable. This makes explicit what is standard practice in ecosystem service science: published and reported measures of ecosystem services are proxies (Seppelt *et al.*, 2011), i.e. some aspect of the relevant social-ecological system that is measurable. These proxies are sometimes labelled with the terms "use", "demand" or "supply" (Martínez-Harms and Balvanera, 2012; Lamothe and Sutherland, 2018; Schirpke *et al.*, 2019; Boesing *et al.*, 2020). These terms, we argue, are no longer observable entities but conceptual interpretations of observable entities in the context of an ecosystem service (e.g. population density as a proxy for demand for water regulation services). The ESM ontology allows for this interpretation by providing the example of essential ecosystem services variables, themselves an attempt at requiring a holistic approach to measuring ecosystem services (Balvanera *et al.*, 2022).

4.3 Further developments

The current ESM ontology is a minimum product that can and should be expanded to include as many relevant and important classes as required. The examples it includes are not exhaustive and neither is the list of ecosystem functions and processes, values generated, or activities associated with each case study (e.g. cultural value of chinook salmon provisioning or sediment deposition for water quality regulation). A user may choose to include as many processes as are relevant to their social-ecological system taking care to relate them appropriately (e.g. through *causally related to* or *output of* relationships). The core terms can be used to expand the ontology downwards, adding more detail about subdomains and specific ecosystem services. Additionally, the ecosystem services monitoring ontology is application-agnostic; its role is not to produce accounts or indicators, nor to value ecosystem services, but to organise the data and information of social-ecological systems to enable monitoring of change. However, these data are necessary for these other applications. Using a modular approach, new sections can be added for specific purposes. We already added a module for EESVs but additional modules that connect specific indicator calculation pipelines could be connected to the ontology. For example, this ontology could support the application of the UN System of Environmental Economic Accounting (SEEA, 2021) and the compilation of headline indicator B1 of the Global Biodiversity Framework (CBD, 2024b) if connected to a specific module able to interpret the social-ecological data collected and how it fits within these applications. This flexibility allows the ESM ontology to be relevant for a multiplicity of users who can share data collected for different purposes in a common tool that allows for it to be used broadly for diverse applications.

As a caveat, attention must be given to avoid including so much detail that the ontology becomes intractable. Much work has already been done to develop ontologies that are relevant to social-ecological science (Madin *et al.*, 2007, 2008; Frey and Cox, 2015; Ayuningsih, 2019). The Environmental Ontology (ENVO, Buttigieg *et al.*, 2013, 2016) and the Biological Collections ontology (Walls *et al.*, 2014) contain terms and relations that should be reused where relevant. Specifically, the classes related to ecosystems and their components could be expanded and revisited to use ENVO terminology on habitats and biomes. Additionally, not all classes need to be used in every case (e.g. ecosystem component being left empty). To support national and global monitoring efforts, we chose to align ecosystems to the IUCN Global Ecosystem Typology (Keith *et al.*, 2022), the global standard recommended in the Monitoring Framework of the Global Biodiversity Framework (CBD, 2024b) and the System of Economic Environmental Accounting (SEEA, 2021). This may need to be aligned with ENVO to allow for the ecosystem services monitoring ontology to be interoperable with other BFO-based ontologies.

Additionally, the role of governance, norms and social behaviors is not well reflected in the ESM ontology. Including these concepts within an ontology is particularly challenging (Adamo and Willis, 2022). IPBES classes these within the term "anthropogenic assets", which we reserve for objects that humans use as part of their activities (e.g. infrastructure, fertiliser, boats, …). However, it essential to recognise the important role that such social variables play in ecosystem service dynamics (Ostrom, 2007). The social-ecological framework recognises the impact of governance and social norms on system dynamics, and there are many examples of the effects of governance on ecosystem service dynamics (Leslie *et al.*, 2015; Yletyinen *et al.*, 2018; Metzger *et al.*, 2021; Coenen *et al.*, 2023). The reliance of the ESM ontology on BFO limits its ability to include such social concepts. Yet, understanding how social norms and governance are changing and the effect this has on ecosystem services is crucial. Alternative top-level ontologies such as the Unified Foundational Ontology (Guizzardi, Falbo and Guizzardi, 2008) or the Descriptive Ontology for Linguistic and Cognitive Engineering (Bottazzi and Ferrario, 2009) are better suited to include these terms, but they have their own drawbacks and their integration with BFO is limited. Interdisciplinary topics such as ecosystem service science would benefit from increased efforts by ontology engineers to bring together top-level ontologies for a complete representation of reality, both objective and conceptual. In the meantime, it will be important for users of the ESM ontology to take care to consider and include the role of governance, norms and social behaviors in shaping ecosystem service dynamics until the ESM ontology can be extended to formally include relevant variables.

