This is the accepted manuscript version of the contribution published as:

Schmidt, S., **Seppelt, R.** (2018):
Information content of global ecosystem service databases and their suitability for decision advice
Ecosyst. Serv. **32** (Part A), 22 – 40

The publisher's version is available at:

http://dx.doi.org/10.1016/j.ecoser.2018.05.007

Titel:

Information content of global ecosystem service databases and their suitability for decision advice

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Abstract

The ecosystem service (ES) framework promises to contribute to a more sustainable management of natural resources. However, a broad scale implementation of the ES framework for decision-making is impeded by the lack of standards in conducting ES analysis; and a permanently increasing volume of heterogeneous information. Databases have the potential to facilitate the integration of ES information into decision advice by collecting and condensing big data volumes in a standardized form. In this article we examined how ES databases support policy instruments to take nature's benefits into account in decision-making. We analyzed 29 databases with global coverage containing information of 36,014 studies, projects and methods within more than 600,000 entries. We identified 93 indicators of information demand for six major policy instruments and matched database entries with these indicators. Findings showed databases contain information for most of the policy instruments. However, databases neglected information on contextual and tacit knowledge about processes and approaches of ES investigations. Also databases were limited regarding geographic representativeness, highlighting major gaps in the application of the ES framework in society's poorest nations. We propose steps forward towards optimized knowledge exploitation and suggest five priority areas for mainstreaming ES information into decision-making: (i) quantitatively recognize nature's value, (ii) develop prioritization schemes based on ES valuation, (iii) sensitive stakeholder engagement, (iv) support information access and capacity building to establish ES-based decision-making and (v) consider long-term returns of interventions in ES. These priority areas contribute to formalize standards for the documentation of knowledge on ES and provide a baseline for the establishment of ontologies that facilitate knowledge accessibility for decision-making.

Keywords

Policy instruments; information supply; information demand; database synthesis; standardization

1 Introduction

Current policies and markets struggle with the consideration of nature's benefits for human well-being and fully accounting for environmental impacts, while the exploitation of natural resources and degradation of nature is accelerating (UNEP 2016). The ES framework has the potential to both awaken the public to its dependency on nature and to engage different research disciplines and non-scientists in shaping and achieving societal goals. There is evidence that achieving societal goals, such as the UN Sustainable Development Goals, strongly depends on ES (Ranganathan et al. 2008). All economic activities are ultimately linked to and influenced by trends in ES supply (Millennium Ecosystem Assessment 2005b). The ES framework is unique and promising for decision-making due to its integrative approach of estimating and valuing: i) the diverse ways in which nature underpins human well-being, ii) the human impact on ecosystems, and iii) the welfare effects of potential ecosystem management policies (Daily et al. 2009; COP 2010). Entry points for incorporating an ES approach into existing decision-making processes occur at all sectors and levels of governance, for instance national accounting systems (PRI & UNEP FI 2011; Bartelmus 2014), corporate disclosure policy (IPIECA 2016; Natural Capital Coalition 2016), public payment systems (Porras et al. 2008a), cooperation between public and private sector (Waage et al. 2012), landscape planning (Hauck et al. 2013) and other large-scale decision contexts (Guerry et al. 2015). Consequently, there is a demand for ES knowledge that can feed into information and decision-support frameworks underpinning the development, implementation and assessment of policies which deal with or are directly related to the use of natural resources or land (Schaefer et al. 2015; Bouwma et al. 2017).

The number of ES studies is fast-growing and rapid advances in information technology, globalization, and increasing networking cause an information overload (Hey et al. 2009; Abson et al. 2014). This involves a number of challenges such as to be aware of, access, and process the ever-growing data volume. Not all data and information is readily available or accessible (IPBES 2016). Existing data and information resources are widely distributed, heterogeneous, and difficult to combine (IPBES 2016; Olander et al. 2016). Moreover, literature provides evidence of a science-policy gap, i.e. limited interactions, infrequent exchanges of information, and different objectives that hinder coordinated science and policy processes (Weichselgartner and Kasperson 2010). The science-policy gap causes a lack of expertise in ES applications among decision-makers and contributes to skepticism about the suitability of the ES tools for the purpose of usage in and informing of decision-making (van den Hove and Chabason 2009; Laurans et al. 2013; Guo and Kildow 2015; Polasky et al. 2015). Guidelines and standards for an improved operationalization of the

ES framework are steadily developed, e.g. for assessment practitioners (Ash et al. 2010; Haines-Young and Potchin 2010; Seppelt et al. 2012), development planning (Kosmus et al. 2012), the business sector (Bartelmus 2014; Natural Capital Coalition 2016), as well as policy and decision makers more generally (Ranganathan et al. 2008; DEFRA 2015). Guidance and overviews of ES databases that document and combine existing data and information on the relationships between ecological supply, social demand and effects of management options on ecosystems and human well-being are missing (McComb et al. 2006; IPBES 2016; Olander et al. 2016).

Through databases large amounts of diverse data can be collected and organized in a standardized form. Databases are important prerequisites to provide easy accessible and consistent knowledge, increase rigor and specificity of the ES framework, and support further implementation mechanisms such as Decision Support Systems (DSS). Databases provide the potential to improve methods and semantics of data collection and measurement through scrutiny of other data users as well as allow the scientific community to reach consensus on methods and semantics (Fienberg 1994). Building upon a prior work avoids duplications, allows us to use data in ways that the original investigators had not envisioned and increase progress. Developing databases and archiving data results in a greater utility of the data, ensures the availability of data in future, and maximize the impact and benefit of research funding (ICPSR 2012). Databases provide an important resource for training and are a powerful force for inclusion and removing barriers to participation across all education backgrounds and at all ages (NSB 2005).

Databases vary greatly in size, scope, standardization, usage, accessibility, and other characteristics. Three functional types of databases can be distinguished (NSB 2005): research, resource, and reference collections. A research collection is the product of one or a few investigators or scientifically focused projects, e.g. a database on quality of ES studies (Seppelt et al. 2011). Usually these lack standardized data policies (file formats, meta-data, access policies, etc.), are not broadly shared or discoverable and, therefore, they are little used beyond their original application. For research collections funding is low and assured for only short terms. They are at the greatest risk of loss through a lack of maintenance. Resource data collections are developed for a specific science and engineering community, such as the database on monetary valuation studies of ES called the Environmental Valuation Reference Inventory (EVRI 2016). They typically conform to community standards or often bring communities together to develop appropriate standards where a need exists. In many cases resource collections migrate to reference collections. Reference collections are intended to serve the general science and education community. For instance, the Socioeconomic Data and Applications Center is one of the Distributed Active Archive Centers (DAACs) in the Earth

Observing System Data and Information System (EOSDIS) of the U.S. National Aeronautics and Space Administration (NASA). Often, standardization in reference collections sets the bar for a large segment of the community, effectively developing a universal standard. Budgets for reference collections are often large and are provided over a long term from one or more funding sources. Reference collections of ES have been entirely absent until today.

Given the information demand on ES knowledge for decision-making and the diversity of ES databases, we here investigated how information demand on ES for decision-making can be fulfilled by knowledge on ES provided in publically available databases. We conducted systematic reviews of literature driven by three research questions:

1) Which databases on ES analysis and methods exist?
2) What information is demanded to integrate ES into decision-making?
3) How is this information demand addressed by the existing databases?

Two separate literature reviews were conducted. The first identified databases containing studies or projects of ES. Based on the second review we developed a systematic taxonomy of indicators representing the information demand. In order to narrow down the manifold demand for information on ES in different areas of governance and identify application contexts in decision-making, we focused on a set of policy instruments for safeguarding nature. Methodologies of both reviews are described in Section 2. In Section 3, we present characteristics of databases, policy instruments, and indicators of information demand. Also, results are presented on how well information supply from databases matches information demand indicators from policy instruments. In Section 4, we discuss options to improve the documentation of ES knowledge in databases and present recommendations to facilitate mainstreaming of ES information into decision-making. This is followed by a conclusion in Section 5.

2 Data and Methods: Review processes

We first searched the Web of Science™ for publications with ‘ecosystem service*’, or ‘ecosystem valuation*’ in the title to obtain a comprehensive overview of ES studies potentially holding information on ES databases. In the last 25 years, 1,848 studies were retrieved (S1 Fig). From these peer-reviewed publications we identified 279 that used or reported on databases containing information about ES. We then traced back references in selected publications and directly talked to authors (39 authors) in order to find and review available databases (229 databases). Only those

databases were included, which i) provided in-depth information on ES, i.e. data entries with detailed reference to ES, and ii) contained case studies with investigation areas that are distributed across the globe (in total 29, see Table 1). The latter criterion ensures a more comprehensive overview of socio-ecological systems, avoids biases due to local peculiarities, and increase relevance for a broader audience. The purpose of the study was not to create a complete list of ES databases, but rather to provide a first overview of the diversity of information contained in ES databases.

In a second step, considering the vast scope of information demand on ES in decision-making, we focused on specific application contexts. These were exemplified by policy instruments that consider nature's benefits for human well-being and help to reform market and policy failure. We used the following six policy instruments suggested by TEEB (2011):

A) Extending accounting system through nature-based indicators;

B) Rewarding benefits through payments and markets;

C) Reforming environmentally harmful subsidies;

D) Addressing environmental degradation through regulation and pricing;

E) Regulating use through protected areas and recognition of their values;

F) Direct public investment in ecological infrastructure and restoration.

We then specified the information demand for each policy instrument by reviewing publications contained in the 29 databases. Because of the vast number of publications (35,851), we selected a set of 715 publications by using the search terms: 'decision*', 'polic*' and 'guid*' for searching in title, abstract and keywords. For the selected publications a full text review was conducted and those discarded which not directly refer to the six policy instruments. We found 64 publications (S1 Table) and synthesized indicators that represent information demand for each of the six policy instruments. The taxonomy of indicators was iteratively adjusted with each step of the review in order to ensure that major information requirements are included and double counting is avoided. This yielded 93 indicators presented in the Results Section (Table 2 lists the top three of most frequent indicators, S3 Table includes all indicators).

To quantify how a specific database k (k = 1,…,29) contributes to the information requirement of a policy instrument p (p = 1,…,6) we defined a function R. R counts in all rows j=1,…,k_m which data-entries of indicators (column in the database), which contribute to the specific policy instrument p, that contain data, i.e. have non-NA,.

with *D* is given by

The overall information available from the databases *k = 1,…,29* which informs a policy instrument p is then estimated by

M(p) = sum_(k=1)^29 R(k, p)

The number of indicators *q_p* for each policy instrument *p* varies considerably (S3 Table). In order to assess the information provided by a database k for a given policy instrument p in relation to the overall information provided by all databases, we estimated this relative contribution by normalizing given the number of indicators q_p for each policy instrument.

#In the final step, we quantified how information demand is addressed by the databases. We counted matches () between databases' data entries and indicators of information demand for all six policy instruments () by selecting data entries () that contain information required by .

(1)

For the counting of relevant) all columns () and all rows of each ES database () for all ES databases () were reviewed.

(2)

The number of indicators for each policy instrument varies considerably (S3 Table). In order to enable comparability across policy instruments we calculated the weighted matches () between data entries and indicators of information demand for all policy instruments (). were weighted by the number of indicators of information demand contained in a policy instrument () and the sum of all .

(3)

In total, 1,945 headers of database columns and more than 600,000 entries were reviewed and assigned respectively to indicators of information demand and policy instruments. The full data set is available at Schmidt (2018).

3 Results

3.1 Characteristics of global databases on ES case studies

From the reviewed 29 databases most (41%[1]) addressed economic valuation, establishment of markets and payment schemes such as payments for ecosystem services (PES) (Table 1). Second most common topics were methodological analysis of applications of the ES framework in practice that aimed to guide practitioners and policy makers in the selection and application of methods and tools (31%), followed by the provision of information for teaching activities, scholarly communication, and the evolution of ES research (10%). The least frequent topics were interlinkages between biophysical components of nature and ES (de Bello et al., 2010, Cardinale et al., 2012), how non-consumptive interactions with nature effect human well-being (e.g. physical, cognitive, psychological, social, spiritual) (Keniger et al., 2013) and financial instruments and funding opportunities for the application of ES analysis (Innovation Seeds, Goldman et al., 2008).

Table 1. Objective and source of 29 databases considered for the analysis.

Database name	Objective of database	Reference
ARtificial Intelligence for Ecosystem Services case studies (ARIES Cases)	Summary of case studies of the model ARIES to illustrate application options and promote ARIES.	Basque Centre for Climate Change, Bilbao (ARIES 2017).
Beneficial Use Values Database (BUVD)	Design a valuation database of water-based amenities that can be used as a guide for decision-makers and policy analysts as well as source of information for general public and interested specialists. The database is a quantitative documentation of scientific and grey literature valuing beneficial uses of water in monetary terms.	University of California, Davis, Department of Agricultural and Resource Economics (BUVD 2001)
Benefits of interacting with nature (Keniger et al., 2013)	Qualitative documentation of evidence on benefits of human interactions with nature based on primary research articles in peer-reviewed scientific journals.	Not online: Database available on request (Keniger et al. 2013)
Catalogue of Assessments on Biodiversity and Ecosystem Services (IPBES Catalogue)	Derive lessons learnt from existing and ongoing assessment processes so as to inform the future development of work programs and associated processes in Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES). The online catalog qualitatively lists details on design, outreach material and impact of both ES and biodiversity assessments.	United Nations Environment Programme - World Conservation Monitoring Centre (UNEP 2012)
Design of ES and biodiversity projects (Goldman et al., 2008)	Analysis whether ES projects attract more financial support than biodiversity projects and expand conservation options. The database contains quantitative and qualitative information of study- and monitoring-design of ES projects.	Not online: Database available on request (Goldman et al. 2008)

1 Percentage values in this paragraph do not sum up to 100%, because of contextual overlaps of some databases. Following percentage values in this subsection (3.1) refer to the total of 29 ES databases, not weighted matches.

EcoService Models Library (ESML)	Documentation library designed to help users find, compare, and combine ecological models for estimating processes and production of ES. The database contains descriptions of ecological models, their variables, source documents, and case study applications.	United States Environmental Protection Agency (US EPA 2017)
Ecosystem Service Indicator Database (ESID)	Standardization of ES indicators for the usage in ecosystem assessments, in policy dialogues and decisions. The database contains synthetic summaries of indicator descriptions and implementation context.	United Nations Environment Programme - World Conservation Monitoring Centre Not online: Database available on request (UNEP 2015)
Ecosystem Service Valuation Database (ESVD)	Review of data on economic valuation studies of ES to support education on sustainable land management. The relational database provides monetary values of ES and other valuation-related information.	Foundation for Sustainable Development (Van der Ploeg et al. 2010)
Ecosystem Services Bibliography (ESB)	Bibliographic collection of ES studies for teaching, learning, and scholarly communication. The informational online database documents references and abstracts of scientific ES literature, tagged in accordance with their core topics and investigation areas.	University of Minnesota. UThink: Blogs at the University Libraries (University of Minnesota 2013)
Environmental & Recreational (Non-Market) Values Library from the National Ocean Economics Program (NOEP Non-Market)	Account for values of oceans economy that are not directly observed in markets. The online database contains synthetic summaries of non-marked valuation studies that document environmental and recreational values of coastal and marine ecosystems.	National Ocean Economics Program, Non-market Valuation Studies (NOEP 2017)
Environmental Valuation and Cost-Benefit News (EVCBN)	Better integration of environmental values into public and private accounts. The database is a bibliographic collection of synthetic summaries of scientific and grey literature pertaining to the benefits and costs of ecosystem (dis-) services.	Cost Benefit Group, LLC (Cost Benefit Group 2017)
Environmental Valuation Database (Envalue)	Encourage greater use of environmental valuation in decision-making process by providing quantitative data on environmental valuation studies. The online searchable database favors benefit transfer research applications by technical specialists.	New South Wales Environmental Protection Authority, Department of Environment, Climate Change and Water (NSW EPA 2004)
Environmental Valuation Reference Inventory (EVRI)	Facilitate the application of benefit transfer techniques for policy analysis and research based on economic valuation studies of ES. The online storehouse contains synthetic summaries of valuation studies that describe and contextualize monetized values of ES.	Environment Canada, Economic Analysis Directorate (EVRI 2016)
Evolution of ES studies and major affecting events (Vihervaara et al., 2010)	Review of evolution of ES research and influence of international environmental policy and research events as driver of ES research.	Not online: Database available on request (Vihervaara et al. 2010).
Historical evolution of ES valuation research (Liu et al., 2010)	Review of historical evolution of ES valuation research and how it has been used in ecosystem management based on peer-reviewed publications. The database is a spreadsheet of selected valuation studies taken from EVRI database.	Not online: Database available on request (Liu et al. 2010)
Innovation Seeds	Promote results from research and development addressing more environmental-friendly technologies or approaches (eco-innovation) to accelerate their uptake as policy measures and market success. The website contains synthetic articles of case studies and good practices as well as information on networks and funding programs.	Greenovate! Europe EEIG, Youris.com EEIG (Innovation Seeds 2017)
Interdependences of biodiversity and ES (Cardinale et al., 2012)	Review the relationships between biodiversity and ES based on peer-reviewed publications. Spreadsheets are used to summarize interlinkages between the variety of genes, species, or functional traits with provisioning and regulating services.	Not online: Database available on request (Cardinale et al. 2012)
Linking functional traits with ES (de	Synthesizing concepts and empirical evidence on linkages between functional traits and ES across different trophic levels.	Not online: Database available on request (de Bello et al. 2010)

Bello et al., 2010)	Information on plants, vertebrates and invertebrates traits and their roles for ES are reviewed, and documented in a spreadsheet format.	
Marine Ecosystem Service Partnership (MESP)	Improve the estimation, dissemination and use by decision makers of social and natural science data about marine ES. The online database provides a library of scientific marine and coastal valuation studies, and monetary value estimates of ES.	Duke University, Nicholas Institute for Environmental Policy Solutions (Duke University 2017)
Marketwatch and News & Articles of Ecosystem Marketplace (EM)	Provision of information on markets dealing with ecosystems and PES in order to increase transparency of such markets, facilitate transactions and spur the development of new markets. The website features article in newsletter format, reports and factsheets on development in markets and market-relevant factors (policy, finance, business, science).	Ecosystem Marketplace, initiated by Forest Trends (Ecosystem Marketplace 2017)
Methodological approaches of ES analysis (Seppelt et al., 2011)	Quantitative review of methodological approaches of ES analysis to identify qualitative requirements on ES studies that help to improve assessments and comparability across studies.	Helmholtz Centre for Environmental Research – UFZ, Department Computational Landscape Ecology (Seppelt et al. 2011)
Payment for Ecosystem Services Database (PESD)	Compilation of PES projects in Latin America and the Caribbean to overcome knowledge gaps and facilitate the implementation of PES in developing countries. The online database features information of PES schemes and quantifies transactions.	Organization of American States, Department of Sustainable Development (OAS 2008)
Payment for watershed markets - Information from schemes in developing countries (IIED Watershed Markets)	Qualitative review on payments for watershed services initiatives in developing countries and their impacts. The online database encompasses summaries of the design, operation and impact of initiatives, their constraints and legislation challenges.	International Institute for Environment and Development (IIED) non-profit organization (IIED 2012)
ReefLink Database	Decision support related to reef ecosystems by providing information on linkages between decisions, human activities, and supply of ES. The online database features a qualitative collection of scientific literature, management options and laws.	United States Environmental Protection Agency, Gulf Ecology Division (US EPA 2016)
Sub-Global Assessments database (SGA)	Qualitative documentation of sub-global assessments from the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2005a) to provide access to assessment reports, guidelines, and other outputs as a resource for practitioners. The online database contains synthetic summaries of sub-global assessments.	United Nations Environment Programme, Millennium Ecosystem Assessment (UNEP 2005)
The Economics of Ecosystems and Biodiversity case studies (TEEB Cases)	Provision of good practice examples where a focus on ES and their economic significance helped decision makers to find more sustainable solutions for the management of ecosystems. The online database encompasses synthetic summaries of ES valuation studies.	TEEB Office, United Nation Environmental Programme under the Economics and Trade Branch of the Division of Technology, Industry and Economics, Helmholtz Centre for Environmental Research (UFZ), Department Environmental Politics (TEEB 2014)
The Economics of Land Degradation case studies (ELD Cases)	Awareness raising on costs and benefits of sustainable land management in political decision-making. The design of the online database (ELD Initiative 2017) and in the ELD Initiative (2013) report differs slightly. The online database features abstracts and references from ES studies. Additionally, in the report are economic relevant details quantified.	ELD Secretariat c/o Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH (ELD Initiative 2013, 2017)
ValuES application cases (ValuES Cases)	Provision of best practices to enhance the relevance of ES assessments in decision support. The online database features qualitative summaries of ES assessments and highlight on-the-ground experiences with assessment design, implementation and usage in decision-making.	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH (ValuES 2016a)

