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RESEARCH ARTICLE

An ecosystem service value chain for sustainable environmental management

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Abstract Managing ecosystems effectively requires managing the ways in which people interact with them, as opposed to managing ecosystems in isolation. However, management decisions often rely predominantly on biophysical data, leaving socio-economic data on the periphery. The absence of centralised socio-economic data collected systematically and purposefully makes their inclusion in decision-making challenging and often impractical. Drawing on the aggregation of a variety of data from heterogeneous stakeholders, we present and test the Ecosystem Service Value Chain (ESVC), a decision-oriented data structuring framework for visualising, organising, and prioritising socio-economic data for ecosystem management decision-making. The ESVC represents the stages and processes involved in delivering ecosystem services, from ecosystems to beneficiaries (government, industries, households, and First Nations Peoples). It reframes ecosystems as traceable value flows, linking ecosystem condition to service use, realised benefits and, where possible, valuation across distinct beneficiary groups. We demonstrate that this data structuring framework enhances transparency around data quality and gaps, providing a practical pathway for prioritising socio-economic information in management.

Keywords Coastal planning · Data · Ecosystem services · Environmental management · Great Barrier Reef (GBR)

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INTRODUCTION

As human-driven global changes increasingly threaten natural systems, understanding the intricate relationships between people and nature has become a global priority for the establishment and operationalisation of effective governance systems (Zoeller and Cumming 2024). However, despite surging demand for actionable ecosystem science and tools, and a burgeoning scientific literature, the actionability of outcomes from this investment to decision-making remains largely unrealised and facing several challenges (Keeler et al. 2012; Cvitanovic et al. 2013; Guerry et al. 2015; Marre et al. 2016; Olander et al. 2018; Mandle et al. 2021).

The first challenge is that datasets that could be used to inform ecosystem management decisions tend to focus predominantly on the biophysical aspects of socio-ecological systems at the expense of understanding the ‘socio’ component (Guerry et al. 2015; Rendon et al. 2019; Chan and Satterfield 2020; Howie 2021; Shi et al. 2022; Saunders et al. 2024). For example, a recent literature review by Mandle et al. (2021) found that only half of over 400 studies reviewed linked ecosystem condition to the supply of a human—benefit. They observe that focusing on the ecological production and projected changes in service provision neglects the socio-economic dimension, resulting in the link between biophysical service delivery and the value of human benefit unaccounted for thereby potentially limiting the usefulness of information for management decisions.

Stemming from the first challenge, the second lies in developing transparent and unambiguous links between the social and ecological components of socio-ecological systems (Keeler et al. 2012). Numerous frameworks have been produced to bridge the connections between ecosystems and people and to capture values in the broadest sense, i.e. as instrumental, relational and/or intrinsic (Chan et al. 2016) (Table 1). However, and despite growing recognition of the benefits of such links plus efforts to strengthen them (see Chan and Satterfield 2020), clear integration between ecosystem and socio-economic science remains elusive.

The final challenge, and the focus of this paper, is that although discrete socio-economic data focused on the value of human benefit from ecosystems and their services exists (Custodio et al. 2023), these datasets are often patchy, disbursed, infrequently collated, difficult to access, clouded in jargon and challenging to translate into decision-relevant information without substantial processing and refinement (Keeler et al. 2012; Cvitanovic et al. 2015; Guerry et al. 2015; Mandle et al. 2021).

We introduce the Ecosystem Service Value Chain (ESVC), a decision-oriented framework for structuring and quality-assuring socio-economic evidence on ecosystem services and making confidence in that evidence explicit. The ESVC addresses several needs as identified in the literature. (i) It provides a way to logically take stock and organise existing data; (ii) the modular approach also enables the identification of missing links and priority data

Table 1 Summary of the main groups of frameworks proposed in the literature to articulate ecosystem uses, benefits and value with the Ecosystem Service Value Chain (ESVC) included for comparison. Literature has put forward various solutions to address the challenge of understanding ecosystem uses and benefits. Among these, we note four main groups of frameworks: (i) Ecosystem valuation frameworks, including the ES and Nature's Contributions to People frameworks, (ii) the Total Economic Valuation (TEV) framework, (iii) Accounting frameworks, including Natural Capital Accounting (NCA) and System of Environmental Economic Accounting (SEEA) frameworks, and (iv) First Nations Perspectives. The ESVC lies at the intersection of these different frameworks, focusing on providing information of direct practical use for decision-making

Groups of frameworks	Overview	Identification and measures of ecosystem uses and benefits	Key studies
Ecosystem valuation frameworks	Ecosystem service (ES) framework: Categorises services into provisioning, regulating, supporting and cultural services	Identifies ES types and flows and proposes assessment methods (typically biophysically grounded). Positivist. Primarily focused on instrumental values	Costanza et al. (1997, 2014); Daily (1997); Millenium Ecosystem Assessment (2005) ; Haines-Young and Potschin (2018)
	Nature's Contributions to People (NCP) and Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES): Broadens ES to better include cultural and social perspectives	Expands to include diverse human values. Typically pluralistic, perspectivist and/or holistic. Encompasses instrumental, relational and intrinsic values	Díaz et al. (2018); IPBES (2019); Pascual et al. (2017, 2023); (Chan et al. 2016)
Total economic valuation (TEV) framework	Encompasses direct and indirect use, option, and non-use values of ecosystems. Provides a comprehensive valuation approach	Captures the full spectrum of ecosystem benefits, including market and non-market benefits. Focusses on value measurement. Positivist, utilitarian. Instrumental values	Barbier et al. (1997); Pearce and Turner (1990); Turner and Daily (2008)
Natural capital accounting frameworks	Natural Capital Accounting (NCA): Integrates the value of natural resources into economic accounts	Quantifies and reports natural resource values in economic terms. Instrumental values	Bateman et al. (2011); Natural Capital Committee (2014); TEEB (2010)
	United Nations (UN) System of Environmental Economic Accounting, Ecosystem Accounting (SEEA EA): Provides standardised methods for incorporating environmental data into economic accounts	Standardises environmental stock and flow data integration with economic accounts. Positivist. Instrumental values	Obst and Vardon (2014); United Nations (2024)
First nations perspectives	Emphasises holistic, culturally embedded views of nature (e.g. Land and Sea Country), often incorporating spiritual, social, cultural and traditional values	Includes spiritual, cultural, and traditional values of ecosystems; often involves community-based assessments and participatory methods. Perspectivist, holistic and experiential. Incorporates intrinsic, instrumental and relational values	Sangha et al. (2019); Normyle, Vardon et al. (2023) Turner and Berkes (2006); Urzedo and Robinson (2023)
The ESVC	Provides a framework to systematically assemble the data and information required to map the extent, distribution and flow of benefit from ecosystems through services to beneficiaries	Like TEV captures market and non-market benefits but provides a way to systematically review existing data and gaps for all ES beneficiaries. Focused on instrumental values	De Valck et al. (2023)