Lastly, whilst we strived to build on the most widely accepted and used conceptual frameworks to develop the ESM ontology, it must be acknowledged that these are mainly designed and used under a Western science paradigm. The very concept of ecosystem service has come under scrutiny for being overly focused on the economic value of ecosystems (Norgaard, 2010; Farley, 2012; Costanza *et al.*, 2017). As such, additional terminology such as nature's contributions to people (NCP) has been introduced to reflect a broader worldview (Díaz *et al.*, 2015; Pascual *et al.*, 2017), although this too has come under critique for being too focused on the one-way directionality of the nature to human relationship (Peterson *et al.*, 2018). We did not include NCP in the ontology as its position in the taxonomy would be equivalent to that of ecosystem service. In fact, for the purpose of monitoring, we contend that there would be no difference in the types of measurements and data needed to understand how NCP are changing, and we are of the view that there is little operationalizable difference between both terms (Kadykalo *et al.*, 2019; Costanza, 2024). However, the need to reflect additional worldviews within the study of ecosystem services is important and much work has been done to recognise the value of ecosystem services beyond their instrumental importance (Chan *et al.*, 2012; Himes and Muraca, 2018; IPBES, 2023; Farley *et al.*, 2024). We welcome the efforts to expand our understanding of the spiritual, cultural and other relational values of ecosystem services. These, and their associated data, should be included in the ontology within the existing value class and related to the appropriate actors, processes and objects that interact to produce and benefit from them. The ecosystem services monitoring ontology is not a final product but an evolving tool that can be expanded to include new knowledge as it becomes available whilst providing the philosophical grounding and framing to include it.

4.4 Towards automation

A key role in the application of the ESM ontology is in supporting the automation of ecosystem service assessments and reporting. Their value in ecosystem service science is proven, providing the semantic underpinnings of the ARIES modelling project (Villa *et al.*, 2017). Today, the advent of artificial intelligence (AI) and extremely large datasets (e.g. remotely sensed data) offers an opportunity to advance the field and meet the needs of policy in producing up-to-date, reliable estimates of ecosystem services (Lu *et al.*, 2022; Galaz García *et al.*, 2023; Chaplin-Kramer *et al.*, 2024). The proposed Global Biodiversity Observing System (Gonzalez *et al.*, 2023), which promises to streamline the process from data collection to detection and attribution of change (Gonzalez, Chase and O'Connor, 2023) to the production of indicators (CBD, 2024a), are only realisable if the appropriate tools are in place. For example, retrieval augmented generation, a process that significantly improves the output of large language models, relies on domain-specific knowledge graphs (Lewis *et al.*, 2020), which themselves rely on ontologies (Ontotext, 2018). The ESM ontology could serve this purpose by being integrated into "BON in a Box software", a platform offered by GEO BON to provide nations with a user-friendly way to analyse biodiversity and ecosystem service data and produce indicators (GEO BON, 2024; Griffith *et al.*, 2024). As such, the call to increase efforts in making ecosystem service science interoperable goes beyond the needs of the scientific community. AI-based tools described here could reduce the capacity barrier faced by many nations in implementing the monitoring framework of the UN CBD's Global Biodiversity Framework's (Affinito *et al.*, 2024).

4.5 Uptake and use

Additionally, ontologies are as much computational as social tools, and it has been argued that their value comes as much from the process of getting domain experts to agree as it does from the finished product [125](Neuhaus and Hastings, 2022). Whilst we worked to engage with others during our work, this ontology remains the output of a small group of people and, to be useful, must gain social acceptance. We do not claim to have captured the only true way of representing ecosystems and the services they provide, and we invite comments and criticism. Ontology building is a social process that must engage the community for which it is intended, and we aim for this work to be a first stepping stone towards a community developed ontology that can be widely used and adopted. The need for the field to improve its standards for findability, accessibility, interoperability and reusability (FAIR, Wilkinson *et al.*, 2016) and collective benefit, authority to control, responsibility and ethics (CARE, Carroll *et al.*, 2020) along with the challenges encountered by many trying to apply the science of ecosystem services (Bull *et al.*, 2016; Carmen *et al.*, 2018; Jax *et al.*, 2018) prompted us to develop the ecosystem services monitoring ontology and we believe it already captures the overall consensus of the field. However, any remaining issues with how terms were treated or classes assigned can be resolved through a collaborative process we hope will be spurred by this work.

