Ecosystem service databases and their contribution to mainstream ecosystem service information

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‘We are drowning in information but starved for knowledge.’
John Naisbitt [1]

Preface

This dissertation begins with the citation: 'We are drowning in information but starved for knowledge.' [1]. Living in the era of knowledge-centric views and increasing global networking, where vast amounts of information are placed in the hands of researchers and decision-makers, holds challenges. Every year, 1.346 million scientific articles are published in 23,750 journals [2]. The number of articles is even growing by 2.5% per year [3]. Attempts to be aware of, access, and process this gigantic volume of information constitute a major challenge. Hence, the question arises how a human being can consider all information relevant for the task at hand and avoid the 'reinvention of the wheel'. This question becomes even more relevant as researchers and decision-makers have to cope with transdisciplinary work. Transdisciplinary work integrates knowledge and methods across conventional academic disciplines such as natural (physics, biology etc.) and social science (psychology, sociology etc.), and real world practice to gain a more comprehensive understanding. Solving real world environmental problems requires transdisciplinary approaches.

In this dissertation methods were examined that save us from drowning in information. The dissertation provides insights into knowledge management techniques such as databases and discusses how to optimize the organization of information based on transdisciplinary databases. Recommendations are given that may enhance the incorporation of information from transdisciplinary approaches into evidence-based decision-making.

Due to my background as a geographer and landscape ecologist, I am familiar with opportunities and challenges of transdisciplinary approaches. During my studies abroad and later work as a scientific consultant, I gained experience in diverse knowledge management tasks linked to transdisciplinary projects. These skills and experiences primed me to design and conduct this dissertation.

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Summary

Concepts determine the way in which we perceive and shape the world. The ecosystem service (ES) concept is seen as an integrative approach that helps us to understand more clearly the links between nature and human well-being with the aim of more sustainable decision-making. Incorporating ES information into decision-making (mainstreaming), however, is a long-term project and requires successfully addressing a number of impediments. One impediment to a comprehensive mainstreaming of ES is the lack of standards that define terminology, acceptable data and methods, and reporting requirements for sharing consistent information on ES. With the growing popularity of the ES concept in a time of knowledge-centric views and increased global networking, a proliferation of terminologies, conceptual frameworks, methods and datasets caused an increasing amount of inconsistent information and confusion on what determines good practice approaches. In recent years several knowledge management approaches have been developed to facilitate the accessibility to ES information and stimulate standardization processes. One knowledge management approach is represented by databases. In databases, vast amounts of information from ES studies and projects can be compiled in a consistent form. Based on consistent information, the identification of commonalities of good practice examples is facilitated and indications are provided for discussions on standards. This leads to the first research question: '*How can ES databases facilitate mainstreaming ES and the development of standards in specific application contexts?'.*

In Chapter 2, I examined how ES database contents meet the needs of six policy instruments that affect resource and land-use decisions. I analyzed 29 ES databases with global coverage containing information of 36,112 studies, projects and methods within more than 600,000 database entries. I identified 93 indicators of information demand for six major policy instruments and matched database entries with these indicators. The results showed that databases contained information for most of the policy instruments. However, ES databases neglected information on contextual and tacit knowledge about process workflows of ES investigations. Also, ES databases were limited regarding geographic representativeness highlighting major information gaps in society's poorest nations. By synthesizing findings across different policy instruments common principles were derived that represent priority areas to formalize standards for the documentation of knowledge on ES: (i) quantitatively recognize nature's value, (ii) develop prioritization schemes based on ES valuation, (iii) sensitive stakeholder engagement, (iv) facilitate information access and capacity building, and (v) evaluate long-term returns of interventions on ES. Based on the priority areas ontologies can be developed that facilitate knowledge accessibility for decision-making.

Learning from ES databases and transferring their information for decision support assumes that information contained in databases is equally applicable and effective in another setting. Economic valuation of ES is increasingly demanded in policy analysis and most lively debated in research. This led to a rapid growth of economic valuation studies, subsequent databases and thus the pool of sources for potential use in value (benefit) transfer. Against this background, the second research question arose: '*What are major sources of uncertainties in benefit transfer models and how do they affect the transferability of monetary valued ES, given information from ES databases*?'.

In Chapter 3, I assessed the transferability and uncertainties of ES database information exemplified by monetary valued ES. Based on a subsample of the ES databases from Chapter 2, I extracted 839 monetary values of twelve different ES from 194 case studies. For the twelve ES, benefit transfer models (value transfer functions) were developed by utilizing boosted regression trees. This provided the first global estimation of the transferability and uncertainties of monetary valued ES. Models explained from 18% (water provision) to 44% (food provision) of variance in monetary values and enabled a statistically reliable transfer of values for 70% (water provision) to 91% (food provision) of the terrestrial earth surface. Although the application of different valuation methods was a source of uncertainty, I found evidence that assuming homogeneity of ecosystems was a more influential error in value transfer functions. Also, results showed that food provision was mainly influenced by variables indicating climate and growing conditions. Water provision and recreation service showed that ownership rights affected valuations. Furthermore, I found statistical indications for the shifting baseline hypothesis in valuing climate regulation. Ecological conditions and societal vulnerability determined valuation of extreme event prevention. Valuation of habitat services was affected by variables characterizing agricultural unfavorable (marginal) areas. The analysis represents a stepping stone to establish a standardized integration of and reporting on uncertainties for reliable and valid benefit transfer, as an important component for decision support.

The promise that the ES concept will contribute to more sustainable decision-making is still debated. With the availability of large ES databases, consistent indicators of evaluation become available, too. This raises the third research question of this dissertation: '*Which indicators for the evaluation of effectiveness and efficiency of ES study outcomes exist in ES databases and which basic principles can be derived to facilitate a more standardized evaluation?'*.

In Chapter 4, I reviewed the ES databases selected in Chapter 2 for indicators that could be used as metrics for the evaluation of efficiency and effectiveness of ES study outcomes. Results showed that although none of the ES databases aimed at monitoring or evaluation of effectiveness and efficiency of ES study outcomes, they contained a broad set of indicators that provided insights into effectiveness and efficiency. However, for the specific determination of most effective and efficient ES study outcomes, information was missing. Based on the synthesis of the results, four basic principles were derived that may facilitate prospective evaluations of effectiveness and efficiency of ES study outcomes. These principles relate to: (i) the determination of the objectives of evaluation; (ii) the selection of indicators for the evaluation; (iii) the consideration of reference standards; and (iv) the conceptual comprehension.

The findings of this dissertation showed that reviewed ES databases contain a large amount of information that can be synthesized to guide discussions on standards and to facilitate the mainstreaming of ES information. However, this dissertation presented only first steps towards mainstreaming of ES information. There is substantial merit in conducting further systematic reviews on how to collect, formalize and interconnect distinct information contained in ES databases. Ontologies hold great promise as a unifying tool that joins together information, describes the relation between them and thus contributes to the development of more standardized approaches. Reaching consensus on standards that codify agreement on good practices will accelerate the mainstreaming of ES information.

Zusammenfassung

Konzepte bestimmen wie wir Menschen die Welt wahrnehmen und gestalten. Das Konzept der Ökosystemleistungen (ES) ist ein integrativer Ansatz, der hilft die Zusammenhänge zwischen Natur und menschlichem Wohlergehen besser zu verstehen, mit dem Ziel nachhaltigere Entscheidungen zu treffen. Die Einbeziehung von ES-Informationen in die Entscheidungsfindung (*Mainstreaming*) ist jedoch ein langfristiges Projekt und erfordert die erfolgreiche Überwindung einer Reihe von Hindernissen. Ein Hindernis für ein umfassendes Mainstreaming von ES ist das Fehlen von Standards, die Terminologie, akzeptable Daten und Methoden sowie Erfordernisse für die Berichterstattung zum Austausch konsistenter Informationen über ES definieren. Mit der wachsenden Popularität des ES-Konzepts in einer Zeit wissensorientierter Sichtweisen und verstärkter globaler Vernetzung führte eine zunehmende Verbreitung von Terminologien, konzeptionellen Vorstellungen, Methoden und Datensätzen zu immer inkonsistenteren Informationen und Verwirrung darüber, was Ansätze guter Praxis ausmacht. In den letzten Jahren wurden verschiedene Ansätze des Wissensmanagement entwickelt, um den Zugang zu ES-Informationen zu erleichtern und Standardisierungsprozesse anzukurbeln. Einen Ansatz im Bereich Wissensmanagement stellen Datenbanken dar. In Datenbanken können große Mengen an Information von ES-Studien oder Projekten in konsistenter Form zusammengestellt werden. Durch konsistente Informationen wird die Identifizierung von Gemeinsamkeiten von Beispielen guter Praxis erleichtert und es werden Hinweise für Diskussionen über Standards gegeben. Dies führt zur ersten Forschungsfrage: ‚*Wie können ES-Datenbanken das Mainstreaming von ES und die Entwicklung von Standards in spezifischen Anwendungskontexten erleichtern?*'.

In Kapitel 2 untersuchte ich, wie Datenbankinhalte den Informationsbedarf von sechs politischen Instrumenten, die Ressourcen und Landnutzung beeinflussen, gerecht werden. Ich analysierte 29 ES-Datenbanken mit globaler Abdeckung, die Informationen zu 36.112 Studien, Projekten und Methoden in mehr als 600.000 Datenbankeinträgen enthielten. Ich identifizierte 93 Indikatoren des Informationsbedarfs von sechs bedeutenden politischen Instrumenten und überprüfte welche der Datenbankeinträge dem Informationsbedarf der Indikatoren gerecht wurden. Die Ergebnisse zeigten, dass Datenbanken Informationen für die meisten politischen Instrumente enthielten. ES-Datenbanken vernachlässigten jedoch Informationen über kontextbezogenes und implizites Wissen bezüglich der Prozessabläufe von ES-Untersuchungen. Darüber hinaus waren ES-Datenbanken hinsichtlich der geografischen Repräsentativität begrenzt, besonders in den ärmsten Ländern der Gesellschaft traten große Informationslücken auf. Durch die Synthese der Ergebnisse über verschiedene politische Instrumente hinweg konnten gemeinsame Prinzipien abgeleitet werden, die Prioritätsbereiche für die Formalisierung von Standards zur Dokumentation von Wissen über ES darstellen: (i) quantitative Erkenntnis des Wertes der Natur, (ii) Entwicklung von Prioritätsmodellen basierend auf ES-Bewertungen, (iii) sensible Beteiligung von Interessensvertretern, (iv) Erleichterung von Informationszugang und Fortbildungsmöglichkeiten, und (v) Auswertung von langfristigen Auswirkungen von Maßnahmen auf ES. Aufbauend auf diesen Prioritätsbereichen können Ontologien entwickelt werden, die den Zugang zu Wissen für die Entscheidungsfindung erleichtern.

Um Erkenntnissen aus Datenbanken zu gewinnen und deren Informationen für die Entscheidungsunterstützung zu übertragen wird vorausgesetzt, dass in Datenbanken enthaltene Informationen in einer anderen Situation gleichermaßen anwendbar und wirksam sind. Die ökonomische Bewertung von ES wird zunehmend in der Politikanalyse gefordert und lebhaft in der Forschung diskutiert. Dies führte zu einem rapiden Wachstum von ökonomischen Bewertungsstudien, nachfolgenden Datenbanken und somit erhöhten Fundus an Quellen für eine mögliche Verwendung für Werte- (*Benefit*-) Transfer-Modelle. Vor diesem Hintergrund stellt sich die zweite Forschungsfrage: ‚*Was sind die Hauptquellen für Unsicherheiten bei Benefit-Transfer-Modellen und wie beeinflussen sie die Übertragbarkeit von monetär bewerteten ES, basierend auf Informationen von ES-Datenbanken?*'.

In Kapitel 3 bewertete ich die Übertragbarkeit und Unsicherheiten von ES-Datenbankinformationen, verdeutlicht am Beispiel von monetär bewerteten ES. Auf der Grundlage einer Teilprobe von ES-Datenbanken aus Kapitel 2 extrahierte ich 839 monetäre Werte von zwölf verschiedenen ES aus 194 Fallstudien. Für die zwölf ES wurden Benefit-Transfer-Modelle (Wertübertragungsfunktionen) unter Verwendung von Regressionsanalysen *(boosted regression trees)* entwickelt. Dies ergab die erste globale Abschätzung der Übertragbarkeit und Unsicherheit von monetär bewerteten ES. Modelle erklärten von 18% (Wasserbereitstellung) bis 44% (Nahrungsmittelversorgung) der Varianz der Geldwerte und ermöglichten eine statistisch vertrauenswürdige Übertragung von Werten für 70% (Wasserversorgung) bis 91% (Nahrungsversorgung) der terrestrischen Erdoberfläche. Obwohl die Anwendung unterschiedlicher Bewertungsmethoden eine Quelle der Unsicherheit war, fand ich Hinweise, dass die Annahme der Homogenität von Ökosystemen einen einflussreicheren Fehler in Wertübertragungsfunktionen darstellte. Weiterhin zeigten die Ergebnisse, dass die Nahrungsmittelversorgung hauptsächlich durch Variablen beeinflusst wurde, die auf Klima- und Wachstumsbedingungen hindeuten. Wasserversorgung und Erholungsleistung zeigten, dass Eigentumsrechte die Bewertungen beeinflussten. Darüber hinaus fand ich statistische Anhaltspunkte für die Hypothese der veränderbaren Normwerte (*shifting baseline*) bei der Bewertung von Klimaregulierung. Ökologische Bedingungen und gesellschaftliche Vulnerabilität bestimmten die Bewertung der Extremereignisprävention. Die Bewertung von Habitatleistungen wurde durch Variablen beeinflusst, die landwirtschaftlich ungünstige Gebiete (*marginal areas*) charakterisieren. Die Analyse stellt einen Baustein dar, um eine standardisierte Integration von und Berichterstattung über Unsicherheiten für einen verlässlichen und validen Benefit-Transfer zu ermöglichen; als wichtige Komponente für die Entscheidungsunterstützung.