gaps; and (iii) once populated, it facilitates the tracing of benefits as they flow from ecosystems to distinct beneficiary groups. In addition to presenting the ESVC concept, we discuss how the ESVC was co-developed and tested operationally with the Great Barrier Reef Marine Park Authority (the Reef Authority), the statutory authority responsible for management of the Great Barrier Reef Marine Park, and present a pilot application in the Great Barrier Reef (GBR or the Reef) using available data on instrumental values.

The Reef presents a real-world example of the challenges of integrating a plethora of data points into useable information for successful management decision-making. For example, in the most recent Scientific Consensus Statement (SCS) for the Reef (Waterhouse et al. 2022), 3800 peer-reviewed studies were identified as evidence about the Reef's ecosystem health, water quality and human impacts on the Reef. Within these reviewed studies, 85 related to values categorised as ecological, social, economic and cultural (Newlands and Olayioye 2024). In other data consolidation efforts, Gooch et al. (2019), focusing on the marine system, identified over 200 datasets relevant to people's use and benefits from the Reef but did not connect these to ecosystems nor provide a framework to guide the use of this Reef-relevant socio-economic information into management decision-making. A key contribution of the ESVC framework is to propose a practical avenue to address these issues.

THEORETICAL FRAMEWORK

Several existing conceptual frameworks were foundational in shaping the approach presented in this study. First is Mandle et al. (2021). They suggest that one way to overcome this *'shortfall between what is needed by decision-makers and [what is provided as] ecosystem science and understanding'* is to develop ecosystem knowledge that provides and links information on ecosystem service (ES) supply and their use and derived benefit by people. Keeler et al. (2012), Olander et al. (2017) and Mandle et al. (2021) all discuss this connection in chain-based frameworks. For example, Keeler et al. (2012) present a chain-based framework linking biophysical and economic understanding related to the flow of value from changes in land and water management to water quality benefits for people and the change in value associated with this. The framework of Keeler et al. (2012) provides a method to link changes in ecosystem extent and/or condition to the services provided and the associated socio-economic values for multiple beneficiary types.

The framework presented by Olander et al. (2018) articulates the difference between ecological assessments (relating to the ecological impacts of a change in a natural space) and frameworks that link to a change in the natural environment with resulting changes in ES, and ultimately societal benefits. They focus on benefit-relevant indicators which apply when linking ecosystems to changes in ES because of a change in management and people. However, their framework does not extend to quantifying benefits to people.

Similarly, Rendon et al. (2019) articulate a framework linking biophysical change to seven domains of human well-being. One conceptual contribution of the framework by Rendon et al. (2019) is the feedback loop from people to ecosystems, reflecting the reciprocal responsibilities between people and the environment (Díaz and Pascual 2025; Stoeckl et al. 2025). A potential challenge when using this framework for decision-making is that it stops before articulating benefits to people. However, Daw et al. (2015) argue that not quantifying the benefits to people is sometimes preferred because this enables a focus on the type and flow of benefits from ecosystems to the spectrum of beneficiaries without the complication of valuation. Others argue that when valuation is also included, trade-offs are better understood, improving the decision relevance of the information (Daily et al. 2011).

An alternate and internationally adopted structured framework to account for ES is the United Nations (UN) System of Environmental Economic Accounting, Ecosystem Accounting (SEEA EA) framework (United Nations 2024). SEEA EA seeks to clearly set out and account for the links between ecosystems, ES and benefits to different beneficiaries, with these links described through a logic chain. However, whilst a set of SEEA EA accounts provide tables of data on ecosystem extent and condition, and separate tables of data on ES, there is no link explicitly indicating how changes to ecosystems may result in changes in ES flows. In addition, the physical metrics used to measure the ES are predominantly biophysical, with any monetary flows required to be measured using exchange values. The SEEA EA approach is increasingly being tested in a range of contexts, with evidence to date suggesting that SEEA EA works well for simple (individualistic, market-based) ES flows and benefits, but shows limitations when considering complex flows, such as non-market use values, non-use values and values held by First Nations Peoples (Finau et al. 2023; Normyle et al. 2024). Researchers are exploring how to capture these complex values within SEEA EA, recognising the benefits that could result from this, for both First Nations Peoples themselves, to society more widely, and to the environment because of better-informed policy decisions (Larson et al. 2025; Normyle et al. 2025; Zilleruelo et al. 2025).

Drawing from Daily et al. (2009), the framework by Mandle et al. (2021) goes one step further to providing a comprehensive picture by emphasising the need to understand ES supply through an ecological production function as well as the value of the ecosystems through a socio-economic utility function. They emphasise the need to understand the entire chain, including mediating factors which influence people's ability to benefit from ES and recognise that ES benefits often flow to multiple beneficiaries. Mandle et al. (2021) apply their framework to critique efforts to use ES knowledge in decision-making, showcasing strengths in application and areas in need of development. When linking ES supply and demand, they also note the importance of acknowledging where gaps may exist in the chain, capturing the correct metrics for ES supply and resulting benefits, disaggregating benefits across multiple beneficiaries and identifying mediating factors of benefits. A synthesis of key features from these available frameworks is provided in Table 2.

The ecosystem service value chain

The ESVC (Fig. 1) consists of a series of links that provide guidance on the information requirements to understand how value flows from ecosystems to one or multiple categories of beneficiaries. Link *a* of the ESVC (Fig. 1) suggests that the first piece of information required to understand the flow of value centres on *extent* and *condition* of an ecosystem. This is consistent with the ecological production function included in the framework presented by Mandle et al. (2021) and the SEEA EA processes for ecosystem accounting (United Nations 2024). As our focus was on translating socio-economic data to information for decision-making rather than strictly complying with SEEA EA reporting, we adopted SEEA EA approaches where feasible to enhance transferability but did not adhere to them rigidly (see De Valck et al. 2023).