ValuES method inventory (ValuES Methods)	Online database that aims to guide practitioners and policy makers in the selection and application of ES methods and tools. The online database contains factsheets summarizing major characteristics as well as application cases of ES methods and tools.	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH (ValuES 2016b)

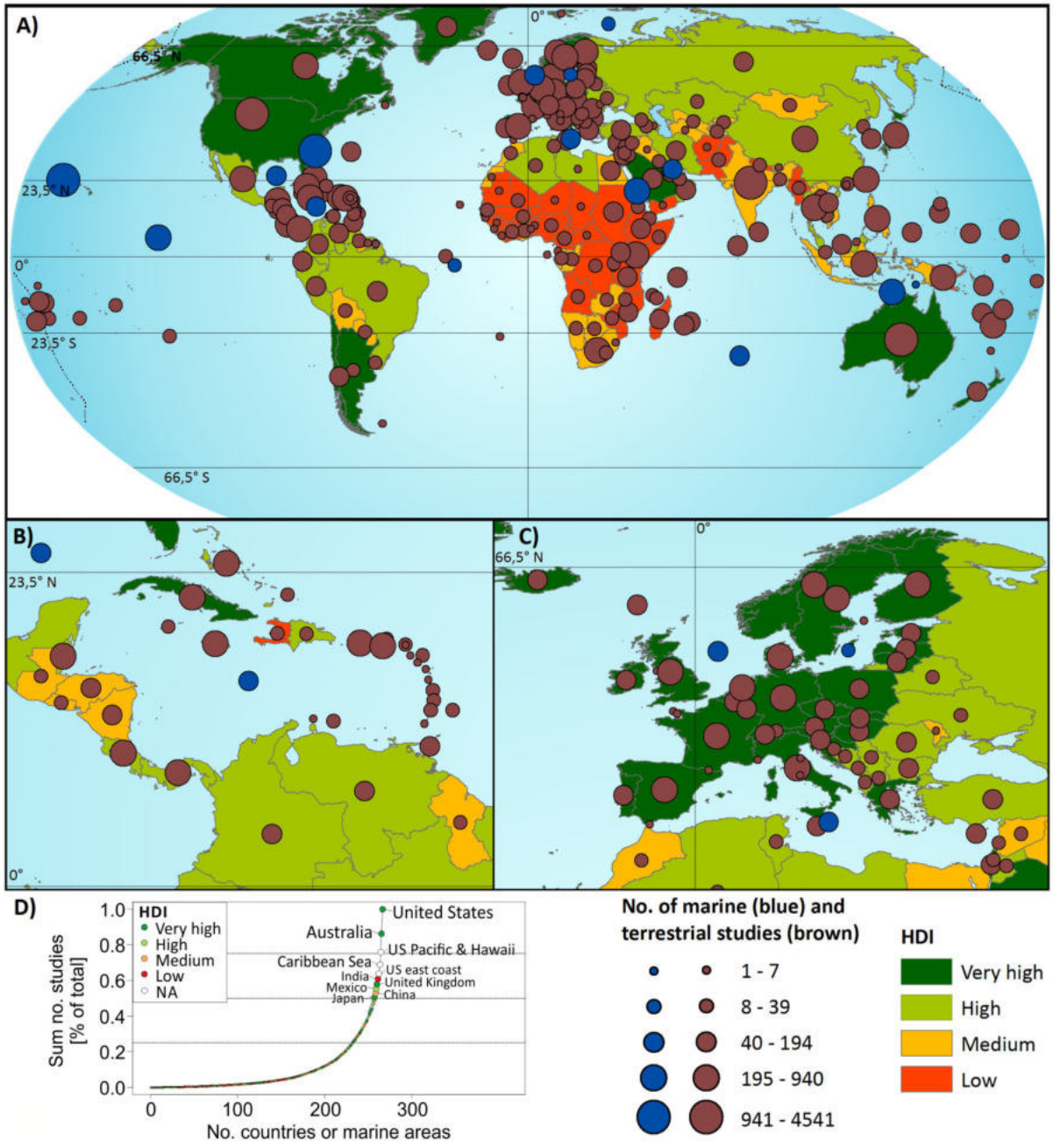

Fig 1. Geographic distribution of ES analysis from 29 databases. The panels (A-C) show the number of ES studies (size of circles) for each country (brown) or marine area (blue). The color codes of the maps represent development status of countries based on the Human Development Index (UNDP 2014) from very high to low for the entire globe (A), Caribbean (B) and Europe (C). Panel D shows the cumulative distribution of ES studies across countries or marine areas (No. countries or marine areas) and their development status (colored ovals).

The horizontal lines indicate the 25-, 50- and 75-percentile. The top ten areas with most ES studies in the sample were displayed, reflecting greater than 50% of all studies. Global studies were excluded.

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The databases collated information from 35,851 studies. Three out of every five studies in all databases contained information for countries with a high Human Development Index (UNDP 2014), while only 4% of all studies were conducted in society's poorest nations[2] (Fig 1). The continent with the fewest number of studies (2%) was Latin America.

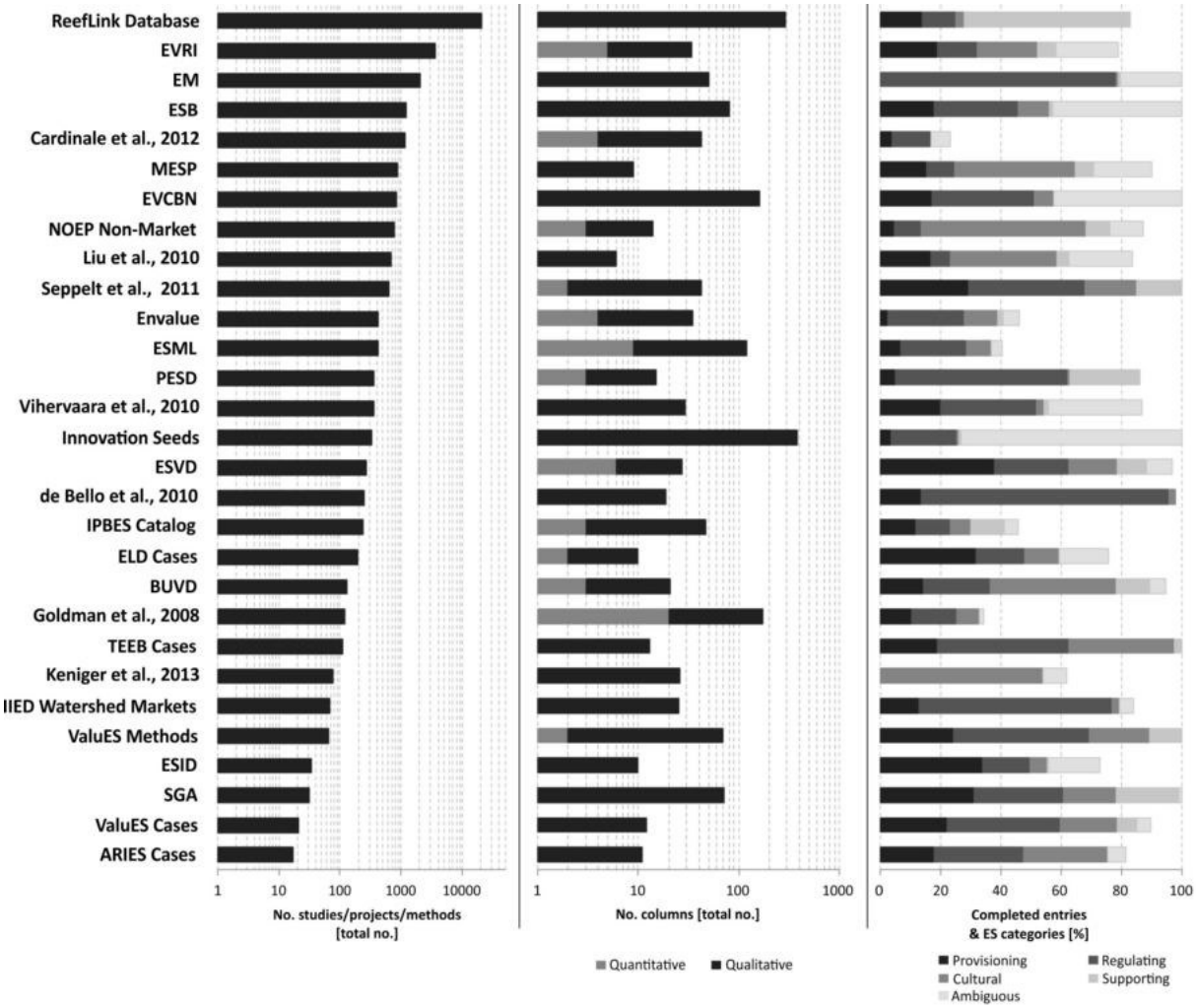

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Fig 2. General characteristics of ES database contents. In 29 databases were 35,851 studies/projects and 163 methods documented (bar plot left). Databases were structured in 6 up to 379 columns (bar plot middle) that provided quantitative (light gray) or qualitative information (dark gray). Eight databases showed fully completed entries, while in five less than the half of data entries remained empty (bar plot right). Most of the

2 Human Development Index 2013 <0.55 (UNDP, 2014).

data entries referred to regulating services, followed by cultural, provisioning and supporting ES (gray scale bar plot right).

Regulating services were most frequently reported, followed by cultural, provisioning, and supporting ES (Fig 2). Quantitative information expressed in numeric variables was recorded in 4% of column headers of databases (Fig 2). In 28% of databases all entries were filled with data, while for the other databases entries remained incomplete (not applicable, not answered or not available).

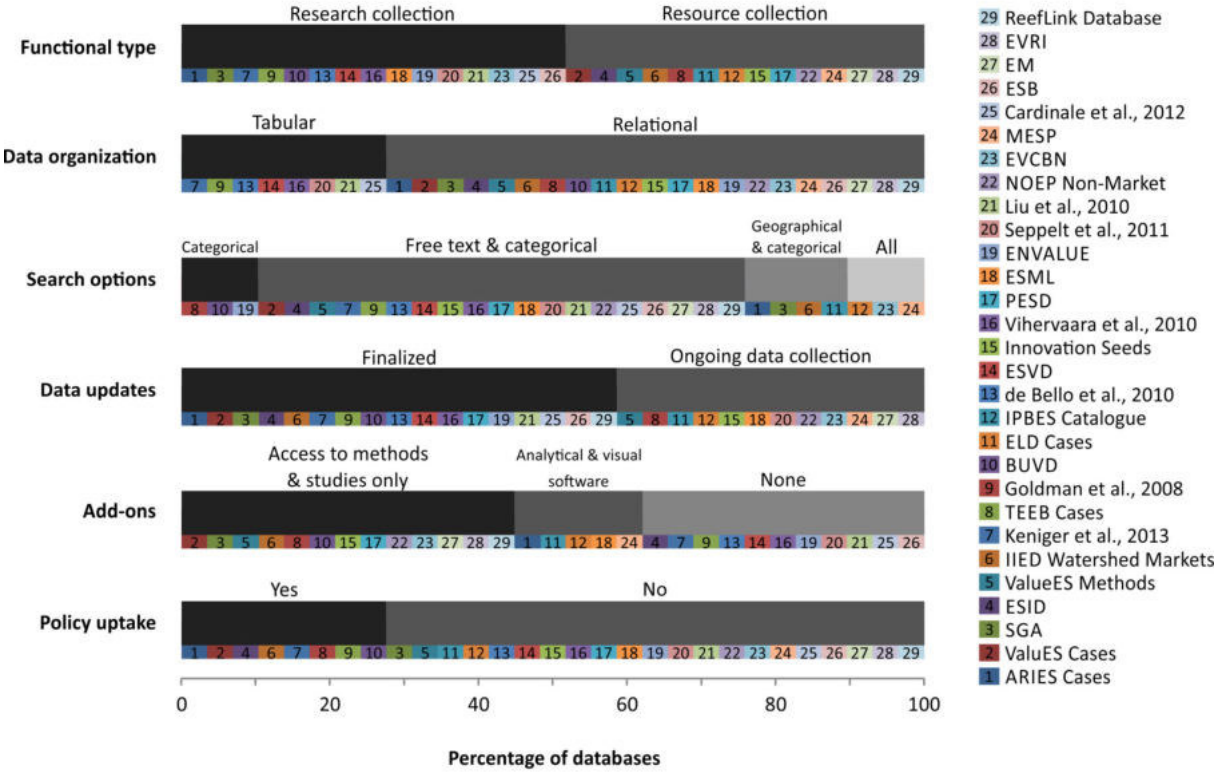


Fig 3. Design and impact of databases. Percentage of the 29 databases that belong to specified characteristics. Characteristics are defined in S2 Table. For the characteristic 'search option' the category 'all' includes 'categorical', 'free text' and 'geographical'. The colored bars (lower part of bar) indicate the database for each characteristic respectively.

Slightly more than half of the databases were research collections (52%) designed to serve a specific group and topic in ES science, and funded through different research grants (Fig 3). In 48% of databases resource collections could be identified. These resource collections were managed under the umbrella of international and national environmental programs and agencies as well as private non-profit organizations.

The majority of the 29 databases (72%) organized data based on a relational data design (Fig 3), i.e. besides the place where data were stored also the relationships between those data were considered. A relational data design reduces redundancy in data and allows data to be accessed through logical rather than physical identification. Also, basic tabular structures were used to organize data on ES (28%). Accordingly, databases could be queried in different ways to retrieve information. The following features were provided (Fig 3): i) free text search that allows users to input keywords or numbers (67%), ii) queries by selecting predefined options of different categories representing database entries (100%), and iii) geographic queries by interactive maps (24%).

None of the databases incorporated an approach that ensured data longevity (e.g. persistent identifier for data archiving) and a permanent access to datasets, even though almost three out of five databases (59%) contained finalized datasets of finished projects (Fig 3). Basic add-ons were used to share information and increased visibility of databases (62%) such as hyperlinks to original methods and studies as well as links to social media sites with additional information (Facebook, YouTube, Twitter, Flickr, Instagram, etc.) (Fig 3). Databases were rarely (17%) linked to analytic programs or visualization software that enable users to develop and customize applications, for instance by using a geographic information system application programming interface (GIS API).

For 28% of the databases their application within a decision-making context or policy uptake was reported (Fig 3). A few were considered for diverse research initiatives beyond their original project (SGA, IPBES Catalogue, ESVD, EVRI, ReefLink Database), for capacity building in university courses or workshops for practitioners and federal employees (Values Cases, ValuES Methods, EVRI, EM), as a trigger for debates on different policy levels (PESD), and for governmental action plans and environmental stewardship (EVRI).

3.2 Information demand for policy instruments

Information demand for decision-making was specified for six policy instruments. The most frequent indicators per policy instrument were summarized in Table 2. Also, a comprehensive list of the identified 93 indicators and their relation to the six policy instruments was provided in S3 Table.

Table 2. Overview of policy instruments and top three indicators of information demand. For each of the six policy instruments (A-F) the three most frequent indicators of information demand were described. The frequency was calculated by quantifying the number of matches between entries in ES databases and indicators of information demand.