Die Verheißung, dass das ES-Konzept zu einer nachhaltigeren Entscheidungsfindung beitragen würde, wird nach wie vor diskutiert. Mit der Verfügbarkeit großer ES-Datenbanken werden auch konsistente Indikatoren zu Evaluation verfügbar. Dies wirft die dritte Forschungsfrage der Dissertation auf: ‚*Welche Indikatoren für die Evaluation der Effektivität und Effizienz von ES-Studienergebnissen existieren in ES-Datenbanken und welche Grundsätze können abgeleitet werden, um eine standardisierte Evaluation zu ermöglichen?*'.

In Kapitel 4 überprüfte ich die in Kapitel 2 ausgewählten ES-Datenbanken auf Indikatoren, die als Messgrößen für die Evaluation der Effizienz und Effektivität von ES-Studienergebnissen verwendet werden können. Die Ergebnisse zeigten, dass obwohl keine der ES-Datenbanken darauf abzielte die

Effektivität und Effizienz von ES-Studienergebnissen zu überwachen oder zu evaluieren, dennoch eine breite Palette von Indikatoren enthalten war, die Einsichten in Effektivität und Effizienz lieferten. Für die konkrete Bestimmung der effektivsten und effizientesten ES-Studienergebnisse fehlten jedoch Informationen. Basierend auf einer Synthese der Ergebnisse wurden vier Grundsätze abgeleitet, die zukünftige Evaluationen der Effektivität und Effizienz von ES-Studienergebnissen erleichtern können. Diese Grundsätze betreffen: (i) die Festlegung der Evaluationsziele; (ii) die Auswahl von Indikatoren für die Evaluation; (iii) die Berücksichtigung von Referenzstandards; und (iv) das konzeptionelle Verständnis.

Die Ergebnisse der Dissertation zeigten, dass die überprüften ES-Datenbanken eine große Menge an Informationen enthalten, die synthetisiert werden können, um Diskussionen über Standards zu führen und das Mainstreaming von ES-Informationen zu erleichtern. Die Dissertation präsentierte jedoch nur erste Schritte zum Mainstreaming von ES-Informationen. Es besteht ein substantieller Verdienst darin, weitere systematische Überprüfungen durchzuführen, wie man verschiedene in ES-Datenbanken enthaltene Informationen sammeln, formalisieren und verbinden kann. Ontologien gelten als ein vielversprechendes, zusammenführendes Werkzeug, das Informationen verbindet, die Beziehung zwischen den Informationen beschreibt und somit zur Entwicklung von standardisierteren Ansätzen beiträgt. Durch das Erreichen eines Konsenses bezüglich Standards, welche eine Vereinbarung über gute Praxis kodifizieren, wird das Mainstreaming von ES-Informationen beschleunigt.

List of articles published as result of this dissertation

The following articles were published before submission of this dissertation and originate from work and results of this dissertation.

Schmidt S, Seppelt R. 2018. Information content of global ecosystem service databases and their suitability for decision advice. Ecosystem Services 32 22-40. doi: 10.1016/j.ecoser.2018.05.007

Schmidt S, Manceur AM, Seppelt R. 2016. Uncertainty of Monetary Valued Ecosystem Services - Value Transfer Functions for Global Mapping. Plos One 11 (3): 22. doi: 10.1371/journal.pone.0148524

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List of abbreviations

ANOVA	Analysis of variance
API	Application programming interface
ARIES	ARtificial Intelligence for Ecosystem Services
BRT	Boosted regression trees
BUVD	Beneficial Use Values Database
CD	Compact disc
DAAC	Distributed Active Archive Centers
DSS	Decission Support Systems
ELD	The Economics of Land Degradation
EM	Marketwatch and News & Articles of Ecosystem Marketplace
Envalue	Environmental Valuation Database
EOSDIS	Earth Observing System Data and Information System
ES	Ecosystem services
ESB	Ecosystem Services Bibliography
ESID	Ecosystem Service Indicator Database
ESIP	Earth Science Ontology Portal
ESML	EcoService Models Library
ESVD	Ecosystem Service Valuation Database
EVCBN	Environmental Valuation and Cost-Benefit News
EVRI	Environmental Valuation Reference Inventory
GDP	Gross domestic product
GEO BON	Group on Earth Observations Biodiversity Observation Network
GIS	Geographic information system
GLUES	Global Assessment of Land Use Dynamics, Greenhouse Gas Emissions and Ecosystem Services
Ha	Hectare
HYDE	History Database of the Global Environment
IIED	International Institute for Environment and Development
INSPIRE	Infrastructure for Spatial Information in the European Community
Int.-$-2007	International Dollar of the reference year 2007
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
Lr	Learning rate
MESP	Marine Ecosystem Service Partnership
Mintn	Minimal number of observations in the terminal nodes
NASA	United States National Aeronautics and Space Administration
NOEP	United States National Ocean Economics Program
Nt	Number of trees
OBOE	Extensible Observation Ontology
OGC	Open Geospatial Consortium
OPERAs	Operational Potential of Ecosystem Research Applications
OWL	Web Ontology Language

PES	Payment for Ecosystem Services
PESD	Payment for Ecosystem Services Database
R^2	Coefficient of determination
SERVES	Simple Effective Resources for Valuing Ecosystem Services
SGA	Sub-global assessments
SONet	Scientific Observation Network
TEEB	The Economics of Ecosystem and Biodiversity
UFZ	Helmholtz Centre for Environmental Research
US-$	United States Dollar
WAVES	Wealth Accounting and the Valuation of Ecosystem Services
WGS	World Geodetic System

1 Introduction

1.1 The ecosystem service concept and main research questions

Concepts are the constituents of human thoughts. They are crucial to psychological processes such as categorization, inference, memory, learning, and decision-making. Concepts determine the way and methods in which we perceive and shape the world [4]. In the time of the industrial revolution concepts from neoclassical economics led to the removal of environmental resources or more generally nature from accountings under the implicit assumption that nature's input could be substituted by manufactured capital. With increasing global environmental deterioration and concerns on resource scarcity in the second half of the 20th century [5], concepts from more interdisciplinary fields such as environmental and resource economics started to address the systematic undervaluation of the ecological dimension in decision-making [6-9]. Since its introduction in 1981 [10] the concept of ES has been attracting increased attention as a way to communicate the value of biodiversity and ecosystem functioning using a language that reflects dominant political and economic views [11]. The ES concept aims to guide the usage of natural resources by better understanding and valuing nature's contributions to human well-being [12]. ES include tangible and intangible benefits which humans obtain from nature, such as provisioning of food, water and raw materials; the regulation of climate, soil, water and bio-control (disease, pollination); and cultural services for spiritual and religious inspiration, cultural heritage and identity, recreation, aesthetic, and education [13-16]. The ES concept is unique and promising for decision-making due to its more holistic research approach, which means that knowledge from various scientific and societal bodies is integrated to produce insights into human-nature interdependencies including welfare effects of management policies. Entry points for incorporating ES information into existing decision-making processes occur at all sectors and levels of governance; from private to public sector [17] and local to international scale [18; 19].

In the 21st century, the majority of ES continues to decline, whereas a small subset of ES for which regulation mechanisms exist have increased [20]. In response to this, hundreds of science-policy bridging initiatives based on the ES concept are underway, engaging individuals, communities, businesses, nongovernmental organizations, governments, and international organizations [21; 22]. There is evidence that the ES concept has triggered policy shifts ranging from governmental to private organizations. For instance, in 2012, 118 countries became signatories to the formation of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), with the mission to strengthen knowledge foundations for better evidence-based policy, for the conservation and sustainable use of the planet's biodiversity, its ecosystems, and the services they provide to society [23]. Since 2012, 70 countries have committed to consider ES in national income and wealth accounts supported by the World Bank's partnership Wealth Accounting and the Valuation of Ecosystem Services (WAVES) [24]. As of 2014, 43 financial and businesses organizations had signed the Natural Capital Declaration to '[…] incorporate ES considerations into loans, equity, fixed income and insurance products, as well as in accounting, disclosure and reporting frameworks.' [25]. Furthermore, several 'payments for ecosystem services' (PES) schemes were launched in different nations around the world for carbon sequestration, watershed services, and biodiversity conservation [26].

With the progressing uptake of the ES concept in society, the demand for ES knowledge is increasing. ES knowledge is needed 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 [27; 28]. Proponents argue that through a better incorporation of ES information into decision-making, incentives can be established for businesses and consumers to conserve the natural assets necessary for the sustainable delivery of ES [29]. Mainstreaming ES, i.e. the practice to routinely incorporating ES information into decision making, however, is a long-term project and requires successfully addressing a number of impediments [30; 31; 18; 32]. One impediment to broad scale mainstreaming of ES stems from the proliferation of terminologies, conceptual frameworks, methods and datasets that cause a growing amount of inconsistent information and confusion on what determines best practice approaches [33]. Individual research disciplines approach ES research with the intent to adapt the ES concept by reframing terminologies and methods to fit within a respective discipline [34]. This approach to research affects (i) how problems are identified, framed and managed, (ii) the relevance of outcomes to policy, and (iii) the extent of capacities for learning [35; 36]. A multitude of definitions complicates the transfer of knowledge between disciplines, may lead to redundant research efforts, slows scientific progress, and ultimately impedes advances towards a unified foundation for ES research [37; 38]. Strategies to reach consensus on standards that define ES terminology, acceptable data and methods, and reporting formalization are required [39]. Common standards may improve rigor and specificity of the ES concept and could increase confidence in the use of scientific information and allow for wide uptake in society, as it is shown in various examples [40; 41].

Knowledge management is increasingly recognized as key to facilitate debates on standardization [42-44]. This is even more relevant as people have to cope with a plethora of data, information and knowledge, within an ever increasing complex and diverse global network caused by steadily advancing information technologies, ubiquitous access to information and knowledge-centric views [45-47]. Knowledge management is a practitioner-driven strategy that stresses the importance to build knowledge management systems as a foundation for a culture in which knowledge can be effectively exploited [48]. Knowledge management in ES research community is at an early stage [49; 50] and initiatives such as IPBES Data and Knowledge Working Group [51] or the Group on Earth Observations Biodiversity Observation Network (GEO BON) [52] set up a common infrastructure and knowledge management systems as a long-term foundation that encourages using, generating, sharing, and exploiting knowledge on ES. Technologies that support knowledge management include databases. Databases can be used for knowledge discovery, capturing and sharing of knowledge, and are a prerequisite for knowledge applications such as decision support systems (DSS) [53]. Databases use a built-in formal reporting protocol that ensure the provision of consistent information and facilitate the identification of commonalities across studies as a basis for knowledge transferability and generalizability beyond the bounds of the study. Therefore, databases hold the potential to contribute to the development of standards and facilitate the adoption of good practices, allow for capacity building and evaluation of good performance, and may improve the quality and reliability of results.

In recent years several ES databases have been developed [54], for instance the Ecosystem Service Valuation Database (ESVD) from the international initiative on The Economics of Ecosystems and Biodiversity (TEEB). The ESVD was initially developed to provide an overview on economic valuation studies of ES and to support education on sustainable land management on a global scale [55]. However, the database was used for other purposes, too [56]. This example showcases the greater utility of a database beyond what the original investigator might had envisioned. By comparing databases, strength and flaws as well as common principles can be derived that help to better understand the suitability of ES databases for the use in different application contexts. In order to better inform analysts and decision-makers on the capabilities and limitations of ES databases systematic reviews are required.