Following the ES terminology of the Millennium Ecosystem Assessment (2005), the second link in the chain (link *b*) identifies *ES flows* named ecosystem service types. This link in the chain recognises that ecosystems are valuable to people primarily because they generate either provisioning, regulating or cultural services. *Provisioning services* are the raw materials or energy outputs like food, water, medicines and other resources extracted from ecosystems. *Regulating services* are the services which regulate the ecological balance (e.g. carbon sequestration). *Cultural services* are the non-material benefits that people obtain from ecosystems, such as recreation and tourism. Cultural services may generate benefit to people not through direct use but simply due to the existence of the ecosystem now (existence value) or for future generations (bequest value) or the option to use the ecosystem for future benefit (option value) (Millennium Ecosystem Assessment 2005).

Links *c* and *d* of the ESVC are consistent with the socio-economic utility component of the framework presented by Mandle et al. (2021) and the benefit-relevant indicators applied by Olander et al. (2017, 2018). Links *c* and *d* connect the ecological supply side to the economic value of the benefits derived from these ecosystems. Links *c* to *e* are the focus for the remainder of the paper. Link *c* is divided into two components *c1* and *c2* in Fig. 1, as it is used to identify the *nature* (*c1*) of interaction with the ecosystem service and the *volume/frequency* (*c2*) of ES flow. Examples of data collected to populate *c1* and *c2* include the quantity of fish caught (provisioning service) or the number of recreational trips to a site (cultural service). Link *d* demonstrates that to understand the magnitude of the benefit, data are needed that quantifies or qualifies the extent of the *benefit* (for example, the economic value of fish caught for a provisioning service or the economic value of the recreational activity, for a cultural service). In some cases, the total value (link *e* in Fig. 1) can be derived from data populating links *c* and *d*, and in some cases, this data may already be available from existing data sources. Alternatively, the data available in links *c* and *d* may not be suitable to derive a total value. Figure 1 also demonstrates that the data sources and calculations that can be used to populate links *c* to *e* exist across a range of sources including publicly available data sets, in the peer-reviewed literature and spatially as map layers.

An important component of actioning the ESVC is understanding ES *beneficiaries*. It is important to note that a single ES may serve multiple beneficiaries simultaneously. For example, an ecosystem which provides fish habitat facilitating the production of fish creates a flow of benefits to commercial fishers through fish catch as well as a flow of benefits to households through the cultural service of recreational fishing. Because we focused on an ESVC designed to capture ES flows based upon instrumental values, three main categories of beneficiaries from final ES were targeted rather than focusing on extensions to the model to enable more complex values and worldviews to be captured. These beneficiary categories were households, industry and Government.

We note that First Nations Peoples are also beneficiaries from interactions with ES. However, in an engagement process with First Nations Peoples conducted in parallel with the development of the ESVC, we found that a linear chain focused on instrumental values was incompatible with their worldviews; their nonlinear, holistic perceptions of nature and nature–people relationships, encompassing relational, reciprocal and stewardship values, require an alternate version of our framework. For example, whilst First Nations People are important beneficiaries from some ES,[1] nature itself can be the beneficiary of the caring for

[1] Therefore, the list of beneficiaries for some ES should be extended to include First Nations households and First Nations businesses.

Table 2 Key distinctions between the ESVC and existing ecosystem service frameworks

Study	Purpose	Value conceptualisation	Key contributions	Key differences with ESVC
Keeler et al. (2012)	Causal pathways from management actions through water quality and ecosystem services to human values	• Value expressed in terms of change related to an action • Lists methods of valuation for each water quality related ES	• Starts at change in water quality not action • Conceptualises how a single change in water quality results in multiple changes in ES and multiple changes in value	• Focused only on water quality • Is presented as a guide only and, whilst examples of valuation methods are presented, is not 'populated' with data
Olander et al. (2018)	Provides guidance on how to establish a link between an ES and the capacity for it to provide benefits to society	Service-specific indicators (e.g. flood regulation quantified through reduced exposure of vulnerable populations)	Provides a guide for types of information needed to understand direction of value (capacity for benefit)	• Does not explicitly differentiate between ES beneficiaries • Is presented as a guide only and is not 'populated' with data • Includes dis-benefits from ES change • Does not include dollar values
Rendon et al. (2019)	Demonstrates flow of benefits from ES linked to well-being domains	Value noted in domains of well-being	Presents a feedback loop from well-being to ES	• Does not explicitly differentiate between ES beneficiaries • Is presented as a guide only and is not 'populated' with data • Includes dis-benefits and feedback loop from human well-being to ES • Does not include dollar values
Mandle et al. (2021)	Spatially explicit framework linking ecosystem condition and processes to ES delivery and benefits, compatible with SEEA EA. Used to review ES valuations incorporating ecological production and utility functions	Reviews existing literature with respect to valuation method—revealed preference, stated preference or benefit transfer for each broad ecosystem service typology	Highlights the lack of studies that link ecosystems, ES, human benefits and values	• Chain used to study global knowledge bank on lining ES supply to human benefit • Is presented as a guide only and is not 'populated' with data • Includes dis-benefits and feedback loop from human well-being to ES • Does not include dollar values
SEEA EA United Nations (2024)	Internationally recognised framework with a logic chain which spatially and temporally links extent and condition of ecosystems to a flow of services and economic values	Exchange value approach: ES flows monetised where market values exist, with biophysical indicators for non-marketed services. Requires data on ecosystem extent, condition and service flows	Provides biophysical data on ecosystem extent and condition at closing date, plus ES flows during the accounting period, linking ecosystem state to service provision	• UN framework tested across multiple countries and scales but not populated with data • Logic chain links ES flows to ecosystem state conceptually but lacks empirical data • Stock accounts (extent/condition) and flow accounts (ES supply/use) remain unlinked • Specifies exchange values rather than welfare values for monetary ES accounts