One last limitation to our work is its dependence on reuse. The major limitation to all ontologies developed to date, irrespective of domain, is the fact that they are often used and developed once then never taken up again (Haller and Polleres, 2020). Whilst this can be powerful for a specific project, it does not contribute to advancing interoperability and may in fact reduce it by proliferating diverse conceptualisations of a single domain. It is likely that the development and maintenance of an ontology for ecosystem services monitoring will require a community of practice dedicated to improving interoperability in the field (Fernández-López *et al.*, 2019; Carriero *et al.*, 2020). We invite others to build on our work towards an interoperable future for ecosystem services science.

5. Conclusion

The language of ecosystem services has been, and will continue to be, used for multiple purposes by diverse stakeholders with different backgrounds (Diaz *et al.*, 2019; IPBES, 2023). This flexibility is useful in some cases (Steger *et al.*, 2018). However, because ecosystem services are already used in multiple policy contexts and in assessments of knowledge, monitoring and reporting (Peterson *et al.*, 2018; CBD, 2022a), there is a risk that semantic ambiguity will complicate the development and use of monitoring systems developed for policy making (Loughlin, 2002; Kerr *et al.*, 2021).

In this work we designed a formal ontology for ecosystem services monitoring that can be used in multiple future applications. The ESM ontology is open source, designed to be interoperable and intended to be a living tool that can be modified and extended as necessary. If adopted and further developed by the ecosystem services community, it could play an important role in the effort to automate ecosystem services assessments and support the efforts of organizations in the public and private sector to monitor ecosystem services (CBD, 2022b; TNFD, 2023).

Data statement
All data used in this article are available from (Schwantes *et al.*, 2024).

Glossary
Ontology: systematic descriptions of concepts, entities, and a full range of relationship types between them, which are logically consistent and fully descriptive. (Bagstad *et al.*, In review)
Domain ontology: domain-specific ontologies represent relevant elements of a specific scientific field (e.g., hydrology, economics, biology, infrastructure). (Bagstad *et al.*, In review)
Class: a maximal collection of particulars falling under a given general term (e.g. "koala", "mongoose" and "sloth" all belong to the class "mammal"). (Arp, Smith and Spear, 2015)
Interoperability: "the ability of data or tools from independent resources to integrate or work together with minimal effort (Wilkinson *et al.*, 2016). Interoperability can be achieved with compatible data formats and communication protocols (syntactic interoperability) or data transfers where a receiving system can properly identify the meaning of exchanged data, reusing it appropriately (semantic interoperability (Heiler, 1995))." (Balbi *et al.*, 2022)
Taxonomy: a hierarchy consisting of terms denoting types (or universals or classes) linked by subtype relations. (Arp, Smith and Spear, 2015)
Entity: anything that exists, including objects, processes, and qualities. (Arp, Smith and Spear, 2015)
Monitoring: the repeated observation of a system in order to detect signs of change. (IPBES, 2019)
Anthropogenic asset: Any human-made or human-influenced object that contributes to human well-being and economic activity. (Adapted from IPBES, 2019)
Ecosystem good: The output of an ecosystem function before it is used in human activity. Components of nature, directly enjoyed, consumed, or used to yield human well-being. The ecosystem good (i.e., ecological end-product) is a biophysical feature and needs minimal translation for relevance to human well-being. (Newcomer-Johnson *et al.*, 2020)
Value: A principle associated with a given worldview or cultural context, a preference someone has, the importance of something for itself or for others, or simply as a means to an end. (Pascual *et al.*, 2017)

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Author contributions
FA, JMH, MJF and AG conceptualised the research. FA curated the data and conducted the analysis. FA and JH designed the methodology. MJF and AG supervised the work. FA wrote the original draft of the manuscript. JMH, MJF and AG reviewed and edited the manuscript.

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