Indicator	Description	Example of database entries
A) Extending accounting systems through nature-based indicators		
Driver	Identification of biophysical or socio-economic factors that exert pressure on the environment and lead to changes in ecosystem conditions such as population growth or climate change (Nelson et al. 2005).	ReefLink Database: 'Socio-Economic Drivers' include the sectors that fulfill human needs for Food & Raw Materials, Water, Shelter, Health, Culture, and Security.
Environmental policies & regulations mentioned	Consideration of or commitments to laws, regulations and other policy mechanisms that manage effects of anthropogenic activities on nature and its natural resources (European Commission 2017).	IIED Watershed Markets: 'Legislation Issues' explain legal provisions related to PES for watersheds.
Metrics	Unit of measurement by which ES are assessed (Kontogianni et al. 2010).	ESVD: 'Unit' encompasses units and currencies of monetary values of ES, e.g. US-Dollar per hectare and year.
B) Rewarding benefits through payments and markets		
Payments for ES considered	Voluntary transaction for specific ES, or a form of land use likely to secure that ES, through a continual series of conditional payments for ES buyer and provider/seller (Jack et al. 2008; FAO 2011).	IIED Watershed Markets: Description of 'Market Design' of different PES schemes by providing information on 'Services' and 'Commodity', 'Payment Mechanism', 'Terms of Payment' and 'Funds Involved'.
Other financial policies for biodiversity-friendly activities	Practice examples concerning the (successful) implementation of tax breaks or exemptions (Shine 2005), public compensation mechanism (Anon 2008) and other financial policies that reward nature-friendly stewardship and spur green markets (Bergsma 2000; Popp 2009).	ReefLink Database: 'Funding & Incentives' includes budgetary decisions by public administration to affect activities related to coral reefs.
Spatial analysis economic benefits	Spatial explicit appraisal of ES benefits for human well-being in monetary terms (Remme et al. 2015).	ESML: Combination of 'EM spatial distribution' and 'Variable values' explain whether or not model calculations are carried out for a spatially differentiated area, and provide results for a model run.
C) Reforming environmentally harmful subsidies		
Subsidies considered	Practice examples on government actions that confer an advantage on consumers or producers in order to supplement their income or lower their cost (OECD 2005).	ReefLink Database: 'Agriculture & Aquaculture: Phase Out Unwanted Subsidies' describes potential actions managers could enact to preserve reef ecosystems.
Sectors of subsidies	Economic sector in which subsidies are implemented (Ulibarri et al. 1998).	ReefLink Database: 'Agriculture & Aquaculture: Phase Out Unwanted Subsidies' describes potential actions managers could enact to preserve reef ecosystems.
Effectiveness against stated objectives	Accuracy and completeness with which implemented subsidies achieve an objective (OECD 1996; Ulibarri et al. 1998).	BUVD: 'General Comments' and 'Methodology Comments' of economic valuation studies.
D) Addressing environmental degradation through regulation and pricing		
(Non-) Financial incentives for ES regulation	Adjustments of incentives through the applications of ES-based standards and procedures that directly authorize or limit certain actions or impacts (price controlling through taxes, fines, fees (Bocker and Finger 2016) or quantity controlling through permits, quotas, licenses (Yandle and Dewees 2008)) or other compensation approaches (offsets, biodiversity banking) (Carroll et al. 2012; Rosa et al. 2016).	Goldman et al. (2008) provides detailed information about 'Conservation Finance Tools' such as redistribution and creation of taxes, fees, right transfers etc. implemented in ES projects.
Illegal conduct	Information on environmental crime and what constitutes illegal conduct such as trade prohibitions (Barnes 1996), or legal regimes for environmental issues (European Commission 2004).	ReefLink Database : 'Accidental & Illegal Harvest' or 'Designated Uses' contain collections of species that are protected from harvest respectively concise statements of a state's management objectives and expectations for each of the individual

		surface waters under its jurisdiction.
Driver with identifiable polluter	Attribution of a person (-s) or a thing (-s) that is directly or indirectly responsible for an ecologically harmful change in the environment (Pasha et al. 2012).	IIED Watershed Markets: 'Driver' and 'Stakeholders' describe the local environmental problems and stakeholders involved in PES for watersheds.
E) Regulating use through protected areas and recognition of their values		
Protected areas considered	Consideration of any area of the terrestrial or aquatic environment that has been reserved by federal, state, tribal, territorial, or local laws or regulations to provide lasting protection for part or all of the natural and cultural resources therein (NOAA 2000; Gray and Campbell 2009; Laurans et al. 2013).	ESVD: 'Protected Status' contains information on the level of protection of the study area.
Win-win situations identified	Identification of synergies in national and international policy commitments to create win-win solutions for environmental conservation and socio-economic co-benefits, e.g. role of habitat protection for recovery of species and their effect on food security (Roberts et al. 2001).	No column headers refer to the indicator, only in titles of references, e.g. in ReefLink Database: (Gjertsen 2005).
Regulatory mechanism for costs & benefits	Documentation of policies or mechanisms for equitable sharing of benefits and costs arising from protected areas (Dixon and Sherman 1990; TEEB 2011). Costs of protection and earning potentials from non-protection choices are often short-term and spatial concentrated while benefits are often long-term, broadly disbursed and non-market.	No column headers refer to the indicator, only in titles of references, e.g. in NOEP Non-Market: Dharmaratne et al. (2000).
F) Direct public investment in ecological infrastructure and restoration		
Restoration	Provision of information on restoration. Restoration in accordance to Aronson et al. (2007) includes the replenishment of natural capital stocks, recovering of resilient and self-sustaining ecosystems as well as the improvement of human welfare on different scales.	ReefLink Database: 'Wetland And Reef Restoration', 'Ecosystem Monitoring And Restoration' etc., describe responses to directly alter the conditions of reef ecosystems.
Proactive strategies used	Application of proactive strategies, i.e. anticipatory, self-initiated behavior, acting, or investigation intervening in advance of a situation that is most likely to happen in future, for instance, the prevention of a hydropower-dam project to preserve natural assets (Reid 1999; Wittich et al. 2014).	BUVD: 'Method Description' of economic valuation studies including approaches of averting behavior.
Needs for adaption	Expected needs for investment in adaption to natural or social crises and catastrophes (Landry et al. 2011; Hochrainer-Stigler et al. 2014). Also methods to identify investment opportunities are considered, e.g. the Resource Investment Optimization System (RIOS) that supports cost-effective investments in watershed services (Vogl et al. 2016).	TEEB Cases: 'What was needed to solve the problem in terms of data, resources and capacity?' and 'What was necessary for developing the instrument?' explain which inputs were required to find more sustainable solutions for the management of ecosystems.

3.2.1 Extending accounting system through nature-based indicators

The first policy instrument aims at the development of new approaches to extend accounting systems and better integrate nature-based indicators. Developing accounting systems that capture the value of ES is seen as a key contribution to improve environmental management and achieve a path to sustainability. In order to implement the policy instrument the following information is required:

- Identification and assessment of functional relationships between nature and human well-being as prerequisite to understand the value of ES and development of indicators.
- Metrics to quantify trade-offs between ES explicitly in space, time, for different management options and beneficiary groups.
- Metrics to evaluate the uncertainty and suitability of ES indicators in terms of valid measures of the issue in question and high ease of use for society (e.g. accountants).
- Characteristics of stakeholder engagement and level of consideration of stakeholders' different points of views in approaches to extend accounting systems. Involving stakeholder contributes to meet the needs of those making policy and management decisions, and legitimize the application in 'real world' (Durham et al. 2014).
- Requirements for information differ on various scales (Hein et al. 2006; TEEB 2011). On global/continental scale rather general objectives are stated by international conventions. Simplified accounts are required that monitor major patterns of ecological changes of ES delivery and quantify actual expenditure for maintaining ecosystems capacity of providing services for all countries. On national/regional scale detailed information for the enforcement of environmental policies and regulations is required by agencies and ministries. On this scale indicators are required that refer to global accounts, but are based on national statistics and monitoring systems in order to adjust common national welfare measures such as Gross National Product. The local scale is the action level where ES are assessed based on real preferences from local actors. Local governments and business increasingly demand good practice examples and guidelines on how to consider nature in their everyday decisions.
- Information on capacity building initiatives that facilitate the development and institutionalization of a plural valuation culture of nature's contribution to human well-being, consistent with recognized best practices.

3.2.2 Rewarding benefits through payments and markets

The second policy instrument aims at rewarding private and public actors who maintain the flow of services that benefit society. Rewarding approaches are, for instance, direct payments, tax incentives or the stimulation of markets for products and services that have reduced environmental impact. The instrument demands information on:

- Evidence on where, in what form, and under what conditions incentive-based instruments work best for both nature conservation and human well-being. For instance, schemes delivering PES

have proven to be a flexible tool, providing rewards for maintaining multiple ES at a range of various scales (TEEB 2011).

- Design and establishment of fair and equitable payment schemes and market-based rewards. This includes information demand on conditions of access and benefit sharing, for instance, for the utilization of genetic resources based on traditional local knowledge.

3.2.3 Reforming environmentally harmful subsidies

Subsidies, i.e.: '… government actions that confer an advantage on consumers or producers in order to supplement their income or lower their cost.' (OECD 2005), can harm or benefit the environment (Pieters 2002). Reforming subsidies in order to alleviate environmental pressures, increase economic efficiency, and reduce burden on government budgets through the consideration of ES values requires information of the following kind:

- Transparent overviews of different forms of subsidies and the extent to which ES are already integrated.
- Information on subsidies' effectiveness against their stated objective, cost-efficiency, and environmental impact.

3.2.4 Addressing environmental degradation through regulation and pricing

Increasing the accountability for environmental degradation and its costs requires information on how ES valuation can help to reduce uncertainties with respect to expected external costs of damages, provide justification for possible regulations, and support the introduction of liability rules. Indicators of information demand include:

- Practice examples which facilitate the internalization of external environmental costs by implementing principles of polluter pays and full cost recovery based on ES valuation.
- Examples for regulatory standards and rules (non-monetary) for resource use that represent reference points upon which environmental liability regimes operate.
- Information on how to adjust incentives by introducing market-based instruments (price controlling through taxes, fines, fees or quantity controlling through permits, quotas, licenses) or other compensation approaches (offsets, biodiversity banking) that build upon ES-related standards to more effectively react to environmental degradation.
- Compliance monitoring, enforcement and prosecution schemes to strengthen ES based regulations in force.

3.2.5 Regulating use through protected areas and recognition of their values

Establishing protected areas and improving their governance through the recognition of ES values requires:

- Information on benefit-cost ratios for the creation and management of protected areas based on ES valuation to show their contribution to human well-being and to increase the social and economic relevance of regulating use in conserved areas. Often costs are short-term and spatially concentrated while benefits of protected areas are long-term, broadly disbursed and non-market.
- Practice examples that implemented regulatory mechanisms for equitable sharing of costs and benefits from protected areas.
- Information on stable financial resources and international funding instruments for the implementation and management of protected areas, in particular to support initiatives in developing countries.
- Identification of synergies in national and international policy commitments to create win-win solutions for environmental conservation and socio-economic co-benefits, and to promote an enabling framework for the establishment and management of protected areas.

3.2.6 Direct public investment in ecological infrastructure and restoration

The last policy instrument aims at the reduction of environmental risks or mitigation of their consequences by using direct public investment in ecological infrastructure and restoration of degraded ecosystems. Information demand for the policy instrument relates to:

- Identification of situations in which direct public investments in ecological infrastructure and restoration is required to reduce natural hazard risks or mitigate their consequences. This encompasses information requirements on threats to ES provision, actual and possible transition processes, timescales of restoration process and recovery to a state of ecosystem resilience and performance (Jones and Schmitz 2009), and evidence on whether benefits exceed costs from restoration.
- Evidence on proactive investment strategies that successfully reduced environmental risks. Instead of reactive restoration where damage has already taken place, proactive strategies and the precautionary principle are stressed in policy (Innocenti and Albrito 2011). Usually it is more cost-efficient to avoid degradation than to pay for ecological restoration.

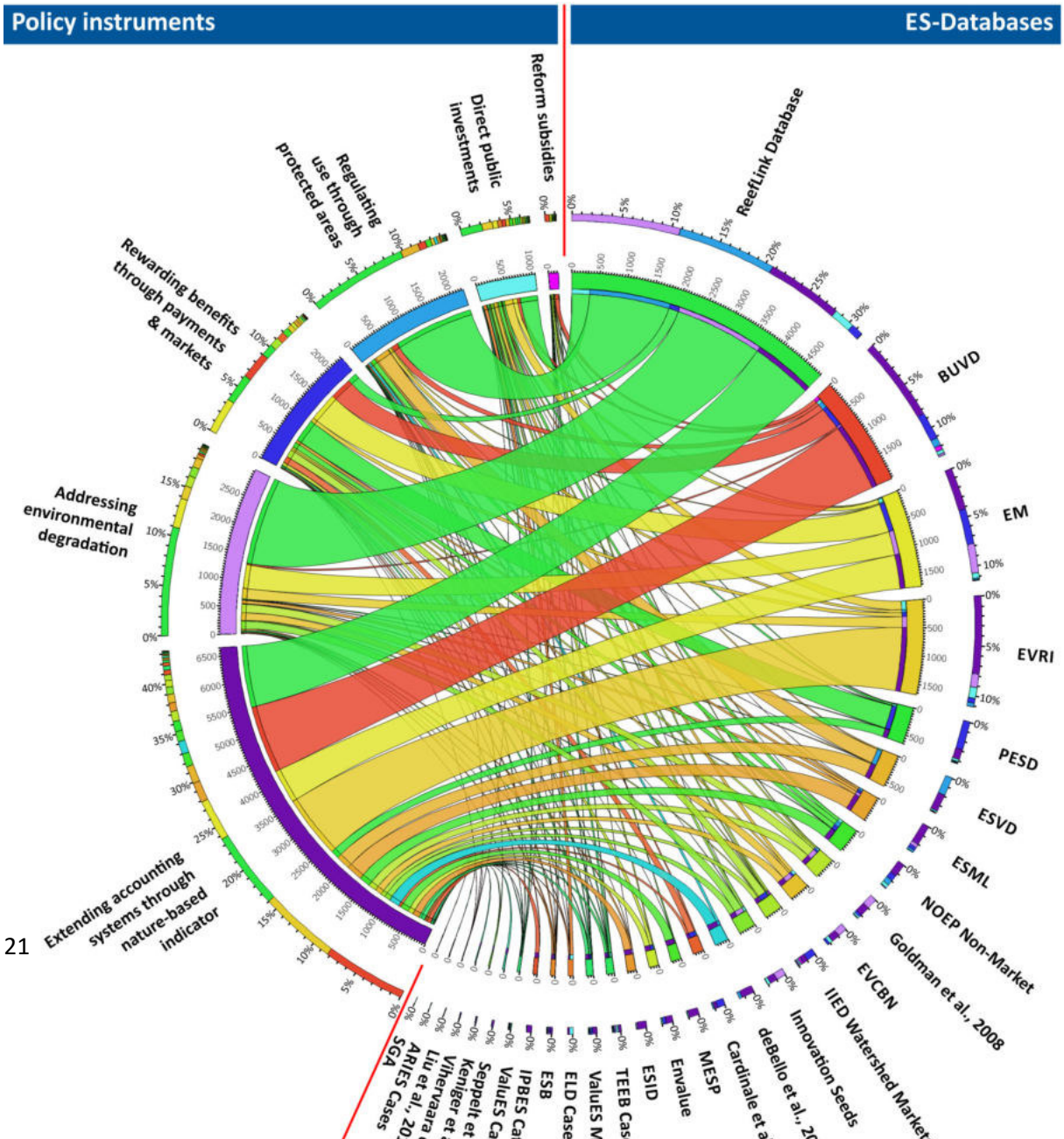
3.3 Information demand fulfilled by ecosystem service databases

The extent to which the 29 available databases provide information for each of the six policy instruments was quantitatively synthesized in Fig 4 (S2 Fig for details on indicator of information demand). This figure visualizes how the content of each database provides data that matches with indicators of information demand for implementing a given policy instrument as described in Section 3.2. In Table 3 the most frequent matches and constraints were summarized.

Across all databases, the most information was provided for the policy instrument that aims at extending accounting systems (in total 43%[3] of data entries from 29 databases). ReefLink Database (32%), BUVD (13%) as well as EM (11%) were the top three databases providing the most information across all policy instruments. Databases addressed different components of the ES framework (Daily et al. 2009) and focused on specific linkages between nature and human-well-being. Biophysical links between policy actions and state of ecosystems, and consequences on ecological production functions were considered in 56%. In contrast, economic and social valuation of services to people were included in 33%, and information on specific decisions made by individuals, communities, corporations, and governments attuned to social and political contexts were contained in 11%. None

3 Percentage values in Section 3.3 (including 3.3.1 to 3.3.6) refer to weighted matches between database entries and indicators of information demand, as described in Section 2. Exceptions were specified separately.

of the databases quantifies relationships for all of the components.



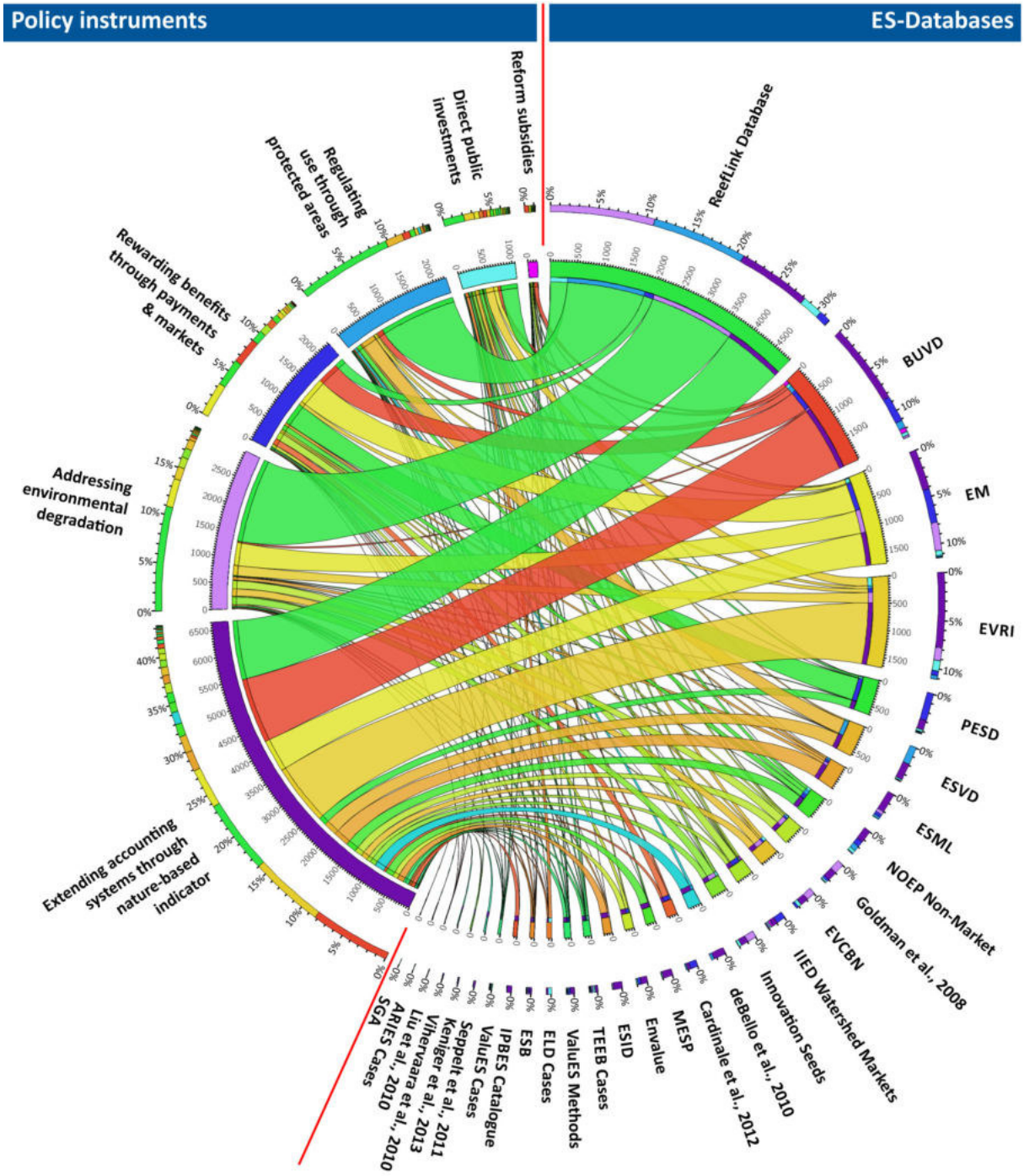


Fig 4. Quantitative matches between information supply provided by databases and information demand in policy instruments for safeguarding ES. The chord diagram connects information supply from 29 databases (right half) with information demand represented by six policy instruments (left half). It shows the weigthed matches (percentage values of outer arc of stacked bars) and total number of (inner monochrome arc) matches between database entries and indicators of information demand aggregated by policy instruments (colored arc connections). Color codes from the outer left arc and inner right differentiate databases (e.g. green, red,

390 yellow, orange), while colors from the inner left and outer right distinguish policy insturments (e.g. purple, bluish). Additionally, S4 Table provides the explicit numbers for the weighted matches.

Table 3. Summary of information supply from databases for policy instruments The table summarizes the information availability (most frequent data entries) and information gaps (missing data entries) and
395 constraints from 29 databases for the six policy instruments. The six policy instruments were codified as follows: A) Extending accounting systems through nature-based indicators; B) Rewarding benefits through payments and markets; C) Reforming environmentally harmful subsidies; D) Addressing environmental degradation through regulation and pricing; E) Regulating use through protected areas and recognition of their values; and F) Direct public investment in ecological infrastructure and restoration.