Given the information demand for ES knowledge and the potential of ES databases to facilitate the integration of ES information into different decision-making contexts, the first research question of the dissertation arises:

> **Research question 1:** *How can ES databases facilitate mainstreaming ES and the development of standards in specific application contexts?*

Applications of the ES concept and conditions in which ES knowledge is used for decision-making are manifold and vary considerably [57-59]. Generic approaches that seek to provide a 'one size fits all' set of standards for ES are open to question whether they accelerate mainstreaming ES information and help practitioners or rather confuse them and slow down uptake. There are suggestions that ES standards should be tailored to specific application contexts [60; 39]. An application context defines a discourse that surrounds specific conditions under which the ES concept is used (including by whom and for what purpose) and helps to determine its interpretation. Examples for application contexts are governmental policies such as the multinational Water Framework Directive in Europe or the Executive Order 12291 in the United States. These governmental policies require methods for calculating and comparing benefits and costs of the impact of regulatory processes and other interventions on ES and society (benefit-cost analysis). Economic valuation of ES is increasingly demanded in policy analysis and lively debated in research. In research, there are controversial discussions on the appropriateness of economic measures to comprehensively capture the diverse ways humans interact with and benefit from nature [61-63]. Stimulated by these discussions, there is a rapid growth of economic valuation studies for both marketable ES (e.g. timber, fisheries), and those that are not bought and sold in markets (e.g. aesthetic, spiritual) [55]. These studies were often conducted for methodological purposes rather than to support benefit-cost analysis. However, this research did increase the pool of sources for potential use in benefit transfer.

Benefit transfer techniques are widely used by analysts and policy makers [64; 65]. Benefit transfer provides a pragmatic approach to estimate values for ES when constraints in time, funding, or informational requirements prevent to conduct primary studies. The basic rationale is that commonalities between ES in different locations allow values from one location (source case) to be transferred to another (target case). The validity and accuracy of benefit transfer rely on a number of conditions [66]. Among potential pitfalls is the lack of correspondence between the locations [67], for example variations in ecological conditions or in socio-economic characteristics of the population between source case and target case. Despite attempts to identify the appropriateness of benefit transfer for different application contexts and the establishment of criteria for ideal benefit transfer [68; 69], consensus about guidelines on how benefit transfer should proceed when a condition is not fully met remains challenging. This leads to recurring questions regarding transfer reliability and validity. At a practical level, the consequences are that practitioners often make informal and sometimes uninformed judgements about the applicability of benefit transfer techniques. There is a substantial divergence between good practices in scholarly literature and those commonly applied within policy analysis [65].

In order to improve benefit transfer practices it is required to identify potential errors [70; 71; 66]. Based on a better understanding of sources of uncertainty guidelines can be developed for a more standardized incorporation of uncertainties to the formal valuation process, including recommendations on how to communicate monetary values directly in association with uncertainties to decision-makers. These issues lead to the second research question:

> **Research question 2:** *What are major sources of uncertainties in benefit transfer models and how do they affect the transferability of monetary valued ES, given information from ES databases?*

With an increasing number of ES studies in diverse application contexts, also critical voices were raised. Most frequently it is criticized that the ES concept is a utilitarian and anthropocentric concept closely associated with commodification and direct payments schemes, which tends towards oversimplification of environmental complexities and may lead to biopiracy and selling out on nature [72-74; 62; 75; 76]. The promise that the ES concept will contribute to more sustainable decision-making is still debated and systematic tests against evidence are neglected [77; 59]. Steering ES science towards improved decision advice and ultimately to ecological and social betterment requires gauging its achievements accordingly. Standardized measures are integral for monitoring and evaluation of progress and performance [78; 39]. In ES research and practice besides sustainability and fairness [79], criteria such as effectiveness and efficiency are commonly used to determine progress and performance. While effectiveness, i.e. doing things right, is well-received as a normative judgment criterion whether a change can be deemed as ‘good’; efficiency, i.e. doing the right things, becomes more prominent in measuring progress and performance in ES research [80; 81].

Approaches for the evaluation of effectiveness and efficiency of ES study outcomes are quite diverse [82; 83] and the principles on which the evaluation process should be based are not always clear [84]. The evaluation of both effectiveness and efficiency of ES study outcomes is goal-dependent and grounded on a comparison between different groups. In Vartiainen [84] it is pointed out that the optimal preconditions for evaluation of effectiveness and efficiency occur when the objectives and objects of evaluation are as similar as possible. However, this is rarely given due to a lack of consistent ES studies [85]. Also, standardized terminologies, indicators or methods for effectiveness and efficiency of ES study outcomes are missing [86-89].

Databases aim to bring together information from individual ES studies in a consistent way that facilitates the detection of similarities and differences prevailing across ES studies and thus enables to identify comparable ES studies. Databases use variables that compile evidence on characteristics of ES studies, which are promising to derive indicators and regularities for their evaluation. Although the number of ES databases is growing, their secondary use for evaluation purposes is neglected. ES databases hold the potential to provide insights on how to improve evaluation of ES study outcomes.

For a more standardized evaluation of effectiveness and efficiency of ES study outcomes, a better understanding of basic principles is required. ES databases provide insights into common patterns across different ES studies and contain indicators that are promising for the usage of evaluating effectiveness and efficiency. Against this background, the third research question of the dissertation arises:

> **Research question 3:** *Which indicators for the evaluation of effectiveness and efficiency of ES study outcomes exist in ES databases and which basic principles can be derived to facilitate a more standardized evaluation?*

1.2 Structure of the dissertation

This dissertation comprises five chapters. After the introduction of the topic and research question of the dissertation in Chapter 1, the following Chapters 2, 3 and 4 address the three major research questions accordingly, and Chapter 5 synthesizes major findings.

Chapter 2 reviews the information content of ES databases and their suitability for mainstreaming ES. Firstly, an extensive review of ES databases is presented and an overview on information contents of selected ES database given. This comprehensive selection of ES databases is used for the investigation of the research question 1 in Chapter 2, but also for answering research questions 2 and 3 in Chapter 3 and 4, respectively (Fig 1.1). Secondly, information demand from policy instruments is identified to integrate ES into decision-making. Thirdly, results are presented on how well information contents from databases match information demand from policy instruments. Fourthly, based on results priority areas for mainstreaming and standardization of ES information are discussed.

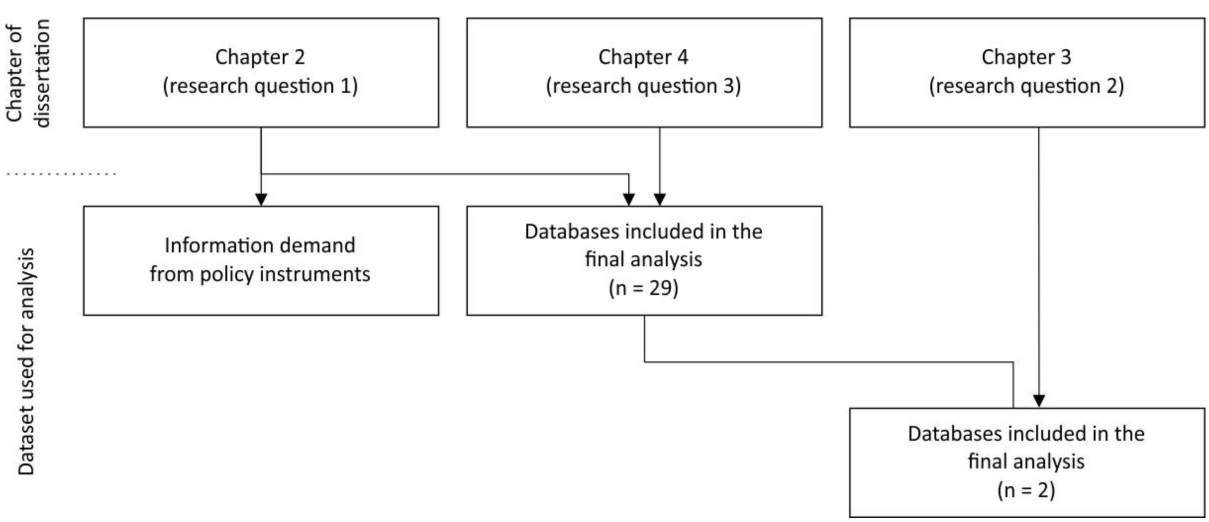


Fig 1.1. Chapters of dissertation and datasets used for analysis. The figure illustrates the chapters of the three research questions and corresponding datasets used for their analysis.

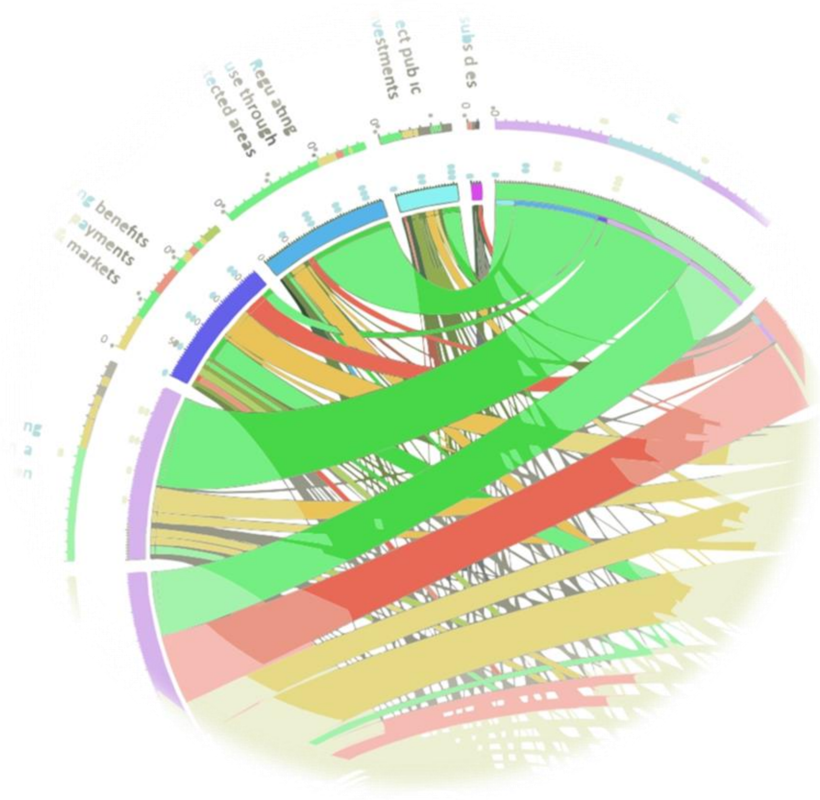
Chapter 3 assesses the transferability and uncertainties of ES database information exemplified by a review of monetary valued ES and application of benefit transfer models. For twelve ES, benefit transfer models are developed and uncertainties of transferred values estimated. Also findings are discussed and a conceptual foundation is derived for the establishment of a more standardized reporting on uncertainties of benefit transfer.

Chapter 4 comprises a review of indicators contained in ES databases for the evaluation of effectiveness and efficiency of ES study outcomes. Firstly, a hierarchical framework for a systematic analysis of effectiveness and efficiency indicators is presented. Secondly, based on the hierarchical framework indicators that contribute to the evaluation of effectiveness and efficiency are identified from ES databases. Thirdly, findings across indicators are synthesized to derive and discuss basic principles for the evaluation of effectiveness and efficiency of ES study outcomes.

In the last Chapter 5, findings and outcomes from Chapter 2 to 4 are summarized and methodological limitations of the dissertation as well as perspectives towards optimized exploitation of ES information from databases are discussed. Chapter 5 ends with conclusions drawn from previous chapters.

The dissertation is based on two publications for which additional information is provided in the Chapter: ‘List of articles published as result of this dissertation’.

2 Information content of global ecosystem service databases and their suitability for mainstreaming ecosystem services



2.1 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 [20]. The ES concept 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 [90]. All economic activities are ultimately linked to and influenced by trends in ES supply [91]. The ES concept 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 [12; 92]. 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 [93; 94], corporate disclosure policy [95; 96], public payment systems [26], cooperation between public and private sector [17], landscape planning [97] and other large-scale decision contexts [19]. 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 [27; 28].

The number of ES studies is fast-growing and rapid advances in information technology, globalization, and increasing networking cause an information overload [45; 80]. 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 [49]. Existing data and information resources are widely distributed, heterogeneous, and difficult to combine [49; 50]. 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 [98]. 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 [99-101; 39]. Guidelines and standards for an improved operationalization of the ES concept are steadily developed, e.g. for assessment practitioners [102; 14; 103], development planning [104], the business sector [94; 96], as well as policy and decision-makers more generally [90; 105]. 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 [54; 49; 50].

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 concept, 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 [106]. 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 [107]. 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 [108].

Databases vary greatly in size, scope, standardization, usage, accessibility, and other characteristics. Three functional types of databases can be distinguished [108]: 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 [85]. 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 [109]. 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.