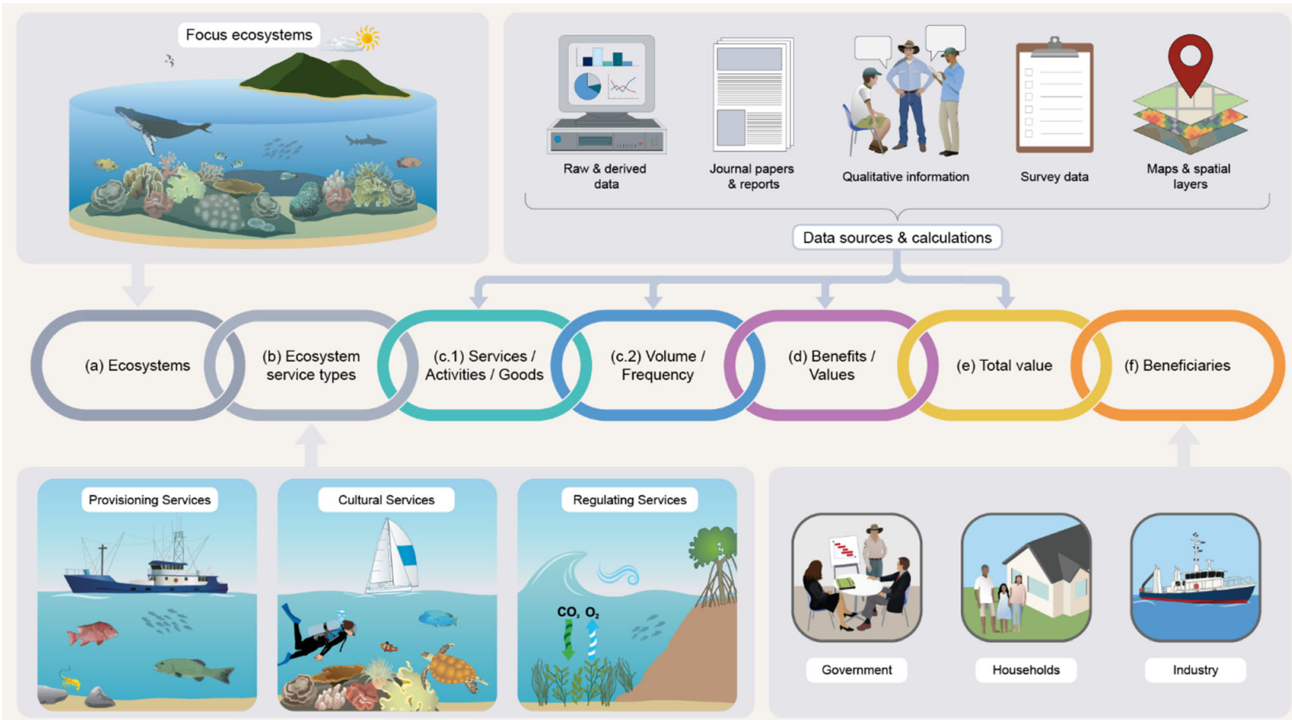

Fig. 1 The Generic Ecosystem Service Value Chain (ESVC). *Notes*: Figure attribution to Ella Schirru @science.graphics.by.ella. IAN Symbol Library (Required Attribution): [images/graphics from] Integration and Application Network (ian.umces.edu/media-library). NESP Symbols (Required Attribution): Symbols courtesy of the NESP Resilient Landscapes Hub (nesplandscapes.edu.au)

Country or stewardship services provided by First Nations Peoples. Furthermore, the service-benefit conceptualisation itself may be incompatible with First Nations worldviews, particularly for (relational) values where nature and people are seen as one. Accordingly, we adopted a phased engagement process, seeking first to understand the perspectives of our First Nations partners, followed by a deeper engagement and co-design process seeking to develop an extended ESVC approach with First Nations partners. The aim of this approach was to provide information on the important flows from First Nations perspectives in a culturally appropriate manner which reflects their world views and values. The engagement process occurred as a part of the broader research following best practice methods consistent with, and building upon the literature (Finau et al. 2023; Normyle et al. 2023; Nursey-Bray et al. 2023; Woodward et al. 2023; see Baker et al. 2024; Larson, Jarvis et al. 2025; Normyle et al. 2025).

MATERIALS AND METHODS

The problem context—The Great Barrier Reef

Stretching over 2300 km along Australia's north-eastern coast and covering 344 400 km^2 (Great Barrier Reef Marine Park Authority 2024) (Fig. 2), the Reef is the world's largest coral reef ecosystem. The Reef contributes A$9 billion annually to the economy and supports 77 000 jobs in tourism and fisheries (Deloitte Access Economics 2025). The Reef is now facing escalating threats from rising sea temperatures, water pollution and overfishing (Great Barrier Reef Marine Park Authority 2024). Given its ecological and socio-economic importance, urgent management efforts are required to mitigate ongoing degradation.

In 2015, the Australian and Queensland Governments and the Reef Authority formulated the Reef 2050 Long-Term Sustainability Plan (the Reef 2050 Plan) (Australian Government 2021) in response to concerns expressed by the World Heritage committee about the state of the Reef's Outstanding Universal Value. The Reef 2050 Plan provides an overarching long-term strategy for managing the GBR to coordinate actions and guide adaptive management to 2050.

The ESVC was developed to support tracking towards the Reef 2050 Plan socio-economic objectives, especially to understand 1. who uses the Reef, 2. for what purposes and 3. to what benefit. An additional objective was to align socio-economic indicators with biophysical indicators of Reef change. The ESVC emerged to reconcile the dual objectives of making socio-economic data accessible to decision-makers and ecosystem-relevant.

RESULT

Applying the ESVC—mapping value flow from ecosystems to households through the cultural service of non-fishing recreation

In consultation with the Reef Authority, two spatial areas were selected for the study: the Cairns Area Plan of Management zone (CAPOM) and the Keppel Capricorn Bunkers (KCB) (Fig. 2). These were chosen due to the complexity of managing multiple beneficiaries and the need for information from data to enable ongoing improvements to Reef Plan of Management.

The Reef is made up of 17 main ecosystems (Great Barrier Reef Marine Park Authority 2024), ten of which are marine and identified by the Reef Authority as important in the CAPOM and KCB spatial focus areas (see De Valck et al. 2023). Through this consultation, it was decided to concentrate on existing data that would help to understand how value flows from ecosystems to (1) commercial fishers, through the provisioning service of edible and non-edible marine biomass, and (2) households, through the cultural service of recreation and leisure, including both recreational and non-recreational fishing.