Database	Information availability	Information gaps and constraints
ReefLink Database	• Most information for D), E) & F); • Most studies in society's poorest nations; • Most global studies; • Extensive information on monitoring (A)	• Focus on coral reefs
EVRI	• Most long term studies; • Most local studies; • Most comprehensive information on monetary valued ES (A); • Insights into proactive investment strategies to reduce environmental risk (F)	• No information on C)
EM	• Most information for B); • Comprehensive information on incentive-based instruments, other compensations (offsets, biodiversity banking) & market based-instruments (B, D)	• Qualitative documentation hinders comparability of data entries
ESB	• Outreach material for capacity building (A)	• Broad thematic categories (column headers) used to organize data entries
Cardinale et al., 2012	• Categorical relationships between biodiversity & ES identified (A)	• No information on C), D), F); • High number of missing data entries
MESP	• Monetary values of costs & benefits of coastal & marine ES (A)	• No information on C), D), E); • Focus on coastal & marine ES
EVCBN	• Insights into cost & benefits of ES (A)	• No information on C), E)
NOEP Non-Market	• Monetary values of costs & benefits of ES (A); • Insights into funding options & instruments for protected areas (E)	• Almost no information on C); • Focus on costal & marine cultural services
Liu et al., 2010	• Basic information on ES type, biome & country of economic valuation studies	• Least information documented for policy instruments; • No information on B), C), D), E), F)
Seppelt et al., 2011	• Insights into ES indicator & uncertainty (A)	• No information on B), C), D), E), F)
ENVALUE	• Monetary values of costs & benefits of ES (A)	• No information on C), D), E)
ESML	• Ecological quantification of ES (A)	• No information on C); • focus on ecological models
PESD	• Insights into PES projects (B); • Insights into public investment for agroforestry systems, biodiversity conservation, carbon sequestration, ecotourism & watershed protection (F)	• Focus on PES project transactions
Vihervaara et al., 2010	• Measures of interdisciplinarity of studies directly addressed (A)	• No information on B), C), D), E), F)
Innovation Seeds	• Information on funding programs & networks for more environmental-friendly approaches or technologies (B); • Insights into proactive approaches & technologies to reduce environmental risk (F)	• Almost no information on C) & E)

ESVD	• Monetary values of costs & benefits of ES (A); • Most information on valuations of cost & benefits of ES in protected areas (E)	• No information on C)
De Bello et al., 2010	• Categorical relationships between functional traits & ES identified (A)	• No information on B), C), D), F)
IPBES Catalogue	• Capacity needs and action taken directly addressed (A)	• No information on C), D), E), F)
ELD Cases	• Monetary values of costs & benefits of ES (A)	• No information on C)
BUVD	• Most information for A) & C); • Monetary values of cost & benefits of ES (A); • Most information on subsidies (C)	• Focus on water-based ES
Goldman et al., 2008	• Information on monitoring & evaluation of project impact (A); • Most information on offsets & compliance monitoring (D)	• No information on E); • High number of missing data entries
TEEB Cases	• Good practice examples on utilizing ES valuations for decision support (A)	• Qualitative documentation hinders comparability of data entries
Keniger et al., 2013	• Categorical relationships between human interactions & nature identified (A)	• No information on B), C), D), F)
IIED Watershed Markets	• Systematic differentiation of stakeholders involved in PES (A); • Most comprehensive information on PES (B)	• Focus on watershed services
ValueES Methods	• Training material & methods for assessment & management options of ES (A)	• Focus on ES methods & tools
ESID	• Insights into ES indicators (A)	• No information on E) & F); • Almost no information on C)
SGA	• Outreach material for capacity building (A)	• No information on B), C), D), E), F)
ValuES Cases	• Good practice examples on utilizing ES assessments for decision support (A)	• Qualitative documentation hinders comparability of data entries
ARIES Cases	• Practice examples on ES modelling	• No information on C); • Almost no information on D)

400

3.3.1 Extending accounting systems through nature-based indicators

Of the 43% of database entries provided for extending accounting systems through nature-based indicators, the following information was available: One database (ESML) contained values of ecologically quantified ES based on production functions. In ESML were maximum, minimum, and
405 central-tendency for predictor and response variables of ecological models documented. Further ecological insights into ES were provided by identifying categorical relationships (positive, neutral and negative) between biophysical components of nature and ES (de Bello et al., 2010, Cardinale et al., 2012) as well as ES and human well-being (Keniger et al., 2013). Measures of critical thresholds (i.e. status of sudden ecosystem collapse) or prioritization schemes to identify need of actions based
410 on biophysical values of ES were absent. Twenty databases contained entries that address the monetary valuation of ES. However, numerical information on monetary values was provided in only 1.4% of data entries across all databases for demand of ES and in 0.7% for the supply of ES. In 1.3% of entries it was distinguished whether approaches were used to assess performance of ES over time or for a specific point in time.

415 The quantification of trade-offs between ES were reported in 0.3% of entries. Information that support trade-off analysis such as where ES were generated (2%), what were drivers of losing them

(3.7%), the economic costs of ES loss (0.3%) and who faced these costs (0.7%), where (0.7%) and when (0.7%) were simultaneously documented in the databases EVRI and IIED Watershed Markets only. Monitoring strategies for performance monitoring of ES were reported in 1.3% of entries. Long-term impacts of resource use decisions (exceed 10 years) were addressed by 0.1% of entries and three databases: EVRI, Goldman et al., 2008 and ESML.

Metrics to evaluate the uncertainty of studies were reported for 0.9% of entries. The ESML database most exhaustively captured uncertainties by providing bivariate information ('yes/no' answer category in 97% of ESMLs' entries) on different quality tests of models and indicators used. None of the databases provide information to measure indicators maturity for application in practice or uptake of indicators in society required to estimate progress in ES indicator development.

Stakeholder engagement was reported in 2.1% of entries. However, a detailed differentiation was less frequently available, for instance, in which processes stakeholder were involved (0.8%), from which institutional scale (0.9%) and socio-economic sectors they came from (0.6%). IIED Watershed Markets divided stakeholders into the groups of supply, demand, intermediary and facilitator, to provide insights into which roles stakeholder played for the design and establishment of nature-based accounting systems. In 1.2% of entries databases directly addressed the topic of transdisciplinary requirements on ES research and documented which scientific and societal bodies supported the studies and projects.

On the global/continental scale (investigation area ≥20 million sqkm) more than 1,731 studies were available, but less than 1% monitored ecological trends of changes in ES supply and quantified actual expenditure for restoration, protection, and resource management to maintain ecosystem capacity of delivering services. In 15 databases information criteria for regional (investigation area <20 million sqkm, >10,000 sqkm) and local scale (investigation area ≤10,000 sqkm) were distinguished. In 2,848 studies information was provided on indicators for taking ES into account on regional scale. Details on whether and how they could be linked to global accounts or integrated in national accounts and statistics were missing. In 2,585 studies real preferences from local actors were assessed. In 1% of the local studies guidelines were provided on how to consider nature in local and private actors' everyday decisions.

Databases provided information on how to build ES assessment capacities for different stakeholder groups (0.2%). Also information on capacity building initiatives were documented for the trade-off analysis of management options in accepted policy assessment systems in place (<0.1%). For these

capacity building efforts databases contained outreach material such as webinars, guidelines, FAQ's, training material or other interactive resources.

3.3.2 Rewarding benefits through payments and markets

In 15% of database entries information was provided for incentive-based policy instruments that aim to reward nature-friendly stewardship and spur green markets. Financial incentives such as tax breaks or indemnifications were documented in 2.3% of entries. While PES were examined in 5.2% of entries, specific information on implementation aspects of PES were dispersed across databases. Most databases reported only on one of the following topics: transaction costs of transition to nature-friendly activities (<0.1%), in what form (1.6%) and under what conditions (0.2%) PES worked for safeguarding ES. Two databases disclosed legal frameworks directly referring to PES in different nations and showed how legal aspects were considered in PES schemes (PESD, IIED Watershed Markets). Information on the engagement of local stakeholders in the design and implementation of PES were provided in 0.5% of databases. Basic information to support the development of new PES schemes, such as spatial analysis of economic benefits (2%) and costs of ES loss (0.6%), the distributions of providers (0.4%) and beneficiaries (0.6%) was also broadly dispersed across databases. Maps that illustrate areas most important for providing ES were shown in no database.

Practice examples on how to design or establish fair and equitable payment schemes and market-based rewards were scattered across databases. Insights were provided for empowering specific groups of stakeholder for the establishment of PES (<0.1%). Also, databases documented conditions of access and benefit sharing for the utilization of ES based on traditional local knowledge (0.8%). Information on capacity building initiatives to support locals in assessing, utilizing and sharing of benefits for genetic resources were provided in 0.8% of databases. The database EM summarized most comprehensively information on established ES markets such as markets for carbon, water and biodiversity.

3.3.3 Reforming environmentally harmful subsidies

Across all databases, the least information was documented for the policy instrument that aims at reforming environmentally harmful subsidies (1.1% of database entries). Neither a transparent and comprehensive inventory of subsidies for different nations nor an overview of the extent to which ES are integrated in subsidies was available. Thirteen databases contained entries that provided qualitative information on subsidies. BUVD and IIED Watershed Markets reported most extensively on subsidies. In 0.5% of entries it was shown how subsidies have been used or where new ones have

been established. Further insights in the socio-economic sector where subsidies have been implemented were given for 0.3% (187 studies).

Information on subsidies effectiveness against stated objectives (0.2%), their cost-efficiency and environmental impact (<0.1%) was disbursed across different databases. Only BUVD and IIED Watershed Markets documented these indicators simultaneously for 12 studies.

3.3.4 Addressing environmental degradation through regulation and pricing

Of all policy instruments, the second most information (19% of database entries) was provided on accountability for environmental degradation and its costs. Measures for spatial allocation of polluters and their costs of damages were reported in 0.9% of entries. Assigning spatially explicit full costs of ES recovery to recipients benefiting from the ES was not covered by any database.

Other standards for environmental regulations were held by databases for prohibitions (0.1%), environmental benchmarks (1%), and technical innovations that reduce pressures on nature (1.5%). ReefLink Database contained the most data entries on environmental benchmarks for land management and environmental prohibitions according to US-laws for a broad set of coral reef related topics, e.g. air and water quality management and monitoring, amendment rules to protect fish, and permits for coastal construction programs. Data entries for technical innovations, such as the sharing of new production and recycling techniques, were most often reported in Innovation Seeds.

Databases also provided practice examples of adjusting incentives through diverse market-based controlling instruments (0.9%) and other environmental offset schemes (0.6%) that integrated ES-related standards. Information on specific techniques and time frames for offsetting environmental degradations were given for 0.3% (EM, EVRI, TEEB Cases, ValuES Cases, IIED Watershed Markets, ESML). However, no database evaluated the long-term added value of specific compensation activities after their implementation.

Information on compliance monitoring (0.2%) as well as approaches for the design of prosecution, arrest, conviction and penalties for perpetrators (0.1%) was disbursed over different databases and individual studies. Most information was provided in ReefLink Database, Goldman et al., 2008 and BUVD. The documentation of international cooperation on law enforcements addressing illegal cross-border activities was considered in 0.1% of data entries, for a total of 252 studies. This includes setting and enforcing international treaties for conservation and trade prohibitions (ReefLink Databases, TEEB Cases, Goldman et al. 2008, NOEP Non-Market, ELD Cases), international compliance markets with penalization agreements (EM), or funding provided by international NGOs

for inspections and other control approaches (IIED Watershed Markets). Innovations Seeds encompassed a network library that provided information on partnerships for multiple scales, sectors, and nations.

3.3.5 Regulating use through protected areas and recognition of their values

Information that support the establishment of protected areas and improve their governance was contained in 15% of database entries. This percentage includes the following indicators: In 6.3% of entries terrestrial and marine protected areas were directly addressed and in 2.2% their ES valued. Entries rarely gave spatial (0.4%) and temporal (0.9%) explicit insights into benefits and costs of ES in protected areas. Expenditures for management of protected areas were directly shown in PESD and EM, for <0.1% (23 studies).

Regulatory mechanisms for equitable sharing of costs and benefits from protected areas were documented in 1.4% of entries, for instance the implementation of PES schemes (EM, IIED Watershed Markets, PESD).

Funding instruments to enable stable financial support for the implementation and management of protected areas were reported in 0.4% of entries. Databases documented funding by governmental sources, non-profit organizations and diverse market-based sources.

Synergies and coherences in national and international policies were documented in 1.7% of entries and win-win situations specified for the influence of habitat protection on ecosystem-based adaptation to climate change, tourism and poverty reduction as well as for recovery of species and their effect on food security in surrounding areas. Databases such as IIED Watershed Markets, TEEB Cases and partly ValuES Cases directly linked and quantified the contribution of protected areas to poverty reduction and local livelihood improvement.

3.3.6 Direct public investment in ecological infrastructure and restoration

Of all policy instruments, the second fewest amount of information (7% of all database entries) was provided on the reduction of environmental risks by using direct investments of public money in ecological infrastructure and restoration of degraded ecosystems. Good practice examples were documented by governmental funds for mitigation of climate change, water management, and preservation of biodiversity (IIED Watershed Markets, PESD; EM, EVCBN, TEEB Cases, ValuES Cases, ReefLink Database, Innovation Seeds) as well as safeguards of recreational amenities (NOEP Non-Market, ESB). Expected needs for adaptation to natural hazard risks were reported by economic valuation of investment needs for restoration, mitigation and avoidance costs (0.7%), general descriptions on restoration requirements to solve in situ problems in terms of data, resources and

capacity (0.2%), and requirements for applying specific restoration methods and technologies (<0.1%, 72 studies). ELD Cases provided the most information for expected needs for adaptation to natural hazard risks. In less than 0.1% of entries information was available for restoration of degraded ecosystems whose returns lie in the realm of non-market ES and public interest, and will be realized only over a long-term perspective, as are brownfield sites, post mining areas, converted forests, etc. EVRI contained most data entries for these types of restoration. Also, EVRI was the only database that quantifies whether benefits from restoration exceeded the costs and elucidated threats to ES and transition processes. No database documented the timescale for the restoration process and recovery to an aimed state of ecosystem resilience and performance.

Proactive investment strategies to reduce environmental risk were documented in 1.1% of entries**.** For instance, direct public investments in recycling techniques were shown in five databases (Innovation Seeds, ReefLink Database, EVCBN, EM, TEEB Cases). These databases documented loops and synergies in and between ES beneficiaries for a more efficient use of limited resources, e.g. straw waste recycling in a rice-wheat rotation farmland (Xuesong et al. 2011) or corporate social responsibility for wastewater treatment (TSMC 2014).

4 Discussion

4.1 Priority areas for mainstreaming ES information into decision-making

Analyzing and comparing contents across all indicators of information demand shows that five key criteria pertain to all policy instruments. Synthesizing these findings suggests that the five key criteria represent priority areas to formalize standards for the documentation of knowledge on ES critical for mainstreaming ES information into decision-making. We discuss these five key criteria and summarize information availability for those criteria provided by databases.

(1) Quantification of values for ES to better recognize nature: The recognition of values of ES for both short-term and long-term benefits is essential to stimulate adjustments of economic and financial incentives for a greater efficiency in solutions of environmental problems and resource use, and contribute to the achievement of sustainability goals (Hejnowicz and Rudd 2017). Values of ES can be expressed in multiple dimensions (biophysical and socio-economic, e.g. monetary) and are implicitly or explicitly part of decision-making and its justification (Jacobs et al. 2016). Most databases valued ES in monetary terms but neglected to transparently relate these values to biophysical measures. Furthermore, no database provided transparent information on propagation of uncertainties associated with results, if biophysical measures are interlinked with socio-economic

values. In general, estimates of uncertainties were rarely quantified in databases, regardless of the fact that the handling of uncertainties is seen as a sensitive topic in science-based policy advice (Polasky et al. 2011). Consequently, the discovery of reliable information on (anthropogenic) transition processes of nature and their impact on benefits for human well-being is hampered. Designing databases by taking into account linkages between ecosystem changes and outcomes that matter to people enhances the provision of policy-relevant information (Kontogianni et al. 2010; Olander et al. 2017).

(2) Transparent prioritization schemes in ES analysis to identify need of action: Values of ES on their own will not provide solutions to halt environmental degradation. The challenge is to use values of ES to redress market and policy failures. Prioritization schemes address the evaluation and ranking of ES, methods, results etc., in accordance with their importance or urgency for a particular purpose. The reviewed ES databases neglected to biophysically quantify the relative importance of ES by magnitude of change and the number of affected beneficiaries. In contrast, monetary valuations through cost-benefit analysis and other trade-off analysis (scenario analysis etc.) were frequently documented. Economic prioritization, however, should be considered with caution since linkage to biophysical measures was missing and information on ecological thresholds was absent in databases. Economic valuations of ES based on estimating marginal changes of environmental benefits become inappropriate when ecological thresholds are transgressed (Farley 2008). ES databases rarely provided explicit and contextualized recommendations for situations in which policy interventions were suitable and efficient. For instance, there was a lack of information on reforming environmentally harmful subsidies. Also rarely shown were specific situations in which directly investing public money in ecological infrastructure or restoration was needed to reduce crises and catastrophes or mitigate their consequences. Databases neglected the documentation of relations between natural capital and extreme event prevention. Success stories of direct public investment in restoration were rarely reliable due to missing information on cost-benefit ratios of restoration, time needed for the restoration process and evaluation whether aimed state of recovery was achieved. Good practice examples that show how to improve governance of protected areas were proposed based on information on regulatory mechanisms that consider ES benefits in their calculations. However, databases were missing comprehensive and transparent overviews on cost-benefit ratios for the creation and management of protected areas; including costs to enable protection, regulate use, and maintain protected areas (McCarthy et al. 2012; Parker et al. 2012). Some databases were designed to help users find ES methods for specific applications based on considerations of cost and

time efforts, for individual purposes, technical maturity, etc. (ESML, ValuES Methods), and thus provided better amenability for decision-making.

(3) Sensitive stakeholder engagement to ensure durable reforms: Stakeholder engagement helps to meet practical needs and contributes to the relevance and legitimacy of information supply for decision-making (Reed 2008; Durham et al. 2014; Posner et al. 2016). Even though a set of generally agreed engagement rules exists (Durham et al. 2014), there is no 'one-size-fits-all' approach that can be applied to projects with strongly varying scopes. Thus, decision makers need guidance on when to involve stakeholders and what are challenges and constraints. The reviewed databases provide general information on stakeholder engagement. For instance IIED Watershed and TEEB Cases provided practice examples on how the integration of local communities in the design of protected areas ensured the compliance of locals with conservation strategies. Also, IIED Watershed and TEEB Cases showed that the engagement of locals in building protected areas contributed to both nature conservation and improvement of local livelihood. However, databases neglected to address risks of stakeholder engagement that may delayed decision-making or led to poor decisions, such as cost and time efforts, labor input, conflicts arising from stakeholder participation or unbalanced engagement (Poolman et al. 2009; Erbout et al. 2010). The development of information sharing mechanisms that disseminate information about challenges and constraints may help to avoid common pitfalls, to identify appropriate situations for participation, and to improve engagement processes in terms of effectiveness and efficiency.