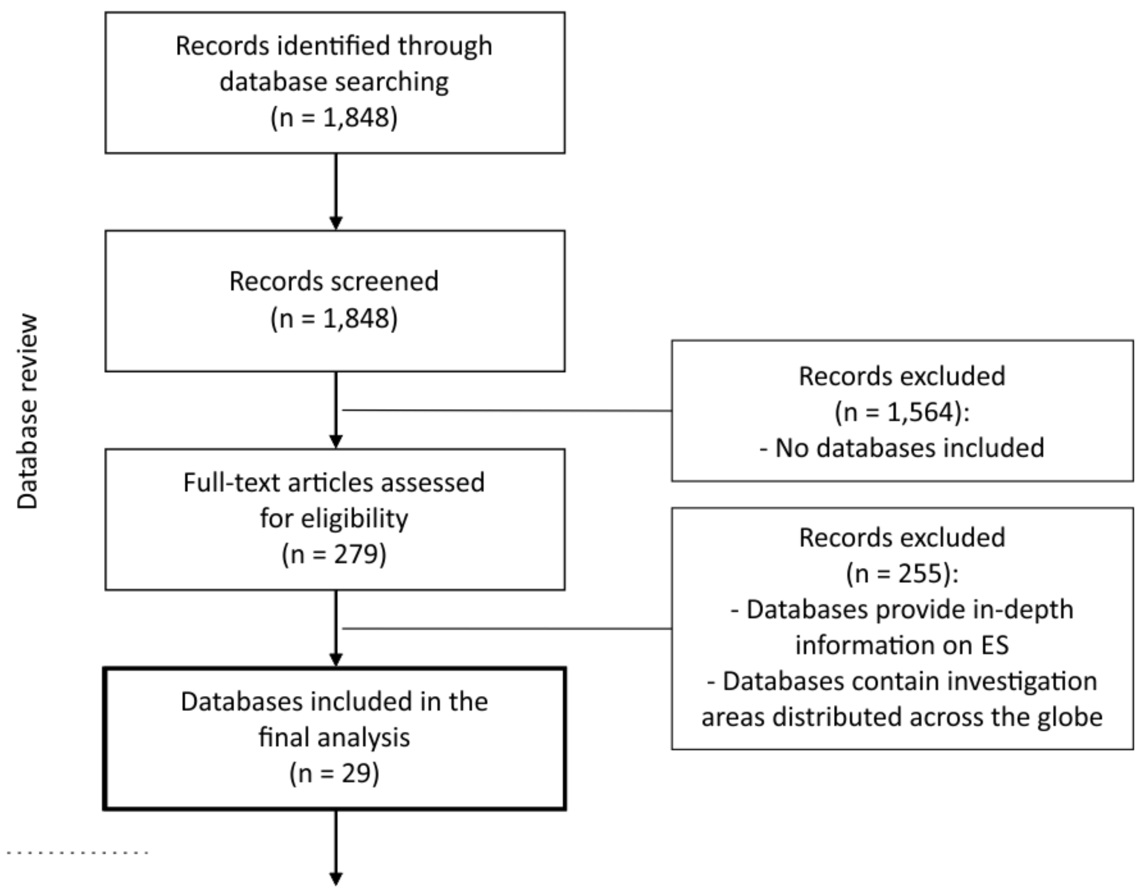
Given the information demand on ES knowledge for decision-making and the diversity of ES databases, I here investigated how information demand on ES for decision-making can be fulfilled by knowledge on ES provided in publically available databases. I conducted systematic reviews of literature driven 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 I 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, I focused on a set of policy instruments for safeguarding nature. Methodologies of both reviews are described in Section 2.2. In Section 2.3, I 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 2.4, I 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 2.5.

2.2 Review processes: Data and methods

I 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 (Fig 2.1). From these peer-reviewed publications I identified 279 that used or reported on databases containing information about ES. I 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 2.1). 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 this review 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.



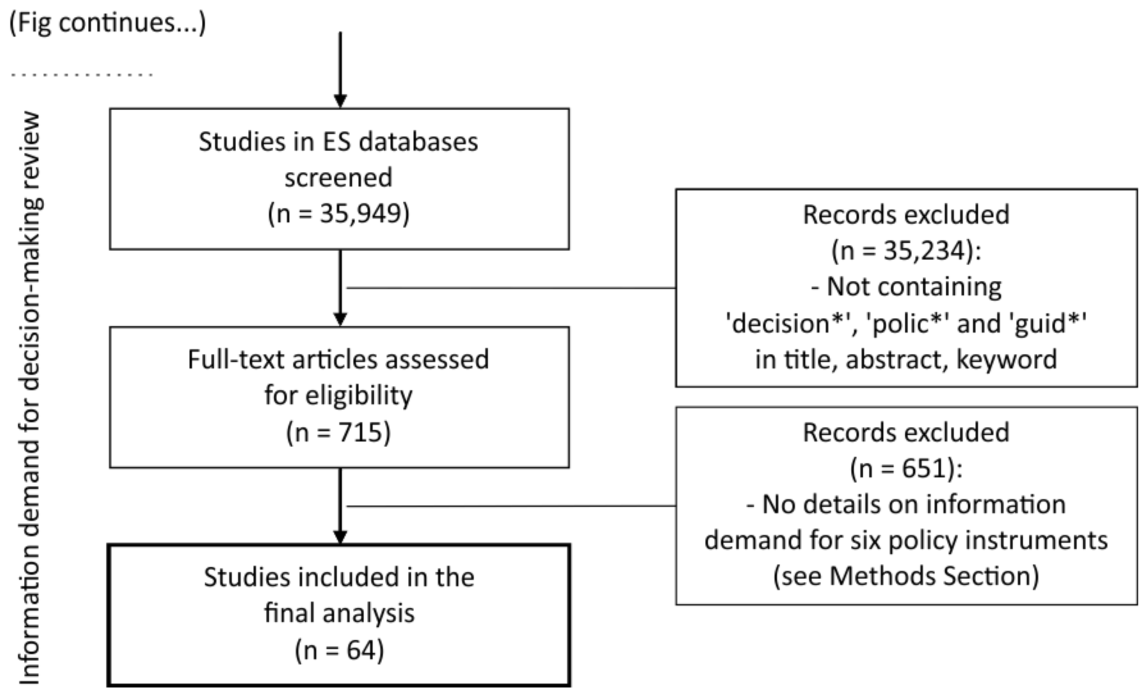


Fig 2.1. Workflow diagram for systematic review. The diagram shows different phases of the review process to identify ES databases and literature addressing information needs for decision-making.

Table 2.1. 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 [110].
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 [111]
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 [112]
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 catalogue qualitatively lists details on design, outreach material and impact of both ES and biodiversity assessments.	United Nations Environment Programme - World Conservation Monitoring Centre [21]
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 [113]

(Table continues…)

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 [114]
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 [115]
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 [116; 55]
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 [117]
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 [118]
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 [119]
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 [120]
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 [109]
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 [121].
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 [79]
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 [122]

(Table continues…)

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 [123]
Linking functional traits with ES (de Bello et al., 2010)	Synthesizing concepts and empirical evidence on linkages between functional traits and ES across different trophic levels. Information on plants, vertebrates and invertebrates traits and their roles for ES are reviewed, and documented in a spreadsheet format.	Not online: Database available on request [124]
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 [125]
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 [126]
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 [85]
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 [127]
Payment for watershed markets (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 [128]
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 [129]
Sub-Global Assessments database (SGA)	Qualitative documentation of sub-global assessments from the Millennium Ecosystem Assessment [130] 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 [131]
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 [22]
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 [132] and in the ELD Initiative [133] 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 [133; 132]

(Table continues…)

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 [134]
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 [135]

In a second step, considering the vast scope of information demand on ES in decision-making, I 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. I used the following six policy instruments suggested by TEEB [136]:

(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.

I then specified the information demand for each policy instrument by reviewing publications contained in the 29 databases. Because of the vast number of publications (35,949), I 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. I found 64 publications (S2.1 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 (2.3 Results).

In the final step, I defined an indicator function $D_p(i,j)$ to quantify the relevance of a specific database k ($k = 1, \dots, 29$) in contributing to indicators of information demand of a policy instrument p ($p = 1, \dots, 6$). This function returns 1 is the data entry (i,j) in column i ($i = 1, \dots, n_k$) and row j ($j = 1, \dots, m_k$) of a database, which contains information, i.e. is non-NA, and informs a policy instrument p.

$$D_p(i,j) = \begin{cases} 1 & i,j \text{ is non-NA and informs policy } p \\ 0 & \text{else} \end{cases} \quad (1)$$

The function R estimates the relevance of a database k to a given policy instrument p by counting the available relevant data entries $D_p(i,j)$.

$$R(k,p) = \sum_{j=1}^{m_k} \sum_{i=1}^{n_k} D_p(i,j) \tag{2}$$

The overall information available from the databases $k = 1, \ldots, 29$ which informs a policy instrument p is then estimated by:

$$M(p) = \sum_{k=1}^{29} R(k,p) \tag{3}$$

The number of indicators of information demand q_p for each policy instrument p varies considerably (S2.3 Table). In order to assess the information provided by databases $M(p)$ for a given policy instrument p in relation to the overall information provided by all databases for all policy instruments $M(p')$, I estimated this relative contribution $\widehat{M}(p)$ by normalizing given the number of indicators q_p for each policy instrument p.

$$\widehat{M}(p) = \frac{M(p)}{q_p \sum_{p'=1}^{6} M(p')} \tag{4}$$

In total, 1,945 database columns and more than 600,000 data entries were reviewed and assigned respectively to indicators of information demand and policy instruments. The full data set is available at Schmidt [137].

2.3 Results

2.3.1 Characteristics of global databases containing ecosystem service 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 2.1). Second most common topics were methodological analysis of applications of the ES concept 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).

[1] Percentage values in this paragraph do not sum up to 100%, because of contextual overlaps of some databases. Following percentage values in this Section 2.3.1 refer to the total of 29 ES databases, not relative contributions ($\widehat{M}(p)$).

The databases collated information from 35,949 studies. Three out of every five studies in all databases contained information for countries with a high Human Development Index [138], while only 4% of all studies were conducted in society's poorest nations[2] (Fig 2.2). The continent with the fewest number of studies (2%) was Latin America.

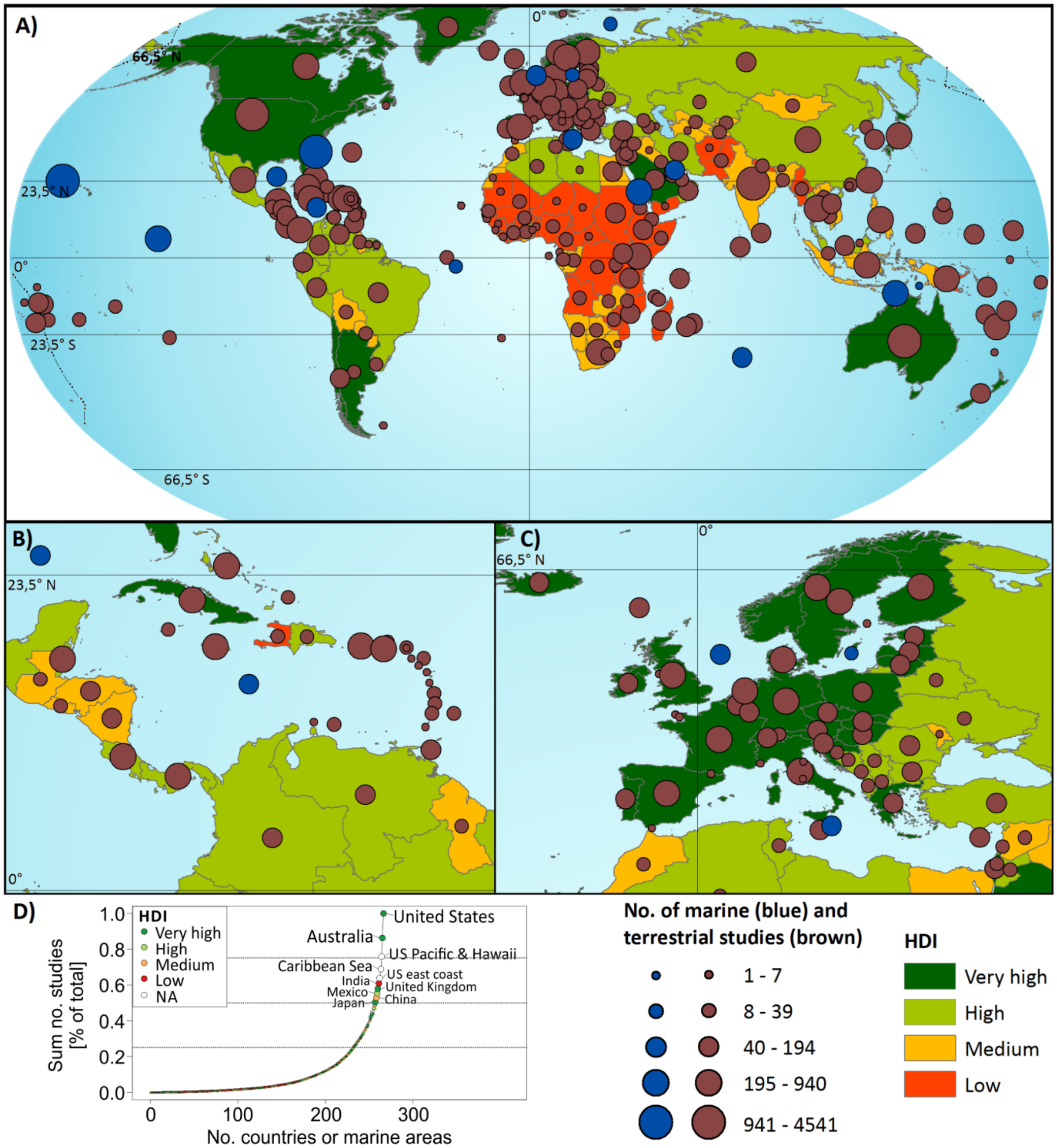


Fig 2.2. Geographic distribution of ES analysis from 29 databases. The panels (A-C) show the number of ES studies (size of circles) for each country (brown) or marine area (blue). The color codes of the maps represent

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

development status of countries based on the Human Development Index [138] 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.