Notably, an ESVC can also be constructed and populated to capture the flow of cultural services to commercial beneficiaries through recreation. In this section, we synthesise a worked example of applying the ESVC concept to assess and organise existing socio-economic data to understand how value flows from ecosystems to households as the beneficiary through the cultural ecosystem service of non-fishing recreation (Fig. 3). For demonstration's sake, this populated ESVC is specifically for instrumental values and focused on the CAPOM spatial area. More research is needed to assess the suitability of the ESVC for organising data related to relational or intrinsic values of ecosystems and adjusting the approach. Recognising the past focus on the biophysical end of the ESVC as well as the availability of biophysical data related to ecosystems, the discussion focusses on how the ESVC assisted in organising the socio-economic data as decision-relevant information. Accordingly, the discussion about populating the ESVC starts at link *c* and does not include discussion of links *a* and *b*.

Populating link c in the ESVC

The first step in applying the ESVC was to determine what information on ecosystem uses the Reef Authority needed for management decisions. Using the ESVC as a guide, the Reef Authority identified priority recreational activities. These are listed under link *c1* in Fig. 3. Once the uses of interest were established, fulfilling link *c2* required exploring existing data about how often beneficiaries enjoyed recreation-related cultural services. For this example, it was identified that a large amount of data about beneficiaries of the Reef for non-fishing recreation and the frequency of their use was available through the 2023 Social and Economic Long-Term Monitoring Program (SELTMP) database (Curnock et al. 2023). Specifically, respondents were asked about their participation in activities such as mainland beach visits, wildlife watching, in-water activities, island visits, boating (with own or hired vessel, motorised and non-motorised), recreational fishing as well as reef visits for research or cultural practices. Respondents had the option of answering that they engaged in activities either once or twice, 2–10 times, 11–20 times, more than 20 times or not at all. Data were presented for different GBR spatial areas. The Wet Tropics/Terrain NRM spatial area in SELTMP corresponded to the CAPOM spatial area. The total number enjoying various recreational activities was then calculated as follows:

1. Total population for the Wet Tropics (for CAPOM) was derived from the ABS 2021 census (Census | Australian Bureau of Statistics (abs.gov.au))
2. Total respondents in each frequency category were derived using the % answer from the SELTMP survey and the Wet Tropics population
3. Total number was derived by multiplying the numbers falling into each frequency category by the frequency amount. For example, in CAPOM, 11% of the population did not visit the beach in the last 12 months. This equalled to 27 500 that were not counted in the numbers visiting the beach. On the other hand, in CAPOM, 13% of the surveyed population visited the beach 11–20 times. This meant that 32 500 people visited the beach 11–20 times. Taking the conservative end of the range, it was estimated that in total there were 357 500 beach visits just from this category (11 multiplied by 32 500). This approach was conducted for each % in each category and totalled to generate a total number partaking in each recreational activity category.

Populating link d in the ESVC

Link *d* focusses on data to quantify or qualify the benefit or value held by the beneficiary of the ecosystem service in question. Ecosystem services generate value through both direct and indirect uses. Value can also be generated through a non-use relationship with an ecosystem and its services (Chan et al. 2016; Kenter et al. 2019; Pascual et al. 2023). Accordingly, different relationships with ecosystems and their services generate a broad spectrum of tangible and intangible benefits. The Reef Authority was

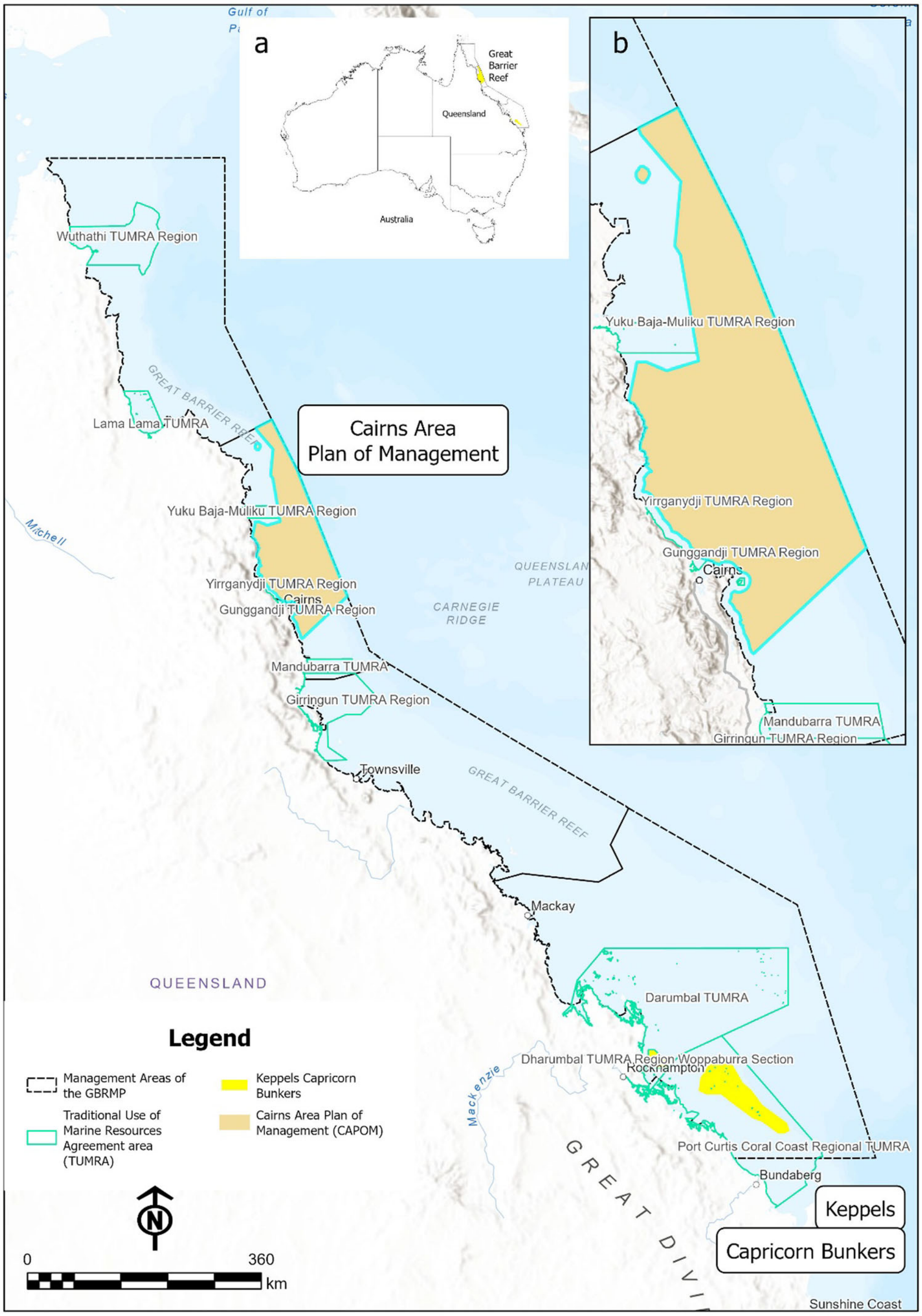

Fig. 2 The Great Barrier Reef, the management areas of the Great Barrier Reef Marine Park, TUMRAs and study spatial focus areas