(4) Support information access and capacity building to establish ES-based decision-making: Building capacities of individuals, communities and organizations is an essential prerequisite to encourage collaborative action and help to sustain long-term commitment. Capacity building can contribute to take scientific findings into account in policy processes, to make environmental assessments and information accessible to stakeholders, to manage environmental data and information, foster national scientific capacity etc. (IPBES 2013). Approaches for capacity building vary considerably in different national and cultural contexts as well as for different purposes of use (OECD 2015). Examples for capacity building approaches include training and workshops, networks to share experiences and information, stakeholder engagement and fellowship programs (UN General Assembly 2012). Compiling an inventory of existing opportunities and arrangements for capacity building is seen as an important baseline for the promotion and facilitation of capacity building initiatives. Databases reported about basic and advanced capacity building options such as webinars and workshops on assessing ES state, value and trade-offs. Capacity building on compliance monitoring and enforcement of ES regulations as well as criminal prosecution and penalty were

missing. Improving capacity in applying ES-based liability and enforcement regimes is critical to give policy teeth and contributes to the reduction of environmental degradation (TEEB 2011). All databases lacked a systematic documentation of capacity building approaches in accordance with topics and purposes of capacity building. Only the database Innovation Seeds contained an inventory of experts and networks providing information on competences and contact details for consultancy. Expert networks play a major role in strengthening capacity. As expert networks develop, their linkage with policymaking bodies grows, fostering more effective communication between experts and policy makers (IPBES 2013). Research should further engage in capacity building and develop knowledge exchange mechanisms that provide fast and simple access to ES research for broad audiences (Scholes et al. 2012; Pickard et al. 2015; OPPLA 2017). Steps towards the development of a more efficient knowledge exchange mechanism were illustrated in Section 4.2.

(5) Consideration of long-term returns of interventions: Revealing ES values and benefits of actions obtained over long-term time horizons is crucial to adjusting the current decision-making bias towards short-term economic benefit (Eliasch 2008). Our findings show that long-term ES studies were rare (2% of all studies) in reviewed databases. Research needs to be directed to three topics: First, proactive strategies to avoid environmental degradation beforehand by modeling long-term impact of resource use decisions. Uncertainties associated with different potential resource use decisions that are difficult to quantify may be approached by safe minimum standards to forestall irreversible damages (Bishop 1978; Margolis and Naevdal 2008). Second, monitoring and evaluation schemes are required to document impact and progress of measures and actions implemented in real-world situations over the long term against clear objectives and measurable targets. For instance, the applicability and effectiveness of an approach or technology can be evaluated by monitoring the maturity level: from the idea to the full deployment of the final product, mechanism or instrument. The database Innovation Seeds provided a practice example with its internal maturity evaluation system that is used to organize environmental-friendly approaches or technologies. Third, research is needed that provides evidence on long-term added value of compensations that would not have occurred without taken actions. Such research comprises long-term returns from offsets gains secured by protecting species or habitats at risk of loss, and restoring degraded or destroyed ecosystems to an acceptable state of ecosystem resilience and performance. Examples from database entries showed that ensuring the additionality of compensation and revealing its benefits positively impacted the reputation of compensations while increasing the societal relevance and economic attractiveness of investing in nature (Porras et al. 2008b; Chapeyama 2012).

4.2 Mechanism for more efficient knowledge exploitation

In addition to the five above mentioned criteria, we found evidence that disciplinary silos also prevail in databases of ES. All databases used individual standardization concepts to organize data entries. Moreover, a common reference collection was missing and only a few well-established standard protocols for archiving and retrieval of information across databases existed. These factors made the data discovery, complementation of information across different databases and processing of information for decision-advice an ambitious and highly labor intensive task.

Ontologies linked into a common cyber-infrastructure hold promise to improve data visibility and accessibility, and enable automation processes to support synthetic research and decision advice (Berners-Lee et al. 2001). Ontologies are explicit formal specifications of terms in a domain and relations among them (Gruber and Olsen 1994). Based upon ontologies common meanings of data entries can be discovered across databases via taxonomies and logical inference rules are introduced that enable automated reasoning (Madin et al. 2008). Therefore, adding ontologies to databases provides benefits by streamlining the accuracy of queries, also for more complex questions whose answers do not reside in a single database. Ontologies even enable users to access and integrate databases which implicitly contain information on ES, i.e. consultation and utilization of available data from sources that not literally refer to ES, but contain information that can be linked to estimate the value of nature, its benefits to human and what a good life encompasses. Additionally considering those databases (see IPBES (2016) for a list of databases) would facilitate interdisciplinary research and would reach user groups beyond ES community, such as actors in charge of the Strategic Plan for Biodiversity 2011-2020 (UNEP 2010) and the Sustainable Development Goals (Geijzendorffer et al. 2017).

Developing and adding an ontology to ES databases has not to start from scratch. There are several efforts within science community to build ontologies that are useful for describing data (Madin et al. 2007; Peterseil et al. 2009). Most of them, however, are domain-specific representing a thematic limited scope and community of relevance, therefore, increasing the risk of a next-generation disciplinary compartmentalized science. Nevertheless, initiatives such as Ontolog (2018), OGC Working Group (2018), SONet (2018), ESIP (2018), Rueda et al. (2009), and INSPIRE from European Comission (2018) provide mechanisms for collaboration and facilitate the development and curation of domain-crossing ES ontologies.

Within this article an empirically based taxonomy of knowledge demand on ES is identified demonstrating that an ontological approach can also be applied to specify and explore information demand for decision-making. By clarifying the terms of discourse in ES science and decision-making,

and annotating available data with those terms based on ontologies scientific knowledge can be aligned with needs of decision-makers. For instance, the five key criteria to mainstream ES information into decision-making could be used as generic framework to steer the development of a demand-driven ontology that takes full advantage of the growing ES databases on the Internet. Such an ontology is a promising approach to set up a common vocabulary, to facilitate information sharing, and ultimately contributes to bridge the science policy gap. By agreeing upon a common vocabulary and determining criteria (entry points) to incorporate information into decision-making critical steps could be made towards the establishment of a reference collection that sets standards in ES community over the long term.

The here determined taxonomy of information demand on ES and the derived key criteria might be criticized for their representativeness, because they rest upon a review of literature rather than surveying information demand requested from decision-makers directly. Although study donors and researchers have their own views on the best use of ES information in many application contexts and assertions for information requirement of mainstreaming ES are stated, they not necessarily represent the actual information demand of practitioners and decision makers. Experts suggest the engaging of decision makers directly to determine information needs, also for systematic reviews (Haddaway et al. 2017). Considering the time and resource restrictions for this work the systematic review of literature, including governmental and policy documents as well as surveys of stakeholder demand (see S1 Table), was a pragmatic approach to get a broad overview of information demand of decision makers.

4.3. Transferability of knowledge from databases

Learning from ES databases and transferring their information to set out a roadmap for reforms of decision-making assumes that information contained in databases is equally applicable and effective in another setting. However, transferring information to solve similar problems in another context needs to take account of environmental surroundings including case-specific peculiarities. For instance, socio-economic and political situations vary considerably between developed and developing countries. Since we found a lack of information in the reviewed ES databases for society's poorest nations (Fig 1) the transferability of knowledge to developing countries should be treated carefully. However, the databases provided a few examples on transfer challenges in developing countries regarding methodological, practical, and policy issues (Barton et al. 1997; UNEP 1999; Christie et al. 2012). For accurately transferring information, users need as much detail as possible about a research situation in order to adapt the information to their own circumstances. In databases contextual and tacit knowledge about processes and socio-cultural differences are often

condensed and lacking in detail for applications elsewhere. However, it is impossible to provide an absolutely complete description of a situation, and missing details lead to transfer information to a situation that is not entirely similar to the original one.

There is a substantial merit in conducting more detailed examinations of the transferability of knowledge in ES databases. Research is needed on whether various components of database information (e.g. descriptions on indicator and methods) can be differentiated according to the extent to which each of these can be transferred. This might for example draw on the work conducted by OECD (2001), which suggested levels of transferability for components of local development practices. Related to this, research on the process of transfer of components of database information would be instructive, also in cases where examples have been transferred between dissimilar situations. The latter could stimulate the development of protocols regarding how information transfer should proceed when a condition is not fully met (Schmidt et al. 2016).

In general, evaluation schemes are needed to assess how information from databases is actually used in decision-making. Further work on that topic would provide insights into relationships between scale of decision-making and the type of required information. This might build on efforts within IPBES (2016), which proposed possible formats for assessing data needs at multiple scales.

Moreover, research is needed on how ES databases can be used beyond their original purpose in different settings. Although we showed which information from ES databases can be used to inform different policy instruments, this analysis represents a limited scope of application contexts which could be extended by others. By including other application contexts further analysis could be carried out to test the extent to which there are common principles across information demand on ES for decision-making. This kind of analysis could complement the five criteria for documentation of knowledge on ES and verify whether the criteria are applicable and desirable for other application contexts, too.

5 Conclusion

Effective mainstreaming of ES information into decision-making requires the consideration of information needs of a specific application context, which are best defined by practitioners and decision makers. Matching information supply from 29 ES databases with information demand from specific application contexts, exemplified in this study for six policy instruments, provided a useful contribution to discussion on standards that define reporting requirements. Reaching consensus on

standards codifying agreement on best practices will accelerate the incorporation of ES information in decision-making (Polasky et al. 2015).

Our analysis showed that databases provided information for most of the policy instruments. None of the databases were designed exclusively for the policy instruments and focused on specific parts only. This overlap in information supply and demand showcased that relevant information for decision-making was contained in ES databases, but difficult to discover and process. Difficulties stemmed from limited interoperability of databases and missing semantic links between heterogeneous terms and concepts used in databases and required in decision making. Within this analysis we suggested important steps towards an optimized knowledge exploitation. First basic step is to determine taxonomies for information supply from databases and information demand from decision-makers and clarify relationships between different terms and concepts. Second, adding knowledge representation systems such as ontologies that introduce logical inference rules as prerequisite for automated reasoning and ease of information access. These two steps help to bring together independently developed ideas and needs from across science and practice, and facilitate communication and collaboration even when the commonality of concepts has not (yet) led to a commonality of terms.

Synthesizing findings of this study showed that there were common principles across indicator of information demand representing priority areas to formalize standards for the documentation of knowledge on ES. We found five priority areas which could be used to design an ontology that tailors the ES framework to decision-making realities. An ontology does not have to be developed from the scratch – mostly domain-specific examples exist (Madin et al. 2008) – but need to be extended and interconnected based on semantics from the integrative ES concept and common principles for information demand. Such an ontology may provide an enabling framework for the establishment of reference collections that set standards for ES in specific application contexts over the long term. An open access, reference collection can be a powerful force for inclusion of standard-setting organizations and may accelerate progress in public endorsement. There are examples showing how reference collections from other fields remove barriers to participation across all education backgrounds and all ages (NSB 2005).

By connecting databases with ontologies also data sources could be discovered and integrated which implicitly contain information on ES. Such an approach helps to make further steps towards interlinking information for transdisciplinary work and contributes to avoid the risk of a next-generation disciplinary compartmentalization of ES research, as shown in the analysis. Knowledge

perceived as unbiased and representative of multiple points of view is of paramount importance for policy impact (Posner et al. 2016).

Challenges remain in the transferability of information from ES databases. By collating and condensing knowledge, databases often neglect contextual information about the study processes and socio-cultural conditions. Databases are also limited regarding geographic representativeness, highlighting major gaps in the application of the ES framework in society's poorest nations. Knowledge transferability from databases should be considered with caution and requires further research efforts. Evaluation schemes are needed that i) provide insights into various components of database information according to the extent these can be transferred and ii) assess how information from databases is actually used for decision advice.

Acknowledgements

We are grateful to Randall Bruins, Bradley J. Cardinale, Francesco de Bello, Richard Huber, Pat Johnston, Lucy Keniger, Judy Kildow, Jean-Michel Lariviere, Shuang Liu, Sander van der Ploeg, Petteri Vihervaara, Susan Yee and many others for providing access to the databases for this analysis. Also we would like to thank Cyrus Philbrick from Earth Economics for editing the text. The work was funded by the grant 308393 'Operational Potential of Ecosystem Research Applications – OPERAs' (7th framework programme of the European Commission) and by grant 01LL0901A 'Global Assessment of Land Use Dynamics, Greenhouse Gas Emissions and Ecosystem Services – GLUES' (German Federal Ministry of Education and Research) under the Helmholtz Programme 'Terrestrial Environmental Research'.

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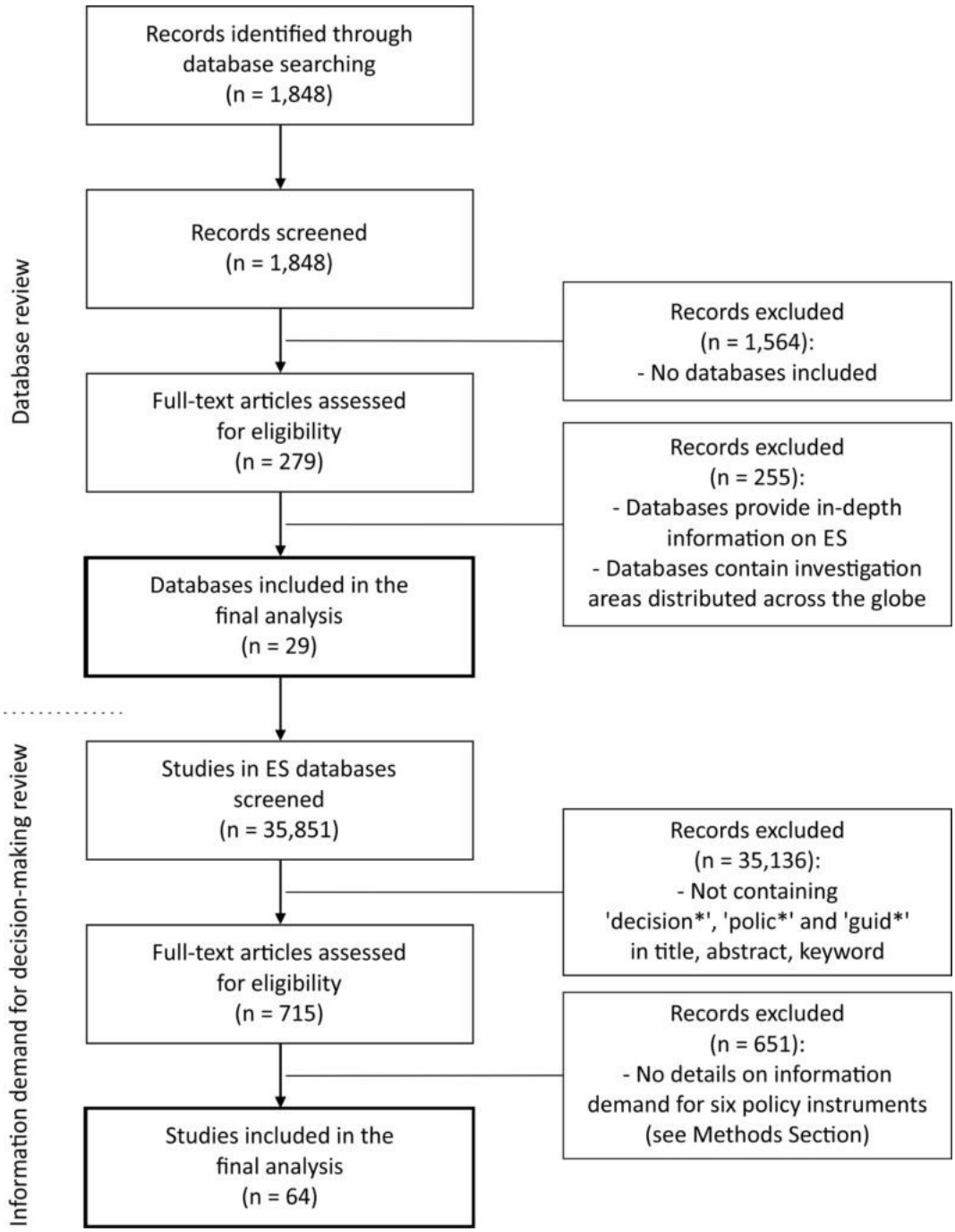
Supplemental Information



S1 Fig. Flow diagram for systematic review. The diagram shows different phases of the review process to identify ES databases and literature addressing information requirements for decision-making based on ES.

S1 Table. References of review on information demand. The reference list shows literature that defines information demand or proposes guidance on how to implement ES into decision-making. Based on the contents of references categories for information demand were identified and assigned to six policy instruments.

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S2 Table. Design and impact of databases – indicator description.

Indicator name	Description
Functional type	This indicator distinguishes between three functional types of databases defined by the National Science Board of the National Science Foundation of United States (NSB 2005). According to purpose, design, funding, and maintenance databases can be divided into 'research', 'resource' and 'reference collections'.
Data organization	The type of data organization and storage. The following factor levels were differentiated: 'tabular' or 'relational'. In a tabular design data entries are stored in cells, with multiple cells represented in a system of rows and columns. A relational data organization uses multiple tables which are interlinked via logical connection to allow interactions between these tables.
Search options	This indicator distinguishes between different abilities provided in databases to narrow queries by different filters. The filters used to retrieve data are: 'categorical' (queries by selecting predefined options of different categories representing database entries), 'free text' (free text search that allows users to input keywords or numbers), and 'geographical' (geographic queries by interactive maps). The filter 'All' includes categorical, free text and geographical.
Data updates	This indicator measures if new or more accurate information is incorporated in the databases. We classified 'ongoing data collection' and 'finalized'.
Add-ons	The type of software used to increase the capability of a database. The factor levels used are: 'access to methods and studies only', 'analytical and visual software', and 'none'. 'Access to methods and studies only' is less an add-on per se rather indicates hyperlinks to other software that stores and manages the original methods and studies analyzed in databases. 'Analytical and visual software' refer to programs that enable users to customize applications, for instance statistical and spatial analysis via geographic information system application programming interface (GIS API).
Policy uptake	The indicator measures if databases were applied within a decision-making context such as political agendas. For this indicator we directly contacted the developers of the databases.

S3 Table. Overview of policy instruments and indicators of information demand. In the table are six policy instruments listed that contain descriptions and examples for 93 indicators of information demand. Examples relate to column headers or entries of the databases considered for the analysis.