Regulating services were most frequently reported, followed by cultural, provisioning, and supporting ES (Fig 2.3). Quantitative information expressed in numeric variables was recorded in 4% of columns of databases (Fig 2.3). 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).

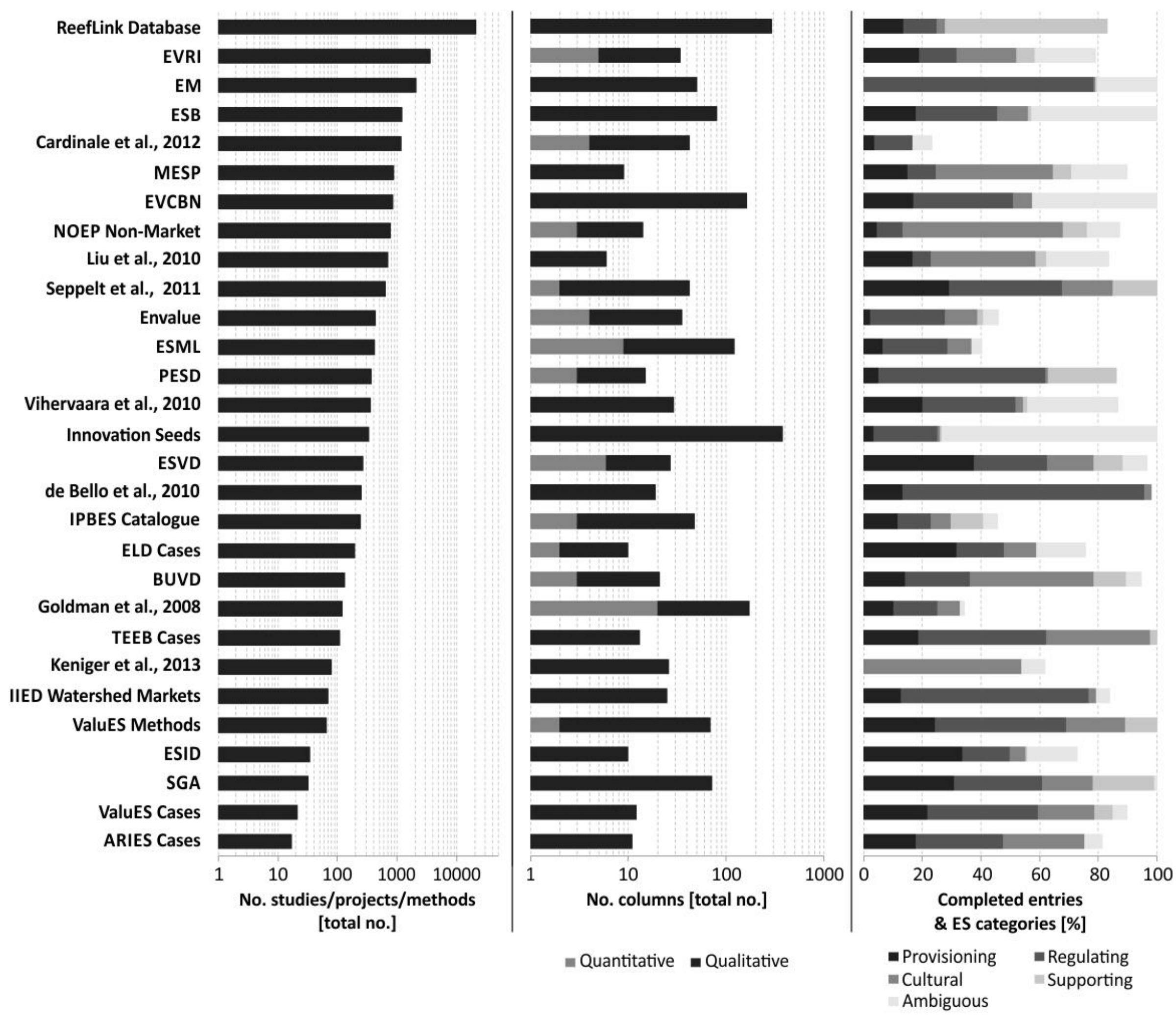


Fig 2.3. General characteristics of ES database contents. In total 35,949 studies/projects and 163 methods were documented in the reviewed 29 databases (bar plot left). Databases were structured in 6 up to 379 columns (bar plot middle) that provided quantitative (light gray) or qualitative information (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 data entries referred to regulating services, followed by cultural, provisioning and supporting ES (gray scale bar plot right).

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 2.4). 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.

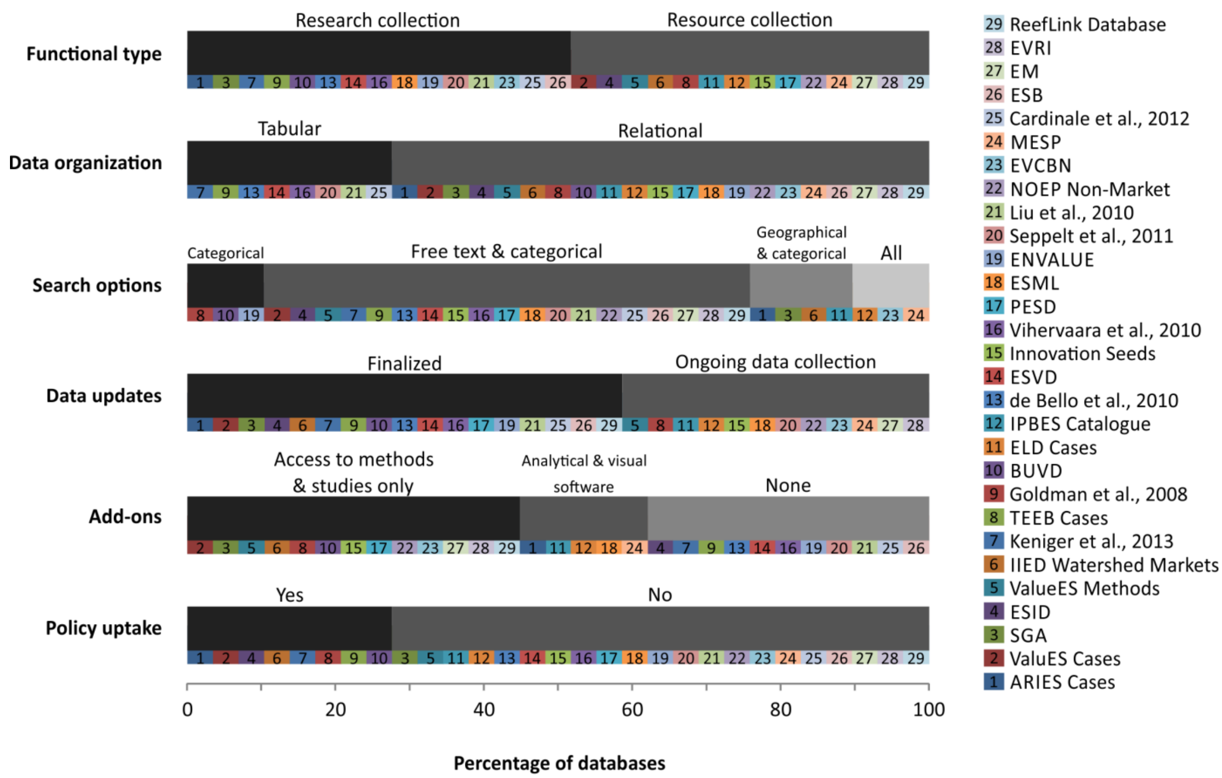


Fig 2.4. Design and impact of databases. Percentage of the 29 databases that belong to specified characteristics. Characteristics are defined in S2.2 Table. For the characteristic 'search option' the category 'all' includes 'categorical', 'free text' and 'geographical'. The colored bars (lower part of bar) indicate the database for each characteristic respectively.

The majority of the 29 databases (72%) organized data based on a relational data design (Fig 2.4), 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 2.4): (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 2.4). 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 2.4). 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 2.4). 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).

2.3.2 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 2.2. Also, a comprehensive list of the identified 93 indicators and their relation to the six policy instruments was provided in S2.3 Table.

Table 2.2. 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 [139].	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 [140].	IIED Watershed Markets: 'Legislation Issues' explain legal provisions related to PES for watersheds.
Metrics	Unit of measurement by which ES are assessed [78].	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 [141; 142].	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 [143], public compensation mechanism [144] and other financial policies that reward nature-friendly stewardship and spur green markets [145; 146].	ReefLink Database: 'Funding & Incentives' includes budgetary decisions by public administration to affect activities related to coral reefs.

(Table continues…)

Spatial analysis economic benefits	Spatial explicit appraisal of ES benefits for human well-being in monetary terms [147].	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 [148].	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 [149].	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 [150; 149].	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 [151] or quantity controlling through permits, quotas, licenses [152]) or other compensation approaches (offsets, biodiversity banking) [153; 154].	Goldman et al. [113] 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 [155], or legal regimes for environmental issues [156].	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 [157].	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 [158; 159; 100].	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 [160].	No column headers refer to the indicator, only in titles of references, e.g. in ReefLink Database: Gjertsen [161].

(Table continues…)

Regulatory mechanism for costs & benefits	Documentation of policies or mechanisms for equitable sharing of benefits and costs arising from protected areas [162; 136]. 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. [163].
F) Direct public investment in ecological infrastructure and restoration		
Restoration	Provision of information on restoration. Restoration in accordance to Aronson et al. [164] 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 [165; 166].	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 [167; 168]. Also methods to identify investment opportunities are considered, e.g. the Resource Investment Optimization System (RIOS) that supports cost-effective investments in watershed services [169].	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.

2.3.2.1 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' [170].
- Requirements for information differ on various scales [171; 136]. 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.

2.3.2.2 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 [136].
- 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.

2.3.2.3 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.' [148], can harm or benefit the environment [172]. 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.

2.3.2.4 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.

2.3.2.5 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.

2.3.2.6 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 [173], 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 [174]. Usually it is more cost-efficient to avoid degradation than to pay for ecological restoration.

2.3.3 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 2.5 (S2.1 Fig for details on indicators 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. In Table 2.3 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 concept [12] 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 of the databases quantifies relationships for all of the components.

[3] Percentage values in Section 2.3.3 (including 2.3.3.1 to 2.3.3.6) refer to relative contribution ($\widehat{M}(p)$) between database entries and indicators of information demand, as described in Section 2.2. Exceptions were specified separately.