specifically interested in direct use values in this first ESVC application. Therefore, we provide an overview of valuation for direct use of Reef ES in the main body of the paper with additional detail and examples of direct use and non-use valuation techniques included in the Supplementary Material S1.

Direct use values can be delineated into *extractive* and *non-extractive* categories. Extractive uses of Reef ecosystems include the harvest of natural resources such as fish (for both recreational and commercial purposes), bioprospecting for pharmaceuticals, and collection for aquariums and curio trades; certain research and educational activities may also conduct extractive activities. In contrast, non-extractive values arise from interactions with the Reef that do not involve the removal of material resources. These include cultural and spiritual engagements (for both First Nations peoples and others), recreational activities such as snorkelling, diving and kayaking, as well as

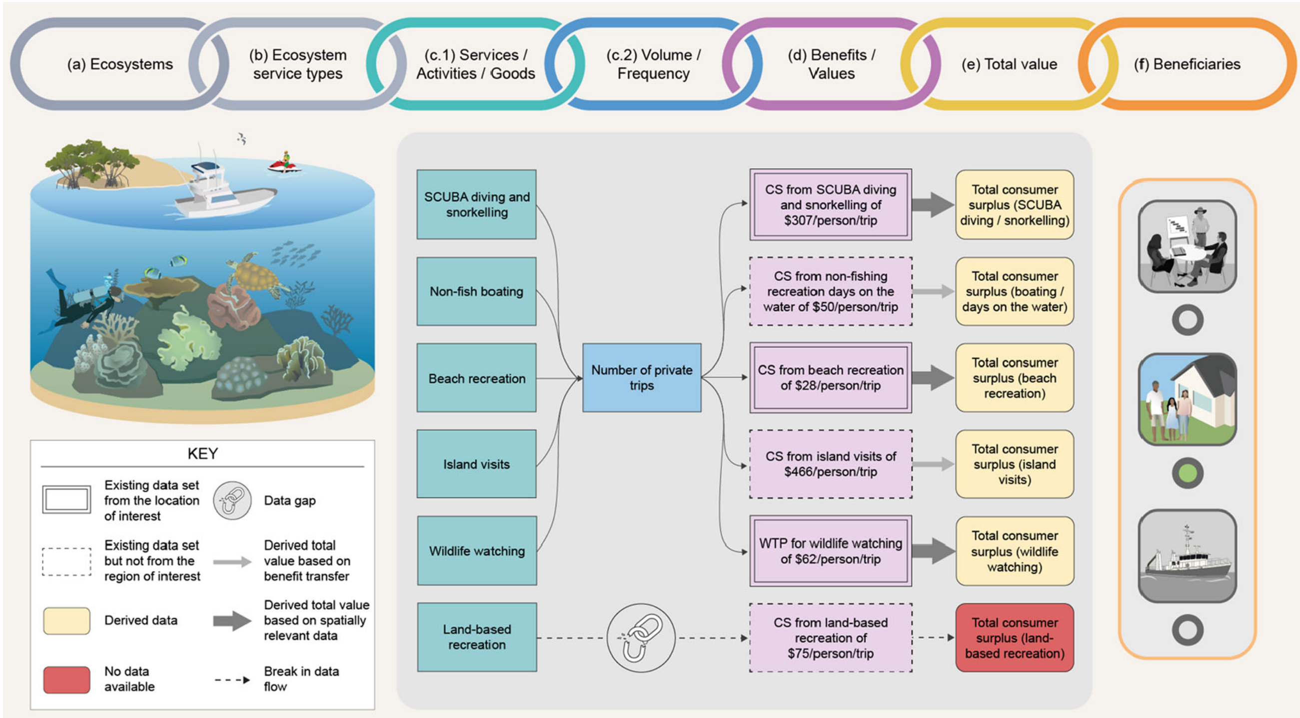

Fig. 3 The populated ESVC to show the data sources available to map the flow of value from ecosystems through the cultural service of non-fishing recreation to households as the beneficiary in CAPOM. Figure attribution to Ella Schirru @science.graphics.by.ella. Figure symbols from: (1) IAN Symbol Library (Required Attribution): [images/graphics from] Integration and Application Network (ian.umces.edu/media-library) and (2) NESP Symbols (Required Attribution): Symbols courtesy of the NESP Resilient Landscapes Hub (nesplandscapes.edu.au). Volume and frequency data for number of private trips for all activities except land-based recreation were sourced from the SELTMP database. CS refers to consumer surplus; WTP refers to Willingness to Pay Dollar; ($) values are Australian dollars adjusted for inflation to 2023 values. Sources for values are included in the methods section

tourism and non-invasive research and education. Among these, tourism often yields the greatest direct commercial benefit of all the Reef's non-extractive uses (Brander et al. 2007).

Indirect use values are gained indirectly from the natural resource, usually through support and protection of other economic activities. For reefs, these include nursery ecosystem services that support fisheries, coastal zone protection and global life support. Indirect use values are typically less straightforward to assess economically. Non-use values for reefs also occur either through potential future uses or option values (see Krutilla and Fisher 1975), through knowing about the presence of the resource for current generations and other people (altruistic value), for future generations (bequest value, see Walsh et al. 1984) and through reefs' mere existence value (see O'Garra 2009; Pascual et al. 2010).