Name	Description	Example from databases

1) Policy instrument: Extending accounting systems through nature-based indicators		
Decision	Formal and informal rules by which human actions are framed and operationalized. This includes decision mechanisms in policies, strategies, responses, and interventions to change human behavior or ecosystem characteristics (Millennium Ecosystem Assessment 2003). Component of the integrative framework defined by (Daily et al. 2009) showing how ES can be integrated into decision-making.	IIED Watershed markets: 'Legislation issues' of different nations and how they are related to the establishment of PES, and 'Main policy lessons' learnt from PES projects.
Action & scenarios	Human actions or modelled scenarios to address specific issues, needs, opportunities, or problems in ecosystem governance and management. They include legal, economic, social and behavioral as well as technological responses; and may operate at local, regional, or international level and at various time scales (Millennium Ecosystem Assessment 2005a, b). Component of the integrative framework defined by (Daily et al. 2009) showing how ES can be integrated into decision-making.	ReefLink Database: 'Responses' representing actions taken by groups or individuals in society and government to prevent, compensate, ameliorate or adapt to changes in ES or their perceived values.
Ecosystem	The state of the ecosystem is the condition, in terms of quantity and quality, of the abiotic and biotic components including physical, chemical, and biological variables. Attributes of ecological structure or process that influence the quantity and/or quality of ES, but do not themselves qualify as final ES; because they are not directly enjoyed, consumed or used (Daily et al. 2009). Component of the integrative framework defined by (Daily et al. 2009) showing how ES can be integrated into decision-making.	ReefLink Database: 'Physical & Chemical Environment' and anthropogenic '(Contact) Uses' which directly affect the survival, growth, & reproduction of 'Reef Life'.
Biophysical models	Approaches and techniques to measure abiotic and biotic components of ecosystems, their interdependences, and dynamic changes to develop ecological production functions that translate the structure and function of ecosystems into the provision of important services (Daily et al. 2009; Peh et al. 2013). Component of the integrative framework defined by (Daily et al. 2009) showing how ES can be integrated into decision-making.	ValuES Methods: Descriptions on functionality and requirements of methods for assessing ES.
Ecosystem services	Components of nature that can be directly enjoyed, consumed or used to yield human well-being. The following four common classes are distinguished: provisioning, regulating, cultural, and supporting services (TEEB 2010). Component of the integrative framework defined by (Daily et al. 2009) showing how ES can be integrated into decision-making.	ESML: 'Ecosystem service' defined as outputs of ecological functions or processes that directly or indirectly contribute to social welfare, or have the potential to do so in the future. Ecological models can be selected according to two different classification systems (CICES, NESCS).
Economic & cultural models	Monetary and non-monetary approaches to measure ES supply as an input for human health and security, and other	Keniger et al., 2012: Overview of 'Research Design' and 'Correlation Or Experimental' approaches for the analysis of benefits of

	socio-cultural benefits (Bagstad et al. 2013; IPBES 2016). Component of the integrative framework defined by (Daily et al. 2009) showing how ES can be integrated into decision-making.	interacting with nature. ESVD: List of 'Valuation Methods' indicating how the monetary value was estimated.
Valuation	Indicators of valuation reflect the magnitude of change in social and economic welfare by determining quantity of service use, human preferences for the service, etc. (IPBES 2016). Depending on the valuation purpose ES values may be conveyed in ecological (Odum and Odum 2000), socio-cultural (Kumar and Kumar 2008) or economic metrics (Liu et al. 2010) based on ecological sustainability, equity and cultural perception or on efficiency and cost-effectiveness. Component of the integrative framework defined by (Daily et al. 2009) showing how ES can be integrated into decision-making.	EVRI: Economic valuation of ES such as 'Estimated (Service Flow) Values' (EVRI). ESML: Ecological model variable typology to position model variables, e.g. 'Social Benefit Indicator' and 'Monetary Value of Social Benefit'.
Information & influence	Approaches for outreach and capacity building that make use of results provided by biophysical and economic and cultural models to support decision-making and institutional change (LWEC 2012). Component of the integrative framework defined by (Daily et al. 2009) showing how ES can be integrated into decision-making.	IPBES Catalogue: 'Assessment outputs' summarizes and links different types of outreach activities used to disseminate results of ES assessments.
Institution	Context of institutions and their effects on human interaction shaping ecosystems change. Institutions operate at various levels and scales, such as global, regional, and local levels and on the basis of ethics, values, and attitudes usually ascribed to larger cultural contexts (Millennium Ecosystem Assessment 2005a; Young 2008). Component of the integrative framework defined by (Daily et al. 2009) showing how ES can be integrated into decision-making.	Goldman et al., 2008: 'What institutional challenges were faced in setting up the project?' summarizes lessons learnt from ES projects.
Incentives	Approaches that examine, reform and develop inducements that motivate changes in decisions and behavior (Tversky and Kahneman 1981)., e.g. monetary rewards, legal sanctions or approval by peers. Component of the integrative framework defined by (Daily et al. 2009) showing how ES can be integrated into decision-making.	ReefLink Database: 'Funding and incentives' summarizing budgetary decisions by public administration to improve the effectiveness of decisions through daily operations, research, monitoring, and outreach.
Trait concept for regulating & cultural services	Species traits describe characteristics of species that affect ecosystem processes and population dynamics across space and time. They seem to play an important role for the provision of ES and are highly relevant for conservation planning (de Bello et al. 2010).	De Bello et al., 2010: 'Relationships' estimates relationships between trait components of plants, vertebrates, and invertebrates; and ES.
Biophysical quantification	Documentation of biophysical values for ES indicating their diversity (García and Martínez 2012), quantity (Reyers et al. 2009), quality (Russo et al. 2017) or alterations of ES (Richter and Thomas	ESML: 'Variable Values' quantify the numerical values for outputs and variables used in ecological models.

	2007).	
Monetary valued	Documentation of monetary values for ES quantitatively (de Groot et al. 2012) or qualitatively by string variables (e.g. yes/no entries). This includes indicators of costs that emerge due to transition to more ES-friendly activities or products, such as transition costs (van Zyl 2014).	EVRI: 'Estimated (Service Flow) Values' from economic valuation studies in protected areas. PESD: 'Transaction Amount (USD$)' to enable PES projects in developing countries.
Metrics	Unit of measurement by which ES are assessed (Kontogianni et al. 2010).	ESVD: 'Unit' encompasses units and currencies of monetary values of ES , e.g. US-Dollar per hectare and year.
Identification of critical thresholds	Quantification of non-linear transitions in the functioning of coupled human-environmental systems affecting ecosystems accretion, productivity and resilience (Lenton et al. 2008; McClanahan et al. 2011).	No information provided, only indirectly indicated, e.g. in ReefLink Database: McClanahan et al. (2011).
Time frames	Temporal extent and resolution of state or flow of ES, payments for ES, or other types of analysis (Gibson et al. 2000).	ESML: 'EM Temporal extent' describes the temporal boundaries of the ecological system modeled, which are typically the earliest and latest dates represented by the data in the modeling application.
Static investigation	Analysis of ES for a specific point in time (Carr and Mendelsohn 2003).	BUVD: 'Methodology Comments' and 'Data Comments' explain assumptions, method type, and data used for monetary valuation of ES.
Dynamic investigation	Analysis of variations of ES as a function of time (Holland et al. 2011).	BUVD: 'Methodology Comments' and 'Data Comments' explain assumptions, method type and data used for monetary valuation of ES.
Prioritized ES	Evaluation and ranking of ES, methods, results, etc., in accordance to their importance or urgency for a particular purpose (Klein et al. 2010).	No column headers refer to the indicator, only in titles of references, e.g. in ReefLink Database: Klein et al. (2010).
Consumption quantified	Numerical valuation of the amount of ES actually used, enjoyed or consumed in a particular time (Stiglitz et al. 2009).	EVRI: Combination of 'Economic Measure(s)' and 'Estimated (Service Flow) Values' that explain the measure of the payment or provide monetary values of ES, respectively.
Trade-offs quantified	Numeric valuation of interactions between ES that involve diminishing or losing quality or quantity of a set of ES in return for gains in other ES (Millennium Ecosystem Assessment 2005c; Haase et al. 2012).	EVRI: Combination of 'Valuation Equation/Function Information' and 'Estimated (Service Flow) Values' which explain the valuation approach used and provide monetary values of ES, respectively.
Driver	Identification of biophysical or socio-economic factors that exert pressure on the environment and lead to changes in ecosystem conditions such as population growth or climate change (Nelson et al. 2005).	ReefLink Database: 'Socio-Economic Drivers' include the sectors that fulfill human needs for 'Food & Raw Materials', 'Water', 'Shelter', 'Health', 'Culture', and 'Security'.
Location of ES	Name of geographic location or description of spatial extent and resolution of investigation area of ES (Gibson et al. 2000; Hein et al. 2006).	ESML: 'Spatial Extent Name' or 'Latitude/Longitude, Granularity (Grain Type and Size)' explain the spatial application areas of ecological models.
Payer of costs	Identification of people that faces the costs of losing ES (not necessarily ES recipients) (TEEB 2011).	Goldman et al., 2008: 'Who pays/who receives payment' explain social groups that pay or receive payment for ES.
Location of costs	Spatial allocation of costs of maintaining or losing ES (TEEB 2011).	EVRI: Combination of 'Location' and 'Estimated (Service Flow) Values' which explain the study area and cost of ES, respectively.
Time of costs	Temporal allocation of costs of maintaining	EVRI: Combination of 'Year(s) of Data' and

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	or losing ES (TEEB 2011).	'Estimated (Service Flow) Values' which explain the study time respectively cost of ES.
Long-term impact	Measurement over long time horizon that exceeds 10 years to estimate the consequences of interventions (Müller et al. 2010).	EVRI: 'Year(s) of Data' indicates the time span of input data that was used for the valuation of ES in monetary terms.
Transdisciplinary	A integrative, reflexive, scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by integrating knowledge from various scientific and societal bodies (Jahn et al. 2012).	IIED Watershed Markets: 'Analysis of Costs and Benefits (Economic, Environmental, Social)' explains analysis of and actions aiming at costs and benefits of PES from different disciplinary perspectives.
Stakeholder engagement	Indication whether stakeholder are involved within the study (yes/no). Stakeholder are any group, directly or indirectly affected by a study, as well as those who may have interests in a study and/or the ability to influence its outcome (Durham et al. 2014).	IPBES Catalogue: 'Key stakeholder groups engaged' explains which stakeholder groups are involved in the ES assessment.
Level of decision makers	Documentation of level of decision makers committed to ES study. Levels are hierarchical structured based on institutional scale and reflect the different tiers at which decisions on the utilization of capital, labor and natural resources are taken (Hein et al. 2006). Institutional levels reach from individuals and households to international level.	IIED Watershed Markets: 'Stakeholder (Supply, Demand, Intermediary, Facilitator)' explains and differentiate stakeholder groups and their functions in PES.
Sector of decision makers	Description of socio-economic sector of decision makers committed to ES study. A sector is a distinct part of the society that reflects similar socio-economic situations (Martín-López et al. 2017), e.g. public and private sector or agriculture, marine fisheries, water supply (Durham et al. 2014).	IIED Watershed Markets: 'Stakeholder (Supply, Demand, Intermediary, Facilitator)' explains and differentiate stakeholder groups and their functions in PES.
Process of stakeholder involvement	Description of the process used in the study to involve relevant stakeholders (AccountAbility 2008). Stakeholder are any group, directly or indirectly affected by a study, as well as those who may have interests in a study and/or the ability to influence its outcome (Durham et al. 2014).	IIED Watershed Markets: 'Stakeholder (Supply, Demand, Intermediary, Facilitator)' and 'Terms of payment' explains and differentiate stakeholder groups and how they are involved in PES.
Uncertainty	Documentation of quality of available evidence (Spiegelhalter and Riesch 2011).	ESML: 'Model uncertainty analysis performed' states whether propagation of uncertainties in model parameters and model structure of ecological models were examined.
Problem	Initial trigger for examination, e.g. how to measure ES, pollution increase, land use conflicts, etc.(TEEB 2011; European Commission 2015).	TEEB Cases: 'What is the problem?' explains the socio-ecological circumstances, drivers, and pressures of a valuation study.
Objective	Aim, goal or target to achieve by conducting a study. Objectives can link the analysis of the problem with options for the policy response (TEEB 2011; European Commission 2015).	Keniger et al., 2013: 'Purpose/Objectives' of studies examining benefits of human-nature interactions.
Policy options	Description of alternative interventions that show how ES and biodiversity can be managed (TEEB 2011; European	ESML: 'EM scenario drivers' are the rationale behind different forcing conditions (such as alternative management strategies) that

	Commission 2015).	form the basis of modeled scenarios.
Impact real world	Documentation of economic, social, and/or environmental alterations due to realized policy option. Impact based on evidence from real world changes (TEEB 2011; European Commission 2015).	IIED Watershed Markets: 'Analysis of Costs and Benefits (Economic, Environmental, Social)' explains analysis of and impacts on costs and benefits of implemented PES mechanisms from different disciplinary perspectives.
Impact modeled	Documentation of economic, social, and/or environmental alterations due to policy options. Impacts are modeled by simple heuristic approaches or complex simulation tools (TEEB 2011; European Commission 2015).	ESML: Combination of 'EM scenario drivers' and 'Variable values' provide alternative management strategies used in ecological models and their results for a model run.
Favorable option	Documentation of process for balancing and prioritization of policy interventions, including the final intervention agreed upon (TEEB 2011; European Commission 2015).	EVRI: 'Estimated (Service Flow) Values' encompasses monetary values of ES for different policy options that are used in benefit-cost analysis for decision support.
Monitoring	Monitoring is a continuous and systematic process of data collection about an implemented policy intervention. It generates information for future evaluation and impact assessments. (TEEB 2011; European Commission 2015).	Goldman et al., 2008: 'Performance monitoring' explains monitoring approaches for ES, biodiversity and other socio-economic issues.
Evaluation of impact of project	Evaluation of economic, social, and/or environmental alterations due to interventions from ES project, and whether an intervention has achieved its objectives (TEEB 2011; European Commission 2015).	Goldman et al., 2008: 'Summary' of impacts from ES projects, e.g. number of acres restored, changes in flood risk, jobs created, or people educated.
Local scale	Number of studies conducted in an investigation area relating to a spatial extent of less than 10.000sqkm.	ESVD: 'Service area' is the quantified investigation area considered for monetary valuation of ES.
Environmental policies & regulations mentioned	Consideration of or commitments to laws, regulations and other policy mechanisms that manage effects of anthropogenic activities on nature and its natural resources (yes/no) (European Commission 2017b).	IIED Watershed Markets: 'Legislation Issues' explain legal provisions related to PES for watersheds.
Resource management policy (-ies) established	Documentation of new established principles, mechanisms, programs or organizations that manage effects of anthropogenic activities on nature and its natural resources based on ES information (yes/no) (European Commission 2017b).	IIED Watershed Markets: Combination of 'Market design' and 'Legislation Issues' explain different PES payment mechanisms established and how they are linked to legal conditions.
Global scale	Number of studies conducted in an investigation area relating to a spatial extent of greater than 20 million sqkm.	ESVD: 'Service area' is the quantified investigation area considered for monetary valuation of ES.
Poor regions	Number of studies conducted in areas of low human development. These areas are defined by a Human Development Index of less than 0.55 (UNDP 2014).	EVRI: 'Country (ies)' encompasses the name of a country (ies) in which a monetary valuation study (ies) took place.
Expenditure for environmental protection	Documentation of actual or potential expenditure for environmental protection or management and mitigation of degradation.	EVRI: Combination of 'Valuation Technique(s)' and 'Estimated (Service Flow) Values' provide monetary values for the costs of replacing or restoring the ES provided by the environmental resource (e.g. replacement costs).
Capacity building for trade-off assessment	Documentation of the development and strengthening of human and institutional resources for assessing and documenting ES state, value, and trade-offs (Bonner et	IPBES Catalogue: 'Capacity building needs identified during the assessment' and 'Actions taken by the assessment to build capacity' include educational measures for

	al. 2012; IPBES 2016).	trade-off assessment.
Capacity building for policy assessment system	Documentation of the development and strengthening of human and institutional resources for advanced understanding of management options and how to establish and utilize an accepted policy assessment system in place (IPBES 2016).	IPBES Catalogue: 'Capacity building needs identified during the assessment' and 'Actions taken by the assessment to build capacity' include educational measures for policy assessment.
Primary studies	Investigation and collection of first-hand, empirical data (yes/no).	Seppelt et al. 2011: 'Data source' indicates primary analysis of ES.
Guidance benefit transfer	Documentation of tools or processes to develop and strengthen human and institutional resources for the application of benefit transfer techniques (TEEB 2011).	ValueES Methods: 'Monetary valuation methods' provides a factsheet on the tool benefit transfer method and introduces: 'How, when and where can the method be applied?'.
Outreach	Information on material in simplified form to explain analysis and results of research to different laypersons and stakeholders (LWEC 2012), e.g. leaflets, newsletters, videos, webinars.	IPBES Catalogue: 'Assessment outputs' summarizes and links different types of outreach activities used to disseminate results of ES assessments.
2) Rewarding benefits through payments and markets		
PES considered	Voluntary transaction for specific ES, or a form of land use likely to secure that ES, through a continual series of conditional payments for ES buyer and provider/seller (Jack et al. 2008; FAO 2011).	IIED Watershed Markets: Description of 'Market Design' of different PES schemes by providing information on 'Services' and 'Commodity', 'Payment Mechanism', 'Terms of Payment', and 'Funds Involved'.
Form of PES	Payment vehicle through which beneficiaries of the ES reward providers, e.g. financially or in-kind (Porras et al. 2008).	IIED Watershed Markets: Description of 'Market Design' of different PES schemes by providing information on 'Services' and 'Commodity', 'Payment Mechanism', 'Terms of Payment', and 'Funds Involved'.
Condition of PES	Terms of payment under which beneficiaries of the ES reward providers (Porras et al. 2008).	IIED Watershed Markets: Description of 'Market Design' of different PES schemes by providing information on 'Services' and 'Commodity', 'Payment Mechanism', 'Terms of Payment', and 'Funds Involved'.
Spatial analysis economic costs	Spatial-explicit appraisal of costs of maintaining or losing ES in monetary terms (Wunscher et al. 2008; Abson et al. 2014).	ESML: Combination of 'EM spatial distribution' and 'Variable values' explain whether or not model calculations are carried out for multiple, spatially differentiated sectors, thus allowing the value of one or more model parameters to be varied over the spatial domain, and provide results for a model run.
Spatial analysis economic benefits	Spatial-explicit appraisal of ES benefits for human well-being in monetary terms (Remme et al. 2015).	ESML: Combination of 'EM spatial distribution' and 'Variable values' explain whether or not model calculations are carried out for multiple, spatially differentiated sectors, thus allowing the value of one or more model parameters to be varied over the spatial domain, and provide results for a model run.
ES areas mapped	Documentation of graphical representations of areas most important for providing ES (Egoh et al. 2008; Burkhard et al. 2012).	No information provided, only indirectly indicated, e.g. in ValuES Cases: van Zyl (2014).
Provider distribution	Spatial-explicit mapping and quantification of provider of (multiple) ES (Schulp et al. 2014).	ESML: Combination of 'Abstract' and 'EM spatial distribution' explain whether or not providers and beneficiaries are spatially-explicit considered in ecological models.