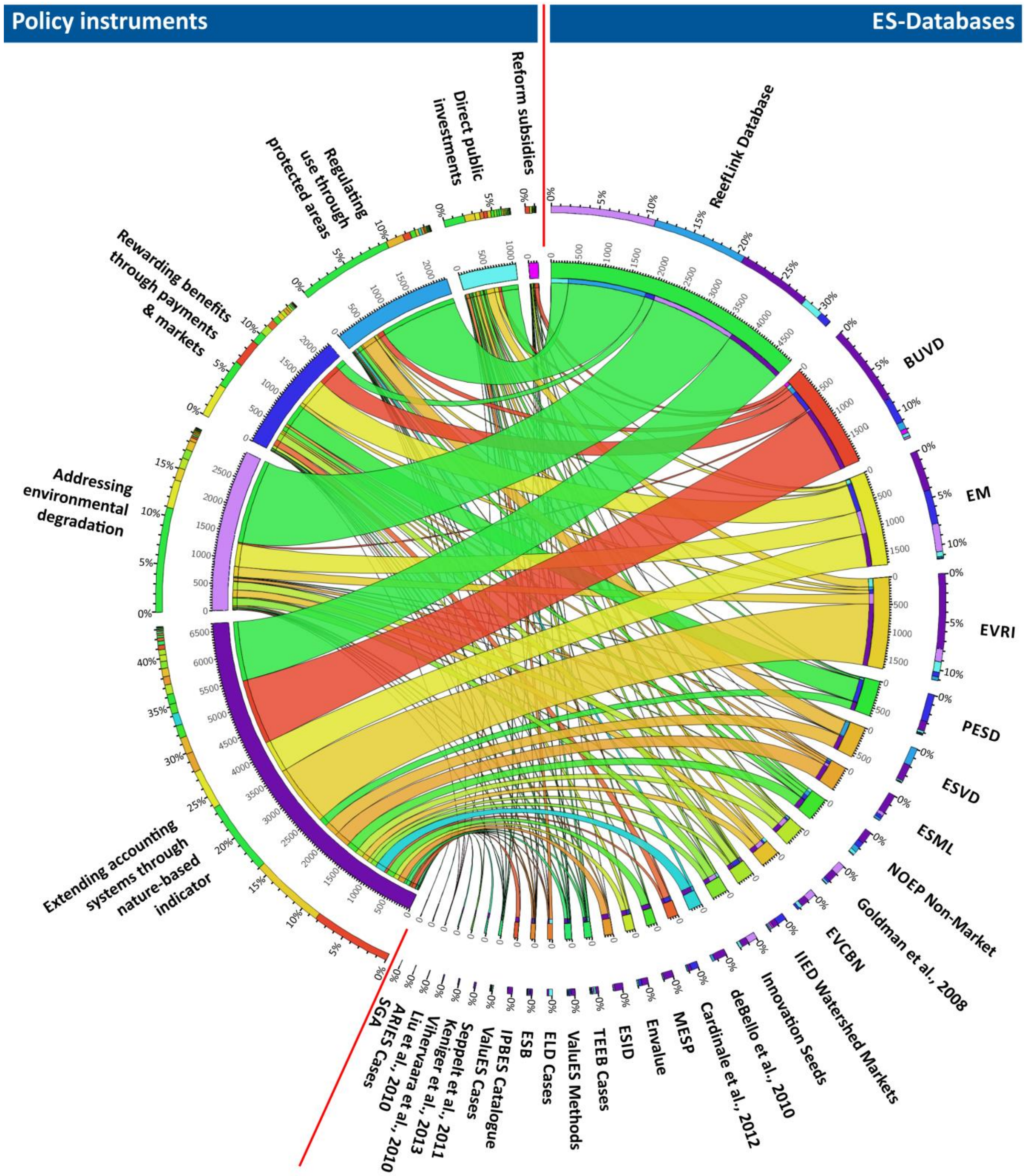


Fig 2.5. Quantitative matches between information supply provided by databases and information demand of policy instruments for safeguarding ES. The chord diagram connects information supply from 29 databases (right half) with information demand represented by six policy instruments (left half). It shows the relative contribution (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, yellow, orange), while colors from the inner left and outer right distinguish policy instruments (e.g. purple, bluish). Additionally, S2.4 Table provides the explicit numbers for the relative contributions.

Table 2.3. 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 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.

Databases	**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 indicators & 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)

(Table continues…)

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)

2.3.3.1 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 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 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.

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.

2.3.3.2 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.

2.3.3.3 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.

2.3.3.4 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.

2.3.3.5 Regulating use through protected areas and recognition of their values

Information that supports the establishment of protected areas and improves 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.

2.3.3.6 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 [175] or corporate social responsibility for wastewater treatment [176].

2.4 Discussion

2.4.1.1 Priority areas for mainstreaming ecosystem service 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. I 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 [177]. 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 [178]. 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 [179]. 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 [78; 180].

(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 [181]. 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 [182; 183]. 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 [184; 170; 185]. Even though a set of generally agreed engagement rules exists [170], 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 [186; 187]. 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) Facilitate 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. [188]. Approaches for capacity building vary considerably in different national and cultural contexts as well as for different purposes of use [189]. Examples for capacity building approaches include training and workshops, networks to share experiences and information, stakeholder engagement and fellowship programs [190]. 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 [136]. 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 [188]. Research should further engage in capacity building and develop knowledge exchange mechanisms that provide fast and simple access to ES research for broad audiences [191-193]. Steps towards the development of a more efficient knowledge exchange mechanism were illustrated in Section 2.4.1.2.

(5) Evaluation 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 [194]. Results of Chapter 2 showed 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 [195; 196]. 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 [26; 197].

2.4.1.2 Mechanism for more efficient knowledge exploitation

In addition to the five above mentioned criteria, I 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 [198]. Ontologies are explicit formal specifications of terms in a domain and relations among them [199]. 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 [200]. 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 [49] 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 [201] and the Sustainable Development Goals [202].

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 [203; 43]. 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 [204], OGC Working Group [205], SONet [206], ESIP [207], Rueda et al. [208], and INSPIRE from European Commission [209] 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 [210]. 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 S2.1 Table), was a pragmatic approach to get a broad overview of information demand of decision-makers.

2.4.1.3 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 I found a lack of information in the reviewed ES databases for society's poorest nations (Fig 2.2) 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 [211-213]. 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 indicators 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 [214], 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 [215].

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 [49], 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 I 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.

2.5 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 review for six policy instruments, provided a useful contribution to discussion on standards that define reporting requirements. Reaching consensus on standards that codify agreement on best practices will accelerate the incorporation of ES information into decision-making [39].

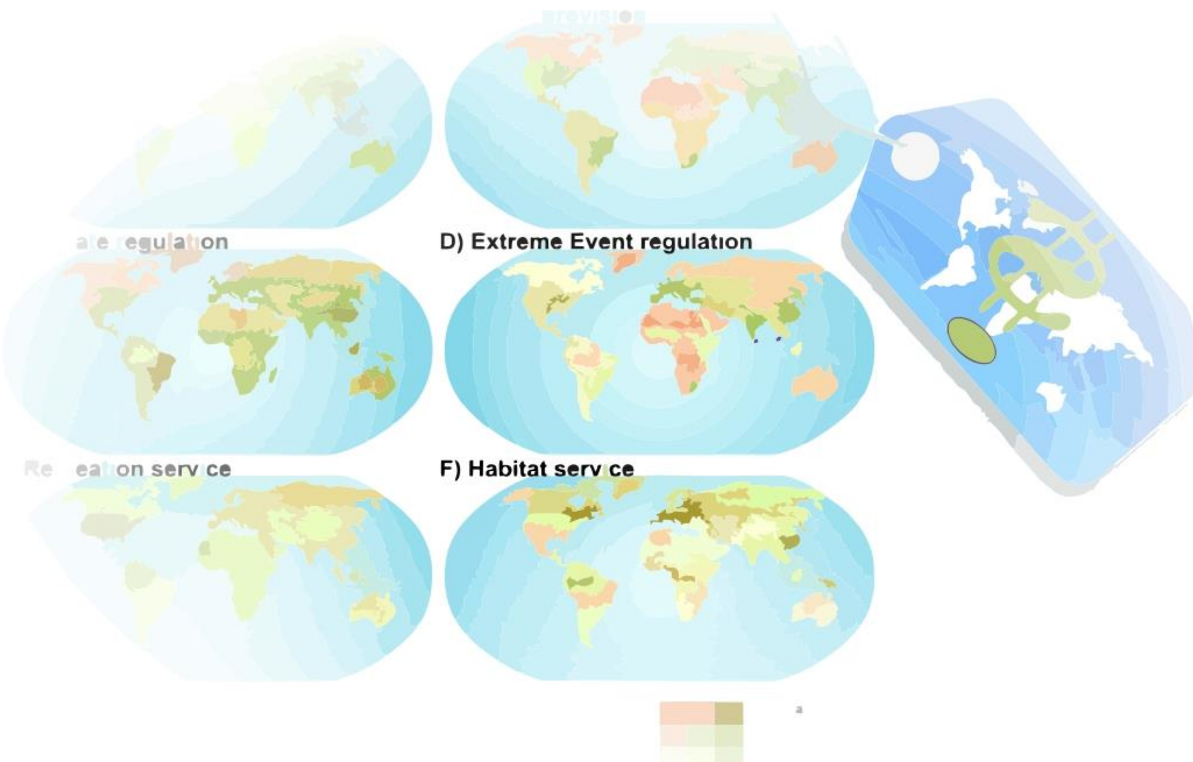
Results of Chapter 2 showed that databases provided information for most of the policy instruments. None of the databases were designed exclusively for the policy instruments and focused on specific parts only. This overlap in information supply and demand showcased that relevant information for decision-making 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 I 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 results of this review showed that there were common principles across indicators of information demand representing priority areas to formalize standards for the documentation of knowledge on ES. I found five priority areas which could be used to design an ontology that tailors the ES concept to decision-making realities. An ontology does not have to be developed from the scratch – mostly domain-specific examples exist [200] – 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 [108].

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 [185].

Challenges remain in the transferability of information from ES databases. By compiling 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 concept 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.

3 Uncertainty of monetary valued ecosystem services – value transfer functions for global mapping



3.1 Introduction

Many ES are common goods whose value is often underestimated or ignored in commercial markets [216] and decision-making processes [217]. This puts natural capital at risk due to possible mismanagement [13]. Proponents of economic valuation argue that with the quantification of ES in monetary terms conservation strategies and economic objectives could be harmonized, decision-makers better informed and ultimately environmental degradation reduced. Economic valuation of ES is lively debated [100; 63], or even substantially criticized [72; 62]. Arguments for the estimation of ES in monetary terms are that monetary values combine a variety of interdisciplinary measurements in one unit, they are understandable and easily to communicate, and promise transferability across sites [218; 219]. Monetary valuation is seen as a powerful tool for decision-making [92]. Also it holds the promise of providing an efficient use of limited funds for conservation and restoration [55]. Besides ethical [72] and conceptual concerns [62], there is substantial scepticism that monetary valued ES are globally comparable and reliable, due to the high diversity in human-environment system and the multifarious socio-ecological linkages that influence the perception of societal groups for and finally values attached to ES [171; 220; 33; 63; 221].

Despite this critique ES are valued in prominent assessments of natural capital [13; 222; 223], in activities of economic development and poverty reduction [224-226], hazard mitigation programs [227] and business studies [228; 229]. Meanwhile a considerable range of monetary values of ES became apparent across the globe [55]. In primary valuation studies, i.e. first-hand monetary appraisal of ES, effects arising from site- and study-crossing factors are frequently neglected. So are covariates that characterize the context of the study site assumed as being constant and are often not reported in primary valuation studies [66]. Secondary valuation approaches, such as benefit transfer, estimate values for unsampled areas utilizing results from distant studies. Benefit transfer thus aims at putting individual studies in a broader context and is promised to be more time and resource efficient than conducting primary studies [230].

A first major critique refers to benefit transfer in its basic form. Benefit transfer averages monetary values (point estimates) from study sites and transfer them to a similar unsampled area by accounting for land use/land cover types only [231; 55; 232]. More sophisticated benefit transfer approaches, such as meta-analytic value transfer functions control for differences between sites and aim at minimizing errors that come with the transfer process [219]. In any case, assigning a monetary value on nature is not considered to be absolute, rather it is an indication in a particular area, over a given time period, for a specific beneficiary group, depending on valuation context and use. Thus, the key question arises: How reliable are value transfer approaches and what are the associated uncertainties?

A second critique originates from the complexity and heterogeneity of human-environmental systems. Due to the variation in site characteristics, e.g. socio-economic or biophysical feature [233; 234], and study characteristics, e.g. valuation method [235; 236], the error resulting from generalization and transfer is the core critique. In order to apply benefit transfer models for decision-making it is required to identify potential errors [70; 71; 66], establish an accepted framework for assessing the magnitude of errors and incorporate the uncertainties to the formal valuation process, as well as communicate monetary values directly in association with uncertainties to decision-makers. Therefore, the second key question of Chapter 3 is: What promises in transferability of monetary valuation of ES can be hold given most up-to date data?

In Chapter 3, I assessed the transferability of monetary values of ES and identified major sources of uncertainty by using meta-analytical value transfer functions. I generated a spatially explicit database of 194 globally distributed valuation studies covering 839 monetary values of ES from peer-reviewed data collections [85; 55]. I built robust meta-analytic value transfer functions and tested the importance (statistical influence) of 93 site- and study-specific covariates in explaining the variance of monetary valued ES. This allows me to identify key sources of uncertainty of the value transfer functions at finer spatial scale (30 arc min). In doing so, I conducted the first comprehensive uncertainty analysis for a set of twelve monetary valued ES on a global scale. Findings in my analysis showed (i) the first global uncertainty maps of benefit transfer based on meta-analytic value transfer functions, and (ii) crucial parameter and uncertainty that needs to be considered to lower transfer errors.

3.2 Methods

3.2.1 Synthesizing databases on monetary values

From the 29 ES databases identified in Chapter 2 only Seppelt et al., 2011 [85] and ESVD [55] were selected to retrieve information for this analysis, see Fig 3.1 and S3.1 Table. Both databases contain monetary values of ES and spatial information for the localization of ES. Considering the time restrictions of this dissertation the usage of the two databases was a purely pragmatic decision. ES from the databases were harmonized to a common, comparable set of ES types using a standardized classification system [15] to avoid semantical differences between varying ES terminologies. In this standardized classification 22 ES types are grouped in four classes: provisioning, regulating, cultural and supporting ES. Monetary values were translated into 2007 'International Dollar' per hectare and year by using the World Bank deflator and purchasing power parity conversion factors [55]. Furthermore, I extracted from the valuation studies detailed information on the investigation areas for each ES type (S3.2 Table) and used ArcGIS 10.2.2 in order to geo-reference the study site spatially explicit. In total 1,033 maps of standardized monetary values were generated.