There are numerous techniques through which values can be derived for use and non-use of an ecosystem and associated services (see De Valck et al. 2023). Price-based valuation is the most straightforward methodology. This approach, however, is not relevant for a lot of ES as they are not traded through existing markets. Price-based valuation uses the market price paid for accessing and/or extracting resources (for example, payment to visit the Reef or payment per tonne of fish caught as value proxies). Ecosystem services that are traded in the market, such as access to the Reef though a commercial operator, provide a measure of what consumers are willing to pay for a good or service, and therefore a way to quantify value.

Alternative valuation methods are based on cost. These substitution methods place a value on an ecosystem service based on either (1) the avoided cost to supply the service, (2) the cost to mitigate damage or restore the function of the ecosystem or (3) the cost to replace the service (Freeman 1993; Brown 2017). Cost-based methods are useful for rapid assessments but are typically associated with multiple limitations. Some examples of valuing an ecosystem through cost-based methods and a discussion of weaknesses of this approach is provided in the Supplementary Material S1.

Revealed preference methods offer an alternative approach, inferring ES values from observed market behaviour rather than direct elicitation (Gunawardena et al. 2020). The most common revealed preference approaches are the Travel Cost Method (TCM), where the value of a place or activity is reflected by the cost incurred to enjoy it, and hedonic pricing, where the natural environmental quality is interpreted as an attribute of a differentiated market good (e.g. a house with a view) (Davis et al. 2019).

The final type of valuation method is based on stated preferences. This family of methods is also best applied to understand non-use value associated with ecosystems. Contingent Behaviour (CB) method asks people how they would change their actual behaviour under hypothetical conditions (Hanley et al. 2003), whilst contingent valuation (CV), discrete choice experiments (DCE) and their variants ask people about their preferences under hypothetical scenarios (Bateman et al. 2002).

Conducting valuation studies can be expensive, so when possible, it is easier to draw on pre-existing stated or revealed preference studies to infer the value of a similar environment. This alternative method is referred to as benefit transfer. Populating the ESVC occurred through benefit transfer with most of the original data collected through revealed preference and contingent benefit valuation.

For this example, no primary dataset existed to quantify beneficiary values for recreational activities (link *d*) and of interest to the Reef Authority. The ESVC guided identification of data for benefit transfer. Seven peer-reviewed non-market valuation studies were identified, providing at least one value estimate for each recreation type of interest. Table 3 summarises the literature used for benefit transfer.

The ESVC framework consolidated ES value data and enabled the assessment of data quality and confidence for application in decision-making. Assessment of data quality applied the FAIR data principles, which stands for Findable, Accessible, Interoperable and Reusable as per Wilkinson et al. (2016). Confidence rating of data for decision-making drew from Kaul et al. (2013) and Johnston et al. (2021) with final confidence ratings developed in collaboration with Reef Authority. Applying a confidence rating on data facilitated a conversation focusing on available data validity and reliability for decision-making and remaining data gaps. Table 4 presents the monetary values of the recreational activities of interest to the Reef Authority for the CAPOM application. Data confidence was scored based on (1) spatial relevance (5 if from the area of interest; 0 otherwise), (2) temporal relevance (5 if post-2014; 0 if older) and (3) robustness (comparability with other studies—0 if no comparative studies or 5 if there was at least one comparative studies). The confidence score was cumulative. If there was high confidence in the data for decision-making, the score was at or above 15, moderate confidence in the data for decision-making scored between 10 and below 15 and low confidence scored below 10. Confidence in all the data available for CAPOM was moderate. The key reasons for the moderate score are described in Table 4. Data scoring and response decisions adjusted based on data confidence has been used in other resource management contexts such as fisheries stock management (Punt et al. 2016) and land-use regulation (Boschetti et al. 2019). Providing a snapshot of existing data with a corresponding data confidence rating has enabled the research team to apply quality control and highlight where investment in new data to inform governance decision-making could be prioritised. This data consolidation and quality assessment informed a A$3 M Australian Government investment in new Reef socio-economic data collection, with a focus on updating the valuation of snorkelling and diving (Australian Government 2025).

Populating link e in the ESVC

Link *e* focusses attention on either finding data that provides a total value or calculating this value from existing data. Data for link *e* in the CAPOM application were derived through multiplying links *c* and *d*. Caution should be applied when calculating a total value from existing data due to the many assumptions and specificities applied to the original data collection. At best, the numbers derived from link *e* should be taken as an estimate of value.

DISCUSSION

The disconnect between ES-related socio-economic data and decision-ready information is well documented (Bisbal and Eaton 2023), with repeated calls for practical solutions to bridge scientific knowledge and management needs. A key challenge for decision-making to date has been the persistent over-reliance on biophysical data at the expense of socio-economic data. As a result, decision-making for environmental outcomes has tended to focus on the supply or provision of services (Ford-Learner et al. 2025) without a connection to how services are used and benefits realised by people (Martinez-Harms et al. 2015). The ESVC decision-oriented data structuring framework presented here was inspired by existing chain-based frameworks (Keeler et al. 2012; Olander et al. 2018; Rendon et al. 2019; Mandle et al. 2021; United Nations 2024) but developed in tight collaboration with the Reef Authority as a direct response to this issue. The objective of the development of the ESVC was to provide a structured, decision-relevant framework to connect the benefit flows from ecosystems to ES to their eventual beneficiaries. Using available data in two spatially demarcated areas, we attempted to populate the ESVC with the most relevant data sets and with a focus on instrumental values. The objective was to highlight extent and confidence in existing data, and understand data

Table 3 Summary of data applied in benefit transfer. *Adjusted to 2023 value using Reserve Bank of Australia (RBA) calculator available at Inflation Calculator | RBA