Beneficiaries distribution	Spatial-explicit mapping and quantification of beneficiaries of (multiple) ES (Schirpke et al. 2014).	ESML: Combination of 'Abstract' and 'EM spatial distribution' explain whether or not providers and beneficiaries are spatially-explicit considered in ecological models.
Specific groups empowered	Documentation of distinct stakeholder groups – e.g. women, indigenous, young folks, etc. – and their authority or power to access, use, manage, or impair ES (Corbera and Brown 2008; Felipe-Lucia et al. 2015).	IIED Watershed Markets: Combination of 'Stakeholder (Supply, Demand, Intermediary, Facilitator)' and 'Market design (Terms of payment)' provide information on stakeholder and their role in PES schemes.
Locals in PES integrated	Engagement of local stakeholder in design and implementation of PES schemes (Porras et al. 2008). Stakeholder are any group, directly or indirectly affected by a study, as well as those who may have interests in a study and/or the ability to influence its outcome (Durham et al. 2014).	IIED Watershed Markets: Combination of 'Stakeholder (Supply, Demand, Intermediary, Facilitator)' and 'Market design (Terms of payment)' provide information on stakeholder and their role in PES schemes.
Traditional local knowledge	Identification and/or utilization of indigenous and local knowledge on ES in valuations, assessments, and interventions (Kovács and Pataki 2016).	IPBES Catalogue: 'Incorporation of scientific and other types of knowledge' indicates whether or not traditional knowledge of local and indigenous communities is considered in an ES assessment.
Rights for access & benefit sharing for locals	Documentation of access rights to genetic resources and approaches for sharing of benefits arising from utilization of genetic resources for local communities (UNEP 2010).	ReefLink Database: 'Health policies', 'Biomedical Research Policies' and 'Pharmaceuticals & Cosmetics' explain activities in biomedical research and development as well as sale of pharmaceuticals and cosmetics, including research funding and patent laws regarding natural biochemical from coral reefs.
Other financial policies for biodiversity-friendly activities	Practice examples concerning the (successful) implementation of tax breaks or exemptions (Shine 2005), indemnification mechanism (Anon 2008) and other financial policies that reward nature-friendly stewardship and spur green markets (Bergsma 2000; Popp 2009).	ReefLink database: 'Funding & Incentives' includes budgetary decisions by public administration to affect activities related to coral reefs.
Number of studies genetic resources	Number of studies investigating genetic material of plants, animals, microbial or other origins containing functional units of heredity of value for human benefit (UNSD 1997).	ESVD: 'ESService' and 'ESSubservice' provide information on which studies examined genepool and genetic material.
Capacity building for genetic resources	Documentation of the development and strengthening of human and institutional resources for assessment, valuation, access, and benefit sharing of genetic material of plants, animals, microbial or other origins containing functional units of heredity of value for human benefit (UNEP 2010).	IPBES Catalogue: 'Capacity building needs identified during the assessment' and 'Actions taken by the assessment to build capacity' include educational measures for assessment, valuation, access, and benefit sharing of genetic resources.
3) Reforming environmentally harmful subsidies		
Subsidies considered	Practice examples on government actions that confer an advantage on consumers or producers in order to supplement their income or lower their cost (OECD 2005).	ReefLink Database: 'Agriculture & Aquaculture: Phase Out Unwanted Subsidies' describes potential actions managers could enact to preserve reef ecosystems.
Sectors of subsidies	Socio-economic sector in which subsidies are implemented (Ulibarri et al. 1998). A sector is a distinct part of the society that reflects similar socio-economic situations (Martín-López et al. 2017), e.g. public and	ReefLink Database: 'Agriculture & Aquaculture: Phase Out Unwanted Subsidies' describes potential actions managers could enact to preserve reef ecosystems.

	private sector or agriculture, marine fisheries, water supply (Durham et al. 2014).	
Effectiveness against stated objectives	Accuracy and completeness with which implemented subsidies achieve an objective (OECD 1996; Ulibarri et al. 1998).	No column headers refer to the indicator, for instance in BUVD only in 'General Comments', 'Methodology Comments', and partly in titles of references information is provided.
Cost-efficiency	Documentation of subsidies' ratio between results achieved (outputs) and resources used (inputs) (OECD 2005).	No column headers refer to the indicator, for instance in BUVD only in 'General Comments', 'Methodology Comments', and partly in titles of references information is provided.
4) Addressing environmental degradation through regulation and pricing		
Driver with identifiable polluter	Attribution of a person (-s) or a thing (-s) that is directly or indirectly responsible for an ecologically harmful change in the environment (Pasha et al. 2012).	IIED Watershed Markets: 'Driver' and 'Stakeholders' describe local environmental problems and people involved in pollution and PES for watersheds.
Full cost recovery	Assigning full costs of ES recovery spatially explicit to recipients benefiting from the ES (TEEB 2011).	No column headers or reference found for the indicator.
(Non-) Financial incentives for ES regulation	Adjustments of incentives by introducing market-based instruments (price controlling through taxes, fines, fees (Bocker and Finger 2016) or quantity controlling through permits, quotas, licenses (Yandle and Dewees 2008)) or other compensation approaches (offsets, biodiversity banking (Carroll et al. 2012; Rosa et al. 2016)) that build upon ES-related standards.	Goldman et al., 2008 provides detailed information about 'Conservation Finance Tools' such as redistribution and creation of taxes, fees, right transfers, etc., implemented in ES projects.
Regulatory standard	Documentation of specific benchmarks that constitute commonly accepted practice upon which provisions of legislation can be enforced (BBOP 2012; Chaplin-Kramer et al. 2015).	Ecosystem Marketplace: 'Marketwatch Carbon Markets', 'Marketwatch Water Markets', and 'Marketwatch Biodiversity Markets' encompass carbon emission standards, standards under the EU Water Directive, and BBOP Standards for Biodiversity Offsets, respectively.
Sustainable techniques	Documentation of technologies that refer to efficient and effective production or distribution activities of factories, transportation, utilities, and other sectors that can lead to healthier, environmentally and economically improved practices, and can save energy, resources, and money over time (Millennium Ecosystem Assessment 2005a).	Innovation Seeds: 'Sharing good practices', 'Technical waste treatment', 'Producing energy', etc., encompass factsheets of sustainable production or distribution activities.
Compliance monitoring	Surveillance and control of illegal conduct by continuously proving and detecting standards, commitments, agreements and/or violations and infractions, respectively (TEEB 2011; Van den Bosch and Matthews 2017).	Goldman et al., 2008: 'Compliance monitoring' explains monitoring approaches for ES, biodiversity, and other socio-economic issues.
Illegal conduct	Information on environmental crime and what constitutes illegal conduct such as trade prohibitions (Barnes 1996) or legal regimes for environmental issues (European Commission 2004).	ReefLink Databases: 'Accidental & Illegal Harvest' or 'Designated Uses' contain collections of species that are protected from harvest or concise statements of a state's management objectives and expectations for each of the individual surface waters under

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		its jurisdiction, respectively.
Prosecution & penalties	Documentation of consequences of illegal conduct and approaches for the design of prosecution, arrest, conviction, and penalties (TEEB 2011).	ReefLink Database: 'Law' encompasses summaries of legal rules in the USA upon which a person accused of a criminal offense is tried in a court by the government.
International law enforcements	International cooperation on law enforcements addressing illegal cross-border activities (Bruckner 2000).	ReefLink Database: 'Collaboration & Partnering' encompasses studies of international commitments on collaboration and partnering referring to management of coral reefs.
Offsets	Documentation of specific compensating equivalences for environmental damages arising from anthropogenic actions and interventions, and/or approaches to calculate offset requirements (Pilgrim et al. 2013). Examples for equivalence are distinguished between protection and conservation offsets (Rosa et al. 2016), and can involve the same kind of habitat or species (like-for-like); different kinds of habitats and species of equal or higher importance; financial compensations through conditional payments for conservation (Zabel and Holm-MÜLler 2008) or traded offset credits (Sedjo and Marland 2003).	Ecosystem Marketplace: 'Marketwatch Carbon Markets', 'Marketwatch Water Markets' and 'Marketwatch Biodiversity Markets' explain offsets used in carbon, water and biodiversity markets.
5) Regulating use through protected areas and recognition of their values		
Protected areas considered	Consideration of any area of the terrestrial or aquatic environment that has been reserved by federal, state, tribal, territorial, or local laws or regulations to provide lasting protection for part or all of the natural and cultural resources therein (NOAA 2000; Gray and Campbell 2009; Laurans et al. 2013).	ESVD: 'Protected Status' contains information on the level of protection of the study area.
Establishment of new protected areas	Documentation of approaches to design and establish a geographically defined area, which is designated or regulated and managed to achieve the long term conservation of nature with associated ES (Sanchirico and Wilen 2001).	No column headers refer to the indicator, only in titles of references, e.g. in ReefLink Database: (Hall-Spencer et al. 2009).
Regulatory mechanism for costs & benefits	Documentation of policies or mechanisms for equitable sharing of benefits and costs arising from protected areas (Dixon and Sherman 1990; TEEB 2011). Costs of protection and earning potentials from non-protection choices are often short-term and spatial concentrated while benefits are often long-term, broadly disbursed and non-market.	No column headers refer to the indicator, only in titles of references, e.g. in NOEP Non-Market: (Dharmaratne et al. 2000).
Funding instruments	Details on financial resources for the implementation, maintenance, and management of protected areas (TEEB 2011).	IIED Watershed Markets: 'Market Design (Funds Involved)' explains details on funds applied for payment for watershed projects.
Win-win situations identified	Identification of synergies in national and international policy commitments to create win-win solutions for environmental conservation and socio-economic co-benefits, e.g. role of habitat protection for recovery of species and their effect on food	No column headers refer to the indicator, only in titles of references, e.g. in ReefLink Database: (Gjertsen 2005).

	security (Roberts et al. 2001).	
Engagement of locals in protected areas	Consideration and involvement of local stakeholder in the design, implementation, and/or management of protected areas (Camargo et al. 2009). Stakeholder are any group, directly or indirectly affected by a study, as well as those who may have interests in a study and/or the ability to influence its outcome (Durham et al. 2014).	IIED Watershed Markets: 'Stakeholder (Supply, Demand, Intermediary, Facilitator)' explains and differentiates stakeholder groups and their functions in PES in protected areas.
6) Direct public investment in ecological infrastructure and restoration		
Direct public investment	Financial resources that a government spends directly for creating, restoring, or conserving a network of interconnected structural elements and functions in the landscape, e.g. investing public funds in natural capital for reduction of environmental risks (UNFCCC 2016) or restoration of public ES with returns realized only over the long term (Liu et al. 2008).	PESD: 'Transaction Amount (USD$)' encompasses different financial resources, including public payment schemes, to enable PES projects in developing countries.
Restoration	Provision of information on restoration. Restoration in accordance to Aronson et al. (2007) includes the replenishment of natural capital stocks, recovering of resilient and self-sustaining ecosystems as well as the improvement of human welfare on different scales.	ReefLink Database: 'Wetland And Reef Restoration', 'Ecosystem Monitoring And Restoration', etc., describe responses to directly alter the conditions of reef ecosystems.
Needs for adaption	Expected needs for investment in adaption to natural or social crises and catastrophes (Landry et al. 2011; Hochrainer-Stigler et al. 2014). Also methods to identify investment opportunities are considered, e.g. the Resource Investment Optimization System (RIOS) that supports cost-effective investments in watershed services (Vogl et al. 2016).	TEEB Cases: 'What was needed to solve the problem in terms of data, resources and capacity?' and 'What was necessary for developing the instrument?' explain which inputs were required to find more sustainable solutions for the management of ecosystems.
Proactive strategies used	Application of proactive strategies, i.e. anticipatory, self-initiated behavior, acting, or investigation intervening in advance of a situation that is most likely to happen in future, for instance, prevention of natural hazards due to climate change (Innocenti and Albrito 2011) or the prevention of a hydropower-dam project to preserve natural assets (Reid 1999; Wittich et al. 2014).	BUVD: 'Method Description' of economic valuation studies includes approaches of averting behavior.
Recycling	Documentation of loop processes in which waste is seen as input and the notion of undesirable by-products is eliminated for a more efficient use of limited resources, e.g. straw waste recycling in a rice-wheat rotation farmland (Xuesong et al. 2011) or the European action plan for implementation of a circular economy (European Commission 2017a).	EVCBN: 'Waste and Recycling' contains summaries of economic studies on waste and recycling issues.
Number of studies dealing with extreme events	Number of studies investigating prevention and moderation of natural hazards or extreme weather events such as droughts, fire, avalanches, landslides, tsunamis,	ReefLink Database: 'Storms & Hurricanes' provide studies of periodic events of high precipitation, winds, wave action, and flooding that can potentially cause damage

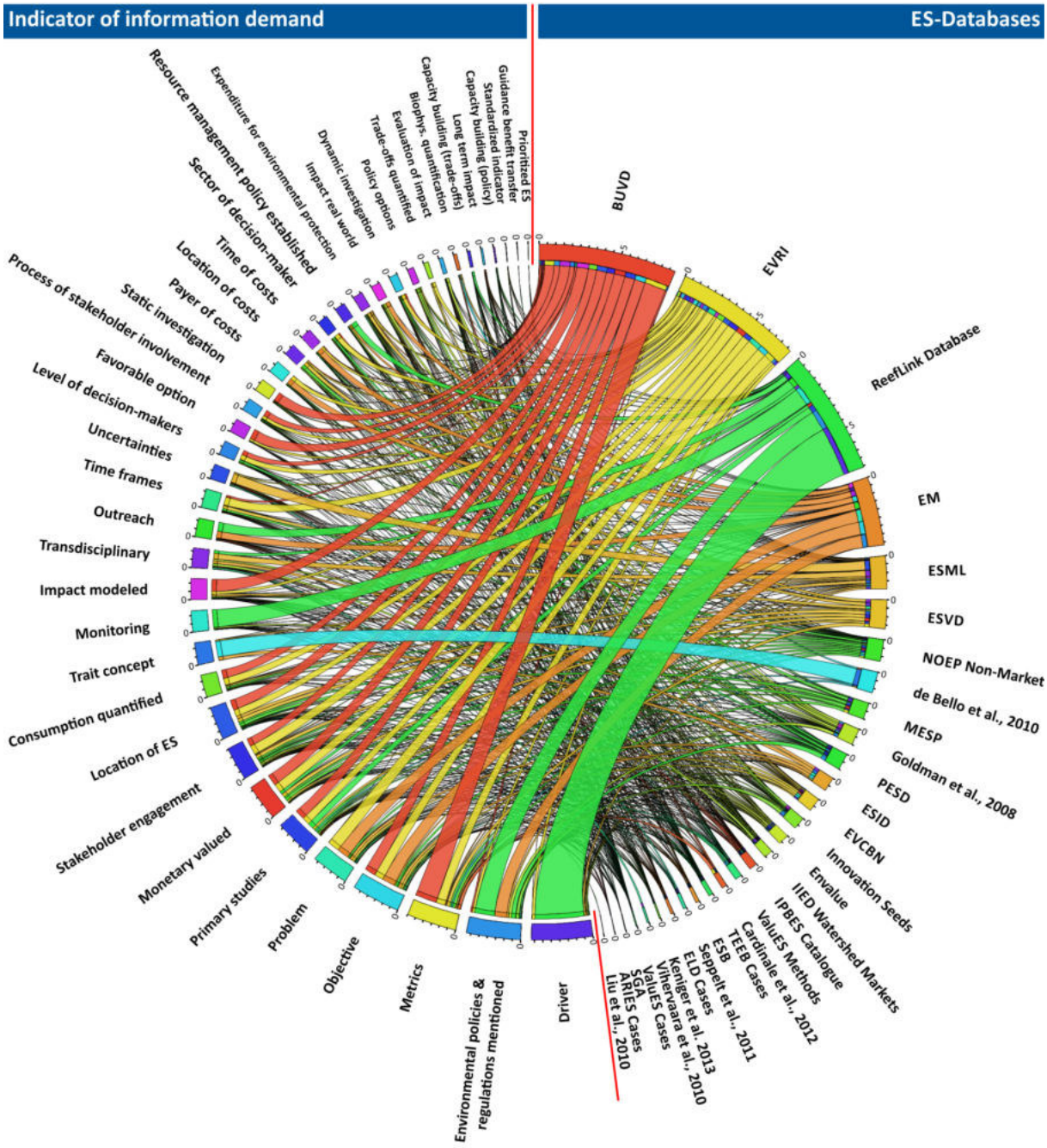
	floods and storms (Feagin et al. 2010).	to reef habitat, property, or human lives.

S4 Table. Quantitative matches between information supply provided by databases and information demand in policy-making instruments for safeguarding ES. This table is the addition to Fig 4 and shows the weighted matches between data entries provided by 29 databases (rows) and six indicator of information demand (columns).

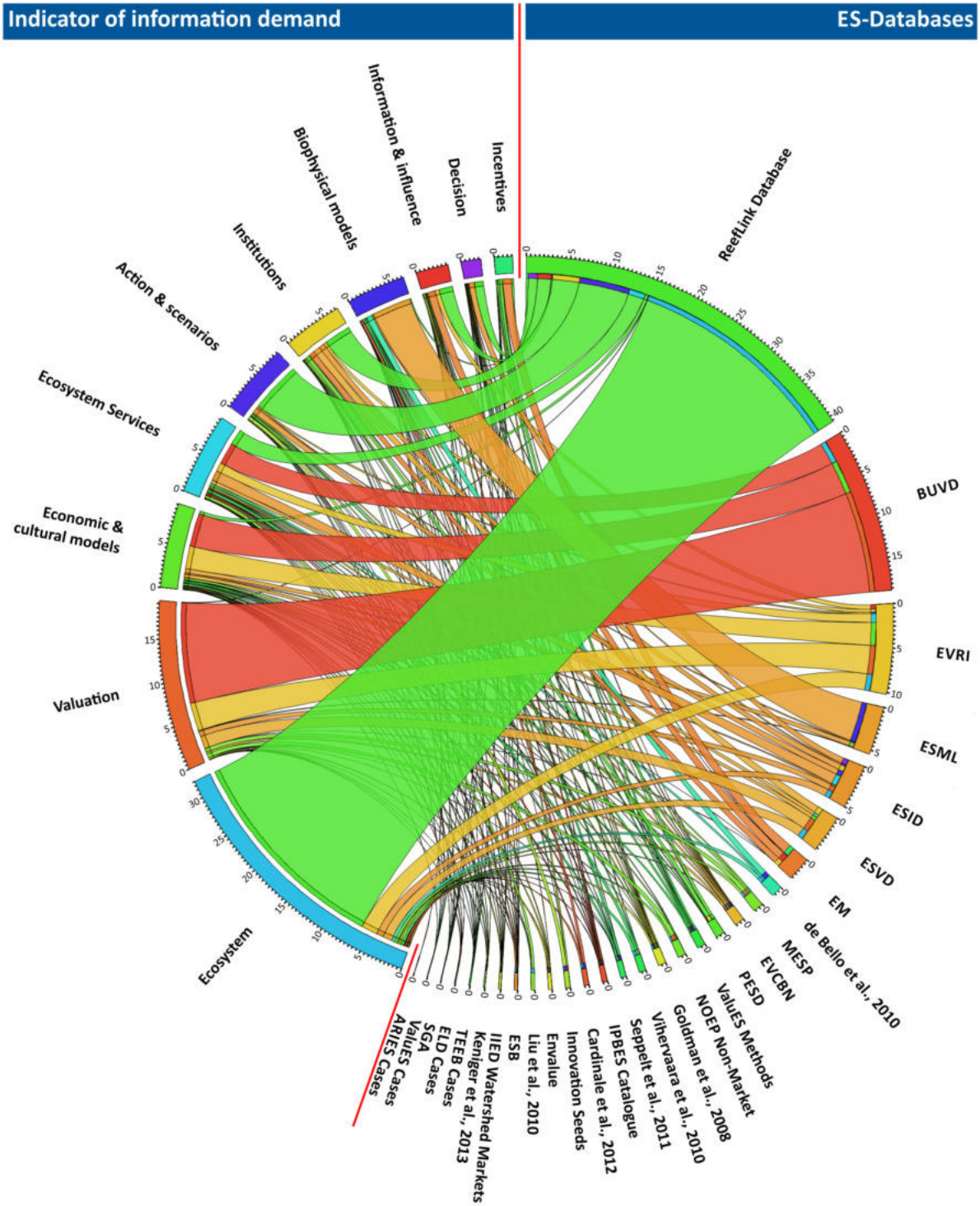
Databases	A) Extending accounting systems through nature-based indicators	B) Rewarding benefits through payments and markets	C) Reforming environmentally harmful subsidies	D) Addressing environmental degradation through regulation and pricing	E) Regulating use through protected areas and recognition of their values	F) Direct public investment in ecological infrastructure and restoration	Total
ReefLink Database	7,582	1,194	0,052	10,794	9,823	2,141	31,586
BUVD	8,363	2,723	0,468	0,199	0,769	0,376	12,899
EM	4,166	3,501	0,083	2,906	0,142	0,518	11,316
EVRI	7,766	0,489	0,000	1,318	0,348	1,075	10,995
PESD	1,005	2,850	0,078	0,075	0,043	0,226	4,276
ESVD	1,739	0,011	0,000	0,083	1,826	0,145	3,804
ESML	2,001	0,334	0,000	0,380	0,227	0,023	2,966
NOEP Non-Market	1,326	0,603	0,003	0,071	0,539	0,348	2,891
Goldman et al., 2008	1,007	0,235	0,075	1,045	0,000	0,181	2,543
EVCBN	0,837	0,240	0,000	0,945	0,000	0,360	2,381
IIED Watershed Markets	0,534	0,957	0,219	0,129	0,092	0,136	2,068
Innovation Seeds	0,744	0,016	0,010	0,955	0,002	0,290	2,016
De Bello et al., 2010	1,278	0,000	0,000	0,000	0,297	0,000	1,575
Cardinale et al., 2012	0,312	0,774	0,000	0,000	0,152	0,000	1,238
Envalue	0,664	0,360	0,000	0,000	0,000	0,116	1,140
MESP	1,011	0,017	0,000	0,000	0,000	0,105	1,133
ESID	0,867	0,004	0,003	0,156	0,000	0,000	1,031
TEEB Cases	0,272	0,066	0,071	0,164	0,093	0,222	0,889
ValueES Methods	0,422	0,172	0,016	0,064	0,086	0,070	0,830
ELD Cases	0,169	0,005	0,000	0,008	0,004	0,388	0,574
ESB	0,204	0,120	0,011	0,115	0,047	0,043	0,540
IPBES Catalogue	0,482	0,026	0,000	0,000	0,000	0,000	0,508
ValuES Cases	0,059	0,021	0,031	0,037	0,040	0,108	0,297
Seppelt et al., 2011	0,196	0,000	0,000	0,000	0,000	0,000	0,196
Keniger et al., 2013	0,099	0,000	0,000	0,000	0,047	0,000	0,146
Vihervaara et al., 2010	0,097	0,000	0,000	0,000	0,000	0,000	0,097
ARIES Cases	0,016	0,006	0,000	0,002	0,004	0,006	0,033
SGA	0,028	0,000	0,000	0,000	0,000	0,000	0,028
Liu et al., 2010	0,002	0,000	0,000	0,000	0,000	0,000	0,002