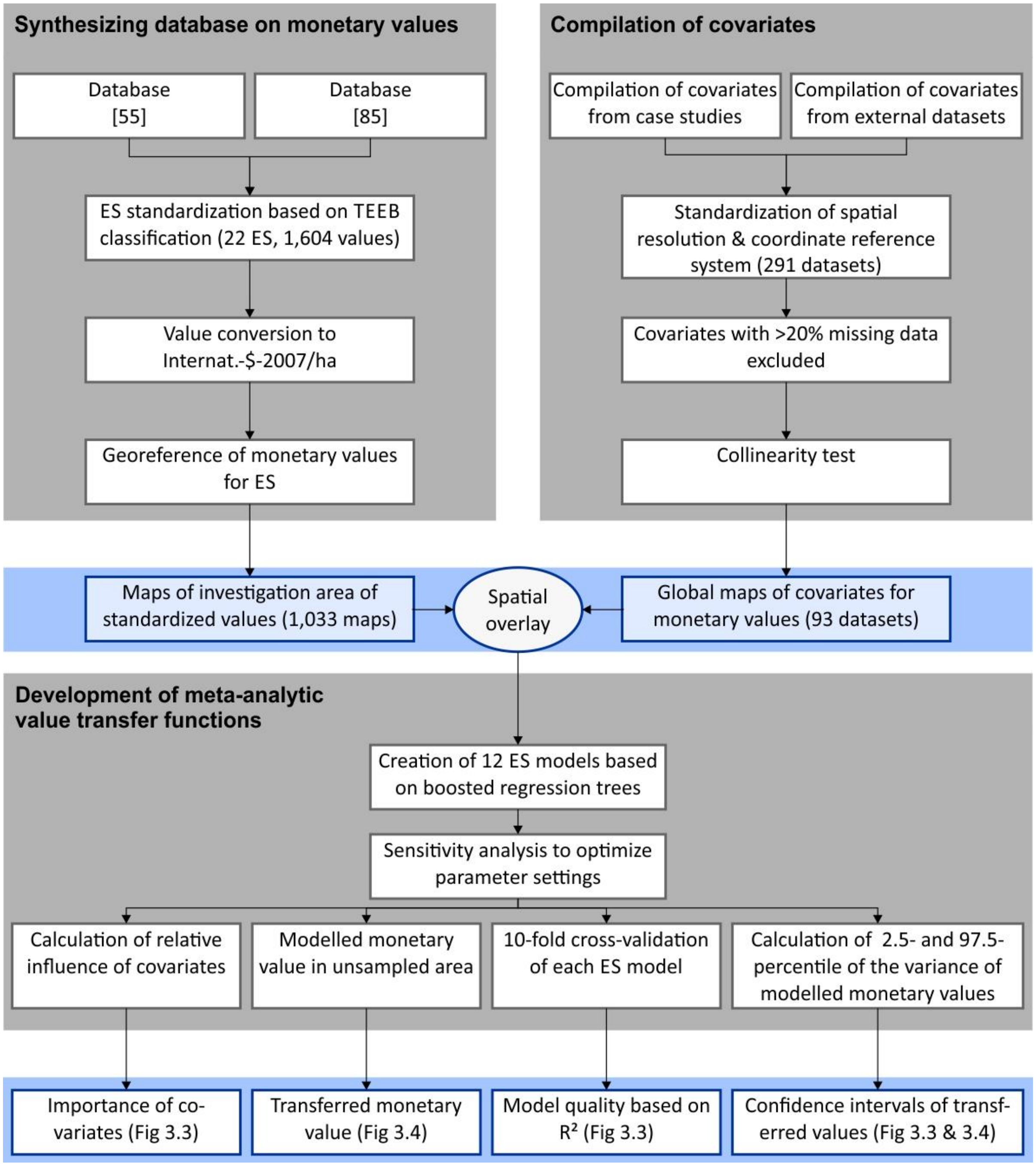


Fig 3.1. Workflow from data compilation to uncertainty estimation. The diagram shows different steps of data preparation and analysis (grey boxes): (i) synthesis of monetary values (response variable), (ii) compilation of covariates that are supposed to affect the variance of monetary values; and (iii) development of value transfer functions. The bluish boxes show (interim-) results of the different steps and refer to figures that visualize these outputs.

3.2.2 Compilation of covariates

Based on a literature review of variables that are supposed to affect the monetary valuation I identified relevant global geo-datasets. These data were used as explanatory variables for the statistical analysis and will be hereinafter referred to as covariates (Fig 3.1). Data captures six groups: economy, policy/governance, other societal data, ecology, valuation methods, and scale. Some of these covariates were derived from the original studies. S3.2 Table provides an overview. All covariates were standardized to the same coordinate reference system (WGS 1984) and same resolution of 30 arc min, see Fig 3.1. If spatial coverage shows more than 20% missing values, covariates were excluded from the analysis. Also covariates were tested for collinearity and highly correlated excluded. For continuous covariates I used Pearson correlation coefficient ($r > 0.75$ or $r < -0.75$) and Spearman's rho ($\rho > 0.75$ or $\rho < -0.75$), for two categorical covariates chi-square test and for testing categorical and continuous one-way ANOVA. From 291 covariates 93 remaining were combined with the maps of standardized monetary values by overlay operation in ArcGIS. Combined maps were used as input for the value transfer functions (Fig 3.1). This data collection is one of the most comprehensive databases available.

3.2.3 Meta-analytic value transfer functions

I computed meta-analytic value transfer functions for each ES type using additive regression models based on boosted regression trees (BRT). A BRT computes the relative influences (importance) of covariates for a BRT model, i.e. they identify major determinants of the variance in monetary values of ES. BRT also provide elasticity curves (partial dependence plots) that account for non-constant marginal value changes over distinct socio-ecological conditions and thus quantify the change of monetary values in response to an alteration in one covariate (i.e. ceteris paribus) [181]; see S3.2 Fig. Resulting BRT models were used to transfer and map values in unsampled areas. BRT are specifically suited to quantify comprehensible covariates in situations where many variables are expected to explain the process at hand, which interact in complex, non-linear ways [237]. They allow for including different types of covariates (numerical, binary, categorical), can accommodate missing data in covariates by using surrogates [238] and show high robustness to the effects of extreme outliers. BRT models were computed utilizing the 'Generalized Boosted Regression Models' library [239; 240] with the programming language R [241].

I tested different parameter of the BRT algorithm such as learning rate, tree complexity, minimal number of observations in terminal nodes and number of trees (see S3.1 Box), and choose a robust model with high explanatory power. The final parameters selected for the BRT models are documented in S3.3 Fig.

Statistical significant value transfer functions could be computed for twelve ES types based on 839 monetary values (out of 1,033 monetary values). Most important covariates were quantified and monetary values in unsampled areas extrapolated (Fig 3.1). If there were less than 11 valuation studies or less than 26 monetary values data were not sufficient to generate reliable value transfer functions (for 10 out of 22 ES). I globally mapped monetary value for twelve ES types on a 30 arc min grid by applying the derived value transfer functions based on global covariates for the entire terrestrial earth surface (except the ant- and artic areas). For the spatial value transfer I used the R library 'Raster'. Moreover, I computed the coefficient of determination R-squared for each value transfer function based on ten-fold cross-validation to estimate the explanatory power.

In an additional step confidence intervals were estimated to examine generalization failure of value transfer functions from training data (Fig 3.1). I rerun the BRT models under different parameter settings (see S3.1 Box), calculated the 2.5- and 97.5-percentile values of the variance of transferred monetary values and mapped the range of percentiles for each grid cell. Three classes of uncertainty (low, middle, high) were used for mapping based on equal-interval classification for each ES separately. Finally, twelve bivariate maps were created by overlaying the classes of uncertainty with maps of extrapolated monetary values mentioned above. These maps were used to estimate the percentage area of terrestrial earth surface covered by transferred values of low, middle and high uncertainty (Fig 3.1).

For the discussion of the results I conceptualized three major sources of uncertainty of value transfer functions: (i) Sample error, such as measurement error in input studies for value transfer functions or publication selection bias; (ii) errors originating from statistical estimation of BRT models (model performance and suitability of chosen approach for benefit transfer); and (iii) transfer error from generalization that encompasses distortions due to value transfer without fully accounting for site and study characteristics. Only covariates with >1% (relative contribution for value transfer functions) were analyzed for the six groups of covariates. Additionally, in a fourth point I provided information of the spatial application of the value transfer functions.

3.3 Results

3.3.1 Overarching findings

Available input data: All studies considered in the synthesized database (Fig 3.2) come from scientific peer-reviewed publications (48%) or grey literature selected by experts with background in ecological economics (52%) [85; 55]. The majority of the studies were conducted in lower latitudes, i.e. areas with an annual mean temperature >15°C (81% of studies), in areas with in average more than 100 inhabitants per square kilometer and in areas with high accessibility to international markets (92%), as well as in areas with high threats of degradation (71%). In only 7% of studies valuations were carried out in countries with a per capita income smaller than 1,045 International-$-2005 (purchasing power parity adjusted).

Model uncertainty: The final twelve cross-validated value transfer functions explain from 18% (water provision) to 44% (food provision) of the variance of monetary values (Fig 3.3). Furthermore, confidence intervals for the value transfer functions were calculated which display low to medium uncertainties for 70% (water provision) to 91% (food provision) of the terrestrial earth surface (Fig 3.3).

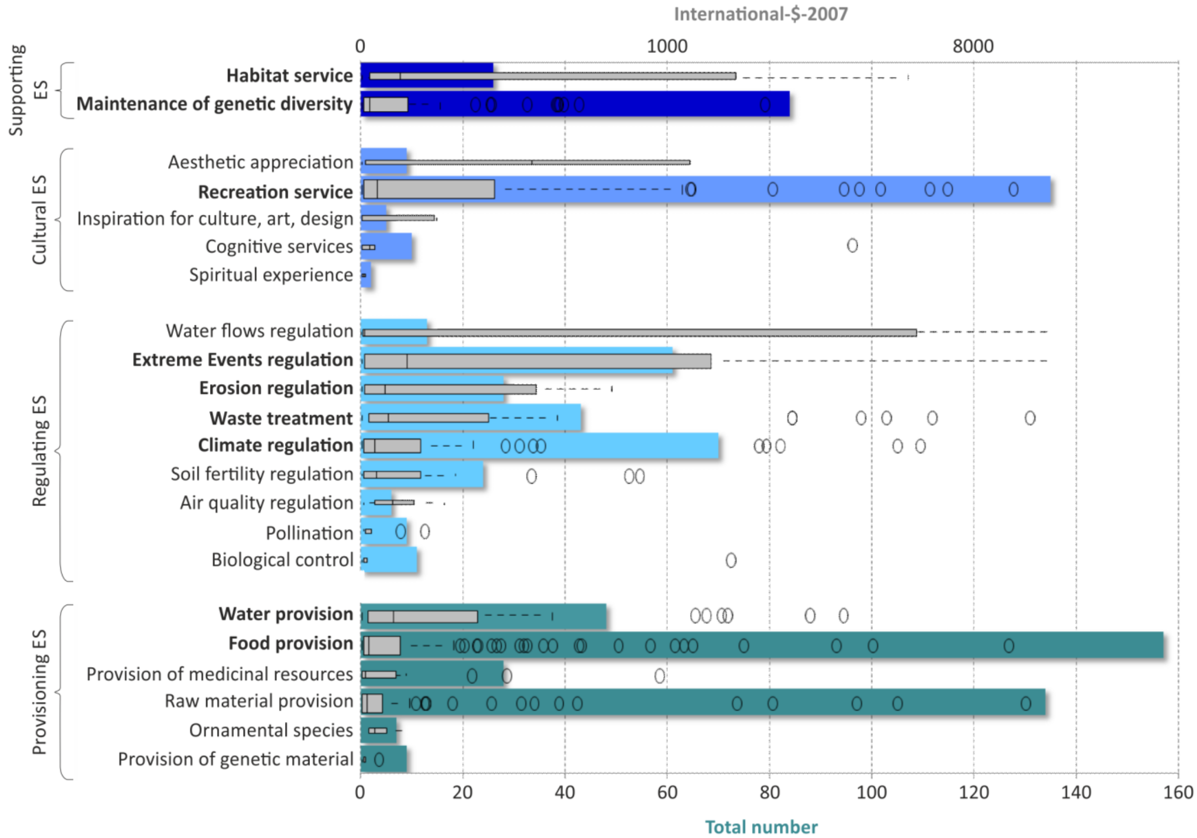


Fig 3.2. Range of monetary valued ES. The figure illustrates the database of unit-adjusted monetary values of standardized ES types from peer-reviewed data collections [85; 55]. The coloured bar charts reflect the total number of monetary values per ES type; the grey boxplots represent the variability of economic values. ES in bold font indicate the selection of twelve ES types (839 values) that were used for the value transfer functions.

Importance of covariates: Results from the quantification of the importance of covariates for the value transfer functions indicate which site and study characteristics need to be considered in order to minimize transfer error from generalization. In Fig 3.3 most influential variables (>1% relative contribution for value transfer function) are shown for six groups of covariates. Ecosystem-based covariates (green) are the most important (up to 90%). Contrary to the frequent critique on the monetary valuation of ES, covariates from the economy (purple, 1%-19%) or from other societal and policy settings (dark- and light blue, 6%-27%) show lower influence. Also covariates describing the analytic dimensions of scale (orange, 1%-26%) and valuation methods (red, 0-15%) are relevant, but contributing little to the explanation of the variance. Subdividing the groups of covariates show that variables indicating environmental degradation are most influential, followed by the variables of spatial extent of investigation area from valuation studies and market accessibility.