Primary reference	Method	Location of data collection	How is value represented?	What is being valued?	Recreational value (year of data collection)	(AUD$) value adjusted for 2023*
Windle and Rolfe (2019)	TCM	Cairns NRM region	Consumer surplus	Beach recreation	$25.97/trip (2019)	$30.32/trip
	TCM	Townsville	Consumer surplus	Beach recreation	$53.45/trip (2019)	$62.76/trip
	TCM	Mackay	Consumer surplus	Beach recreation	$33.76/trip (2019)	$39.42/trip
	TCM	Fitzroy	Consumer surplus	Beach recreation	$55.23/trip (2019)	$64.49/trip
	TCM	Gladstone	Consumer surplus	Beach recreation	$71.76/trip (2019)	$83.79/trip
	TCM	Bundaberg	Consumer surplus	Beach recreation	$54.26/trip (2019)	$63.34/trip
	TCM	GBR All	Consumer surplus	Beach recreation	$61/trip (2019)	$71.32/trip
Prayaga (2017)	TCM	Capricorn coast	Consumer surplus	Beach recreation	$25/trip (2019)	$26.86/trip
Windle et al. (2017)	TCM	Gladstone	Consumer surplus	Beach recreation	$35/trip (2016)	$43/trip
			Consumer surplus	Non-fishing water-based recreation	$41.49/person/trip (2016)	$50/person/trip
			Consumer surplus	Land based recreation	$61/trip (2016)	$75.19/trip
Rolfe and Gregg (2012)	TCM and CB	GBR (all)	Consumer surplus	Beach recreation	$35.09/person/trip $42/person/trip (2019)	$41.48/person/trip
		Cairns	Consumer surplus	Beach recreation	$23.79/person/trip (2019)	$29.56/person/trip
		Capricorn	Consumer surplus	Beach recreation	$56.98/person/trip (2019)	$70.81/person/trip
Rolfe et al. (2011)	TCM	GBR	Consumer surplus	Beach recreation	$35/person/trip/day (2011)	$47/person/trip/day
			Consumer surplus	Island visit	$397/person/trip/day (2011)	$465/person/trip/day
Stoeckl et al. (2010)	CV	Northern GBR	WTP	Marine wildlife spotting	$27.56/person/day (fish) to $64.28/person/day (sharks) (2007/08)	$42.14/person/day (large fish) to $98.29/person/day (sharks)
Kragt et al. (2009)	TCM and CB	GBR (Port Douglas)	Consumer surplus	Diving and snorkelling	$184.84/person/trip (2004)	$307/person/trip

gaps especially as these relate to management decisions. More exploration is needed to establish the suitability of the ESVC in organising data for non-instrumental values.

A major strength of the ESVC lies in its ability to synthesise diverse data needs and sources into a coherent structure that aligns with real-world decision-making. By providing a space to organise existing data and then explicitly link biophysical, socio-economic and governance data, it offers a comprehensive mechanism to reconcile data availability and quality against data needs, facilitating understanding of the benefits derived from the use of ES. The structured nature of the framework also enhances transparency, making it easier for decision-makers to observe all data types together, determine confidence in existing information, identify and understand data limitations and trade-offs incurred when using different data sets and identify gaps and prioritise future data collection efforts. Additionally, its modular design allows for

Table 4 Value (AUD) used for non-fishing recreation for beneficiaries and confidence in the data point. * Derived as the average from the results from the study by Stoeckl et al. (2010)

Activity	2023 adjusted CS value/person/ TRIP ($AUD)	Confidence	Reason for confidence score
Diving and Snorkelling	$307	Moderate	Collected in spatial focus area but from only one study which occurred more than 10 years ago
Beach recreation (CAPOM)	$29.56	Moderate	Collected in spatial focus area but from a single study more than 10 years ago
Water based non-fishing recreation	$50	Moderate	Not from spatial focus area or multiple data sources but data source is less than 10 years old
Island visits	$466	Moderate	Not from spatial focus area or multiple data sources but data source is less than 10 years old
Land based recreation	$75	Moderate	Not from spatial focus area or multiple data sources but data source is less than 10 years old
Marine wildlife watching	$62.75*	Moderate	Collected in spatial focus area but from a single study more than 10 years ago

flexibility, enabling its application across different spatial scales and ecosystem types. Whilst the ESVC was designed for the GBR specifically, the concept and modularity should enable the ESVC framework to be used in broader ES management contexts.

Alongside these strengths, the ESVC, as presented in this paper, has a few limitations. The development and application of the ESVC framework presented in this paper focused on data related to instrumental values associated with the supply and use of services provided by ecosystems. We did not explore the application of the ESVC in organising data related to more intangible (on non-use) values, reciprocal value flows or to intrinsic or relational values. The linear structure of the ESVC in its current form means that it cannot easily capture complex nonlinear values that are not based on a separable one-way benefit flow from ecosystems to people (e.g. reciprocal values from stewardship); non-use values (including many spiritual and cultural values); and relational values where nature and people are seen as one. Such complex values are integral to the worldviews and perspectives held by First Nations Peoples. Consequently, capturing First Nations values within the ESVC remains challenging. We are exploring extensions of the ESVC to address this challenge; this substantial and complementary work is, however, beyond the scope of this paper.

Additionally, the framework depends on the availability of suitable socio-economic data, which remains sparse. Whilst the ESVC improves transparency around data needed for improved decision-making, its broader implementation requires appropriate resourcing, collaboration and commitment to outcomes across disciplines and institutions to resolve data gaps (Gluckman et al. 2021). This alone can pose logistical, resourcing and political challenges. Finally, the ESVC, on its own, does not completely resolve the broader difficulties of integrating the spectrum of ES values into policy processes which enable appropriate governance responses. Future applications of the ESVC framework should seek to test its suitability for incorporating a broader diversity of ES values, including non-market and relational values often underrepresented in decision-making processes (Vatn et al. 2024). This requires understanding trade-offs when integrating data across value types and further close collaboration between scientists and decision-makers to translate diverse values into actionable information. Embedding research within management practice (and vice versa) can reduce this translation burden over time, given sustained commitment and resourcing (Gluckman et al. 2021).

Strengthening the integration of ESVC outputs with management frameworks will also be critical to ensuring that ES values are not just quantified but meaningfully incorporated into adaptive governance and management strategies. This remains an ongoing challenge that will always be context-specific. This is because using scientific evidence for policy-making is not a linear, unidirectional process (Gluckman et al. 2021). To meaningfully engage research for policy and management applications, the development of bespoke tools, such as ES-based toolkits suggested by Keeler et al. (2012), can be helpful, particularly when used in conjunction with approaches to translate evidence into actionable information (Gluckman et al. 2021).

CONCLUSIONS

Ultimately, the ESVC represents an important step towards bridging the long-known and persistent gap between science and decision-making, offering a replicable framework that places greater emphasis on socio-economic considerations compared with traditional biophysically driven approaches. Whilst challenges remain, its structured yet adaptable nature makes it a valuable decision-oriented data structuring framework for improving the way ES values are understood and used in environmental governance.

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Declarations

Competing interests All authors certify that they have no affiliations with or involvement in any organisation or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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