Total	43,250	14,723	1,121	19,449	14,579	6,877	100,000

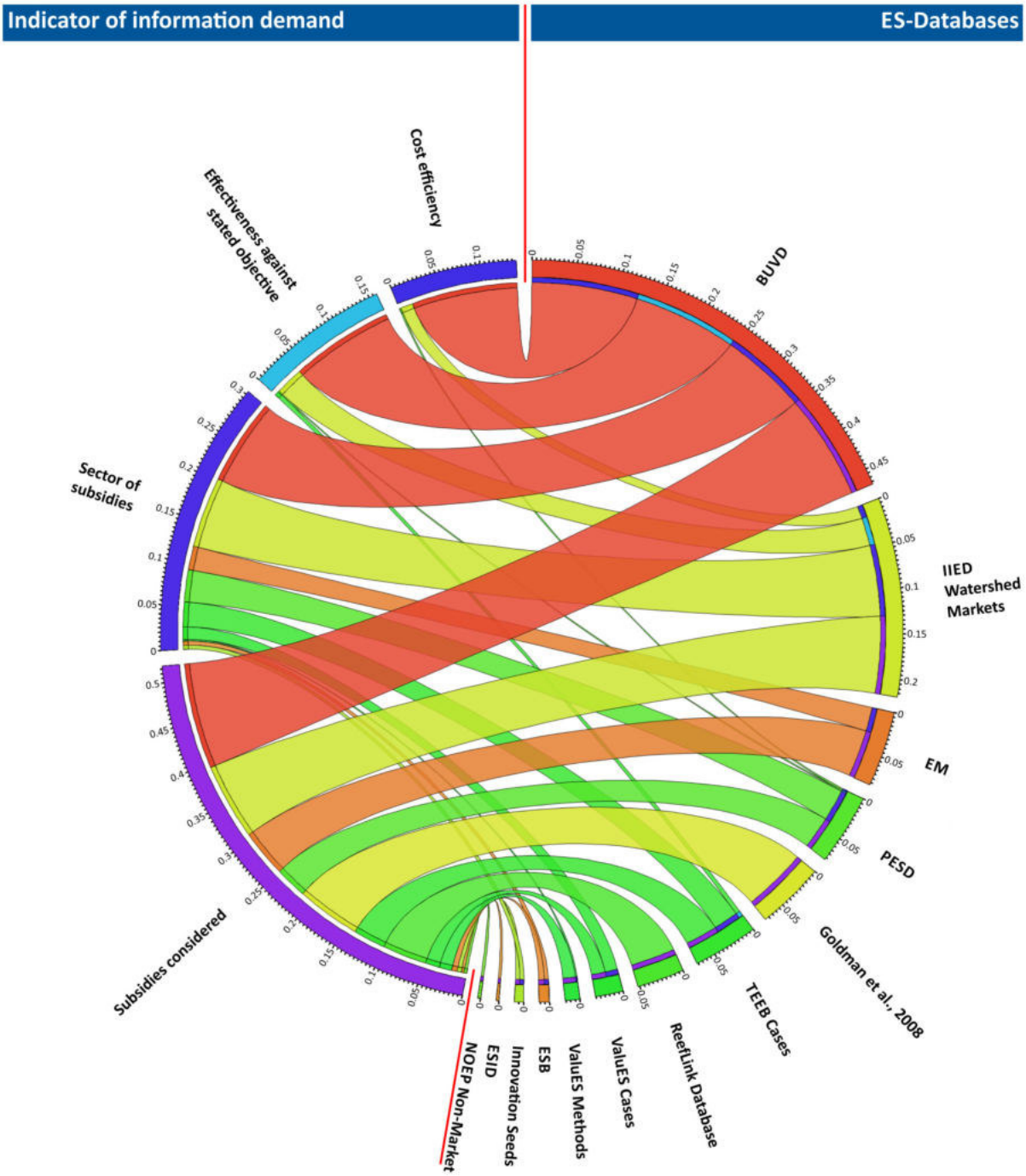
A.1) Extend accounting systems through nature-based indicator



A.2) Extend accounting systems through nature-based indicator



C) Reform environmentally harmful subsidies



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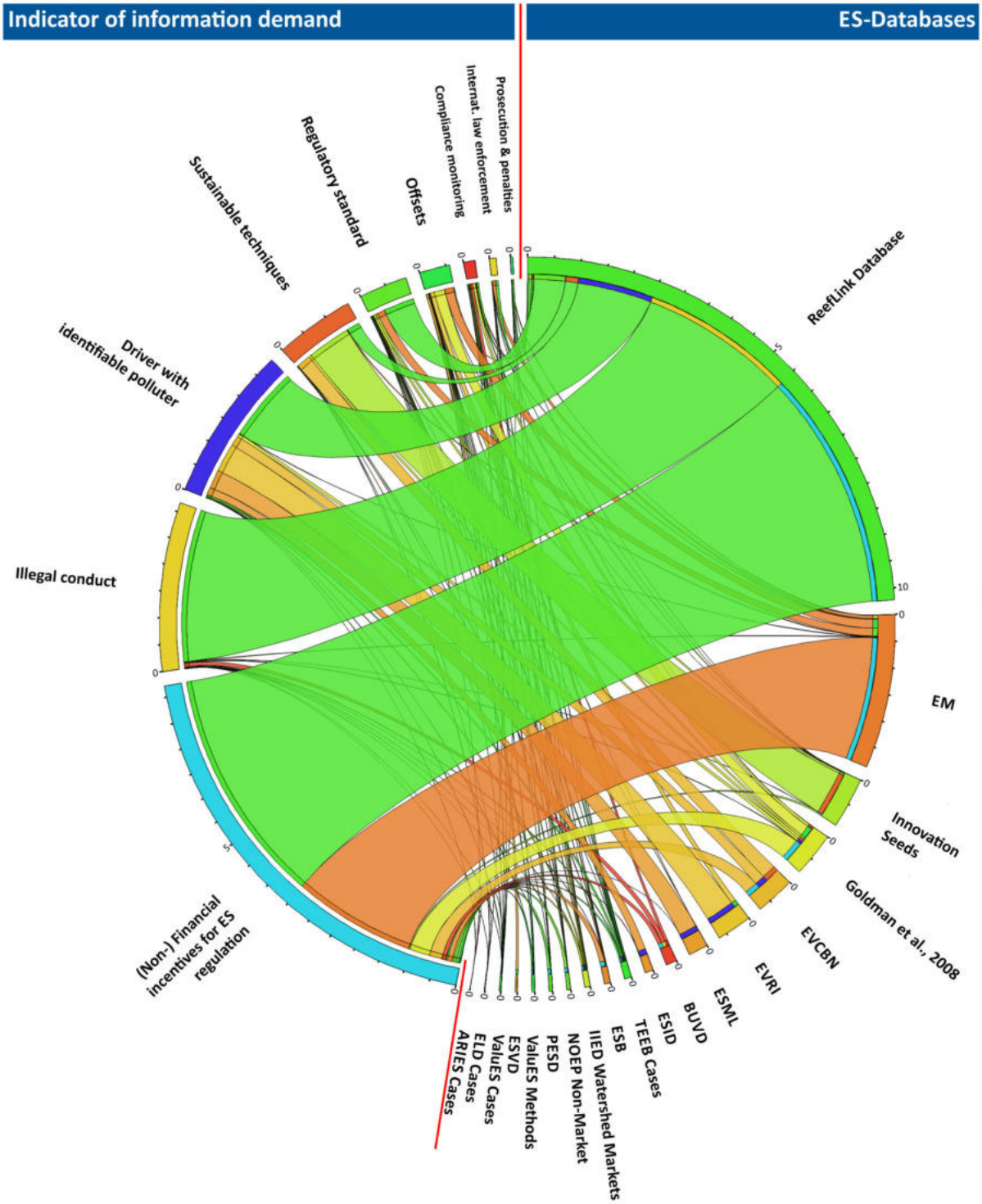
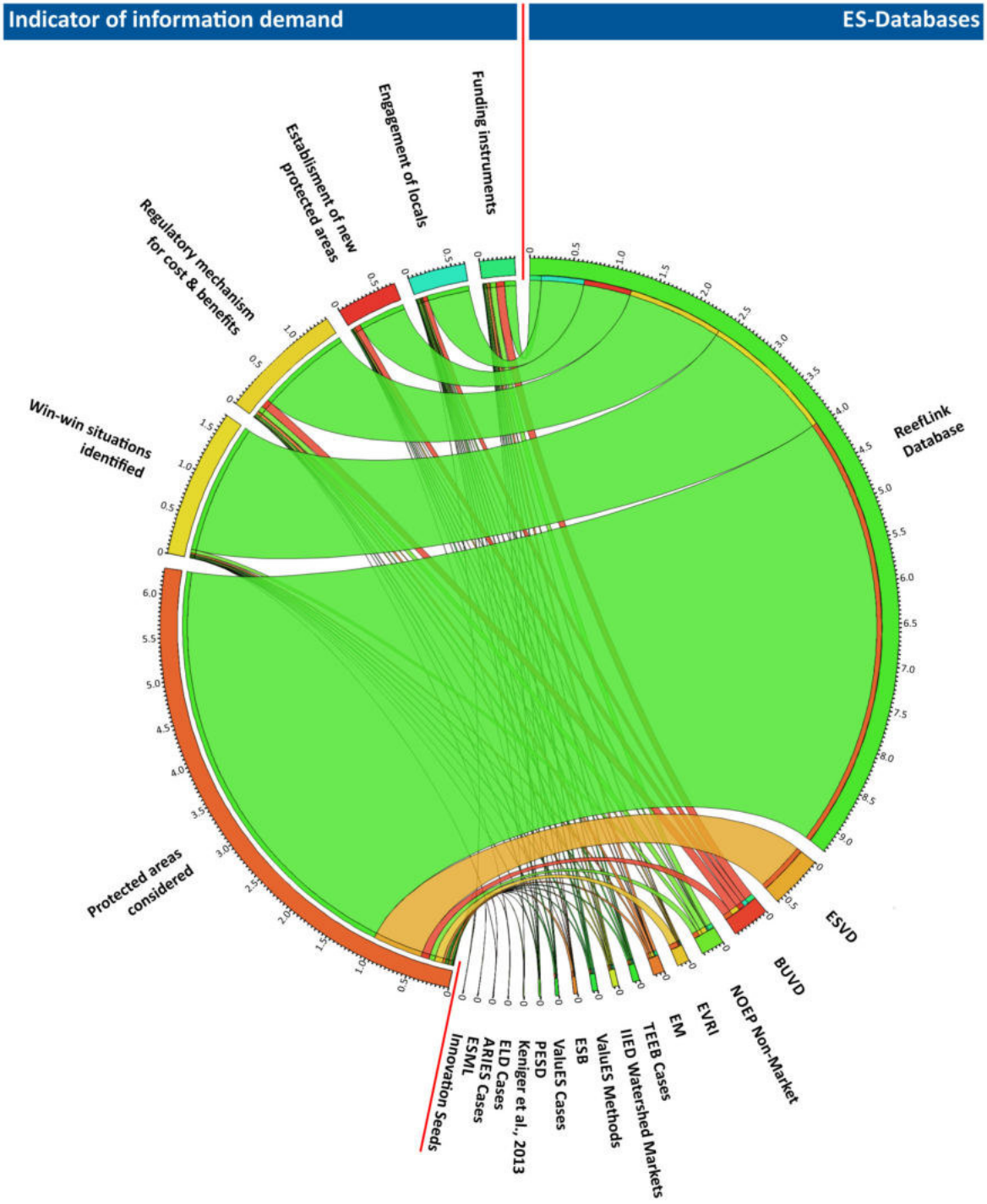
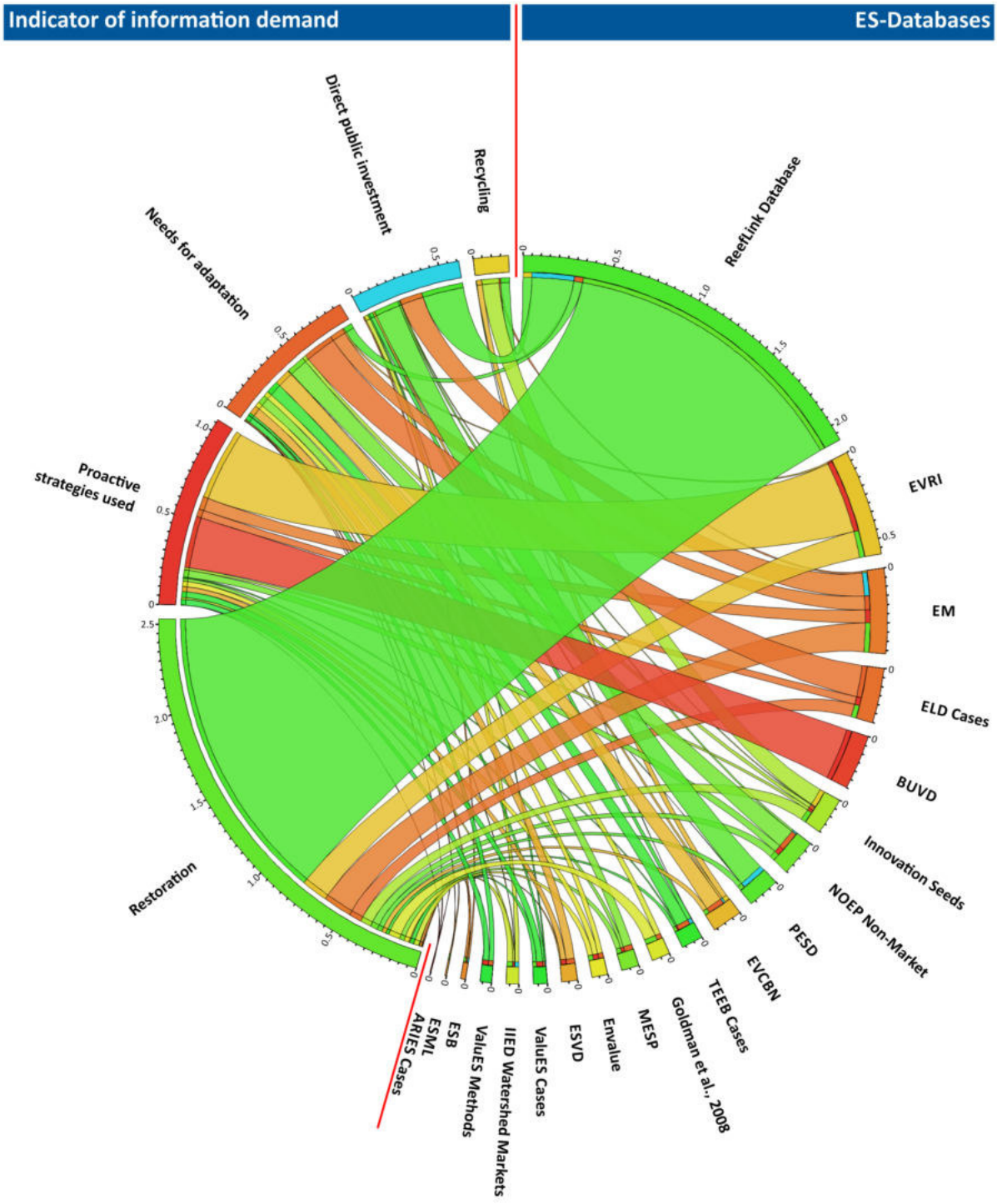
D) Addressing environmental degradation through regulation and pricing



E) Regulating use through protected areas and recognition of their values



F) Direct public investment in ecological infrastructure and restoration



S2 Fig. Matches between information supply provided by databases and indicator of information demand for six policy instruments of safeguarding ES. The chord diagrams face information supply from 29 databases (right half) against indicator of infromation demand (left half) for six policy instruments (A-F). The diagrams link visually matches between database entries and indicator of information demand (colored arc connections) by quantifying the weighted matches (percentage values in monochrome arcs) between database entries and indicator of information demand. For A) two chord diagrams are shown to emphasize in A.2) the interdisciplinary and multidimensional character of all data entries of the databases in accordance to the integrative framework defined by Daily et al. (2009).

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