Application of value transfer function: The application of the value transfer function for spatial extrapolation of values in unsampled areas results in a map shown in Fig 3.4. Summarizing findings across all ES show that highest uncertainties are computed in areas where no valuation studies are available or covariates are missing. These are sparsely populated areas such as big deserts (Sahara, Kalahari, Desert of Australia, Arabian Desert), taiga and tundra (parts of Siberia, eastern Canada), ice and snow area (Greenland) as well as highlands (North America).

In the following Section 3.3.2 I discussed the results in detail for six out of twelve ES. Food and water provision, climate and extreme events regulation as well as recreation and habitat service were selected, because they represent the highest variance of monetary values from each ES group (provisioning, regulating, cultural and supporting), see Fig 3.2.

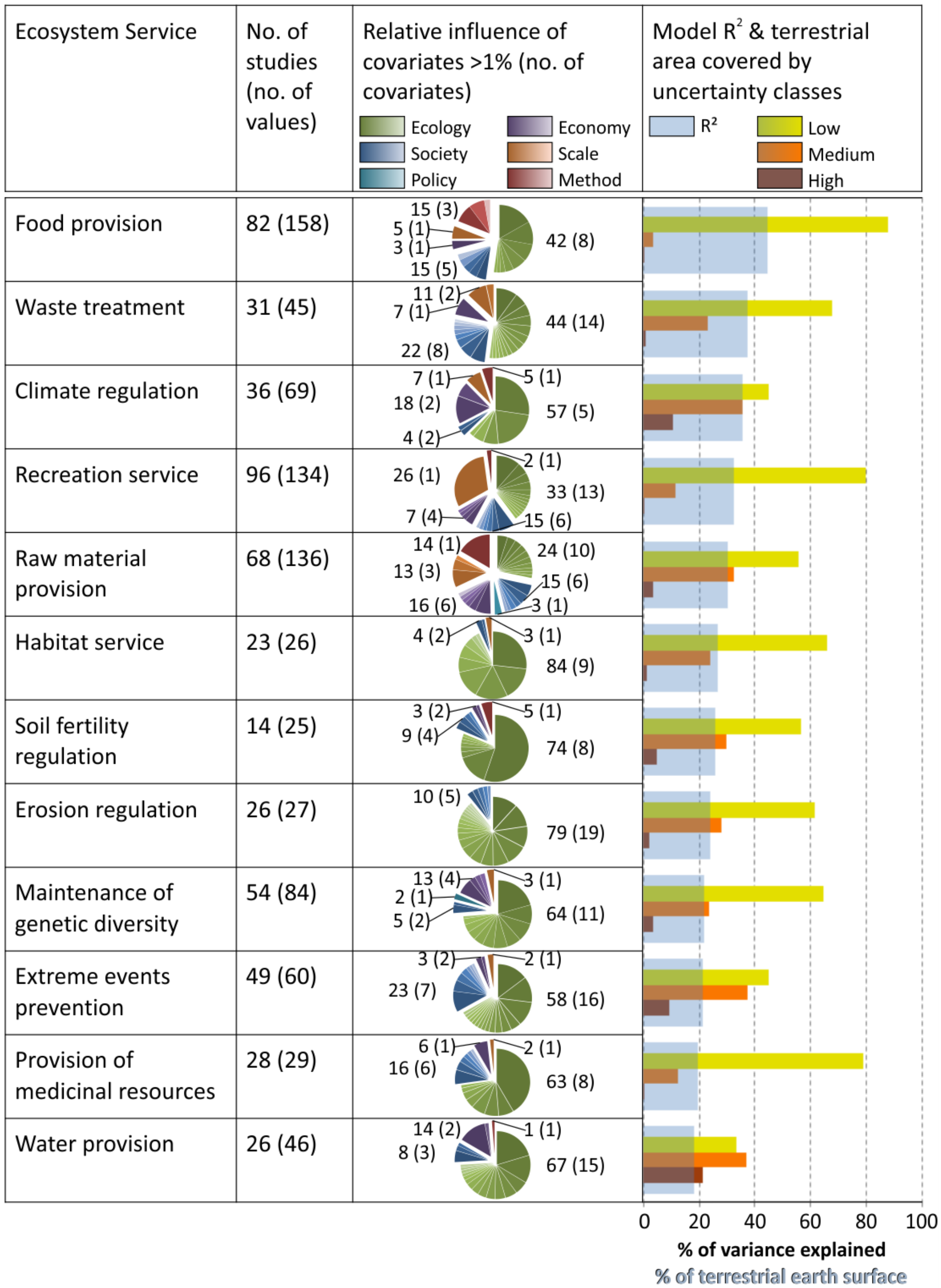


Fig 3.3. Overview of input data and characteristics of value transfer functions for twelve ES. The table shows the number of valuation studies and monetary values for each ES (2nd column). In the 3rd column pie charts

reflect the relative influence (importance) of groups of covariates expressed in percentage values and number of covariates (number in brackets) in these groups. The importance of covariates is illustrated by the size of the pie slide and quantified in S3.2 Fig. The bluish bar charts in column 4 represent the model quality based on percentage of variance explained by the model (R-squared). Additionally, column 4 shows the percentage area of terrestrial earth surface covered accordingly to uncertainty classes (low, medium, high).

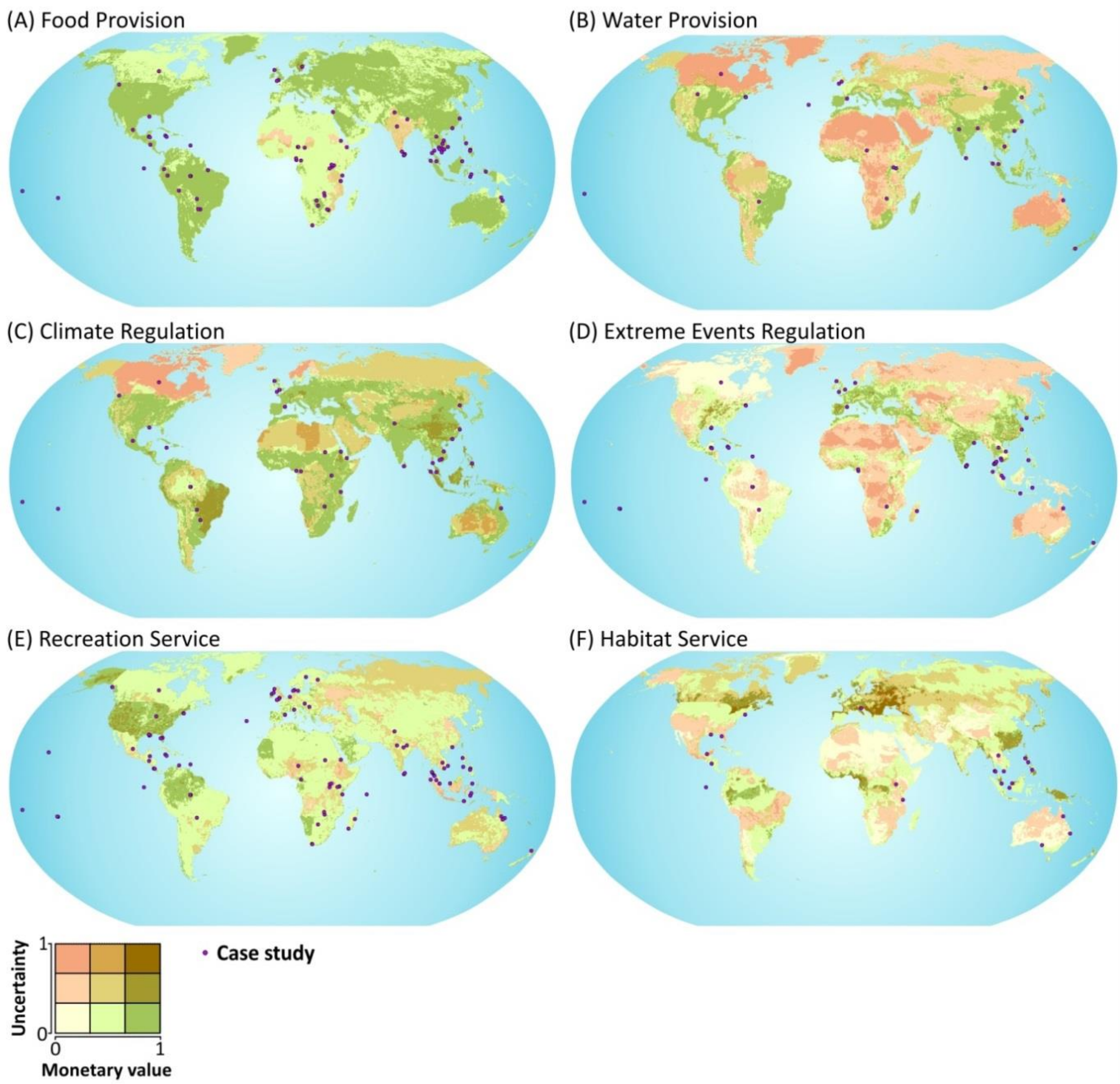


Fig 3.4. Global spatial distribution of monetary estimates and uncertainties. The bivariate maps show the extrapolated relative monetary values (yellow to green) and uncertainties (yellow to red) of the meta-analytic value transfer functions for the ES: (A) food provision, (B) water provision, (C) climate regulation, (D) extreme events regulation, (E) recreation service, and (F) habitat service. Monetary values and uncertainties are grouped into three classes (low, medium, high) accordingly to the spatial extrapolations of the optimized value transfer functions respectively the confidence intervals of transferred monetary values (see Method Section 3.2). The classes were defined by equal interval distances for each ES separately. Accordingly, classes between ES contain different ranges of values. However, a standardized color code (0-1) was used for simplicity of visualization.

3.3.2 Ecosystem service specific results

3.3.2.1 Food provision

Available input data: With 158 monetary values the largest data set is available for food provision. The majority of valuation studies examine fish provision (51%) in lower latitudes (93%) and in coastal ecosystems or inland wetlands (69%). Lower latitudes (annual mean temperature >15°C) are most likely food-insecure regions with a high vulnerability to climate change [242]. Coastal ecosystems and inland wetlands are among the most human-impacted habitats globally [243; 244].

Model uncertainty: The value transfer function shows the lowest uncertainty and explains 44% of the variance in the data. Estimations of the confidence intervals show that for 91% of the terrestrial earth surface monetary values can be computed with low and medium uncertainty (1 to 80 Int.-$-2007 per ha), due to a high number of data points (Fig 3.3).

Importance of covariates: Most important covariates are climate indicators (22%), followed by geographic and nature endowment (15%) and valuation methods (15%). Further influential are social covariates such as better life domains of human well-being (12%) and religion (3%) as well as the economic covariate agricultural subsidies (3%).

Ecology*:* Covariates indicating climate and those on geographic and nature endowment show low values in areas with prevailing unfavourable growing conditions (14%, annual mean temperature >29°C, 7% annual mean moisture index <0.78) and low human-induced alteration of ecosystems (2%, Human appropriation of net primary production (HANPP) <11%) or high amounts of alternative food products (3%, extent of agricultural areas >30km^2 per grid cell). Variance explained by distance to sea (9%) is a logical consequence from the distribution of studies and the focus on fish as food resource. In more landlocked areas the importance of fish in the food supply reduces and so does the monetary valuation of fish. Moreover, different types of biomes explain 6% of the variance. Biome types such as coastal wetlands, coastal systems and cultivated areas (aquaculture) are most valued, and confirm previous findings from [55].

Valuation method: Direct market pricing is most often used for monetary valuation of food (70%), followed by benefit transfer (17%) and group valuation (5%). With group valuation significant lower values are derived. Most studies (75%) based on group valuation were conducted for fish in India, a country where fish consumption represents only 2% of protein intake [245], which might explain the lower valuation. Also the value type calculated in the studies influences the variance of monetary valuation. Annual values (91% of valuation) are systematically lower than one time payments (3%) and net present values (3%). The latter two value types consider more complex ecological and economic features, which may explain the higher values. Apart from fish (51%) also plants/vegetable food (15%) and non-timber forest products (15%), unspecific food (14%) and meat (5%) were valued. The ES subtypes explain 6% of the variance. Fish is highest valued and, on the contrary, meat lowest. Valuation studies focusing on the provision of meat were all conducted in developing countries, where starchy staples (e.g. maize, manioc, millet) are major part of the diets.

Society: The valuation of food increases with a lower unemployment rates (<10% of labour force) and a high number of people in working age (15-59 years), good education system (loss of schooling years due to inequality <30%) as well as with improving sustainable well-being measured by years of life satisfaction achieved per unit of resource used (Happy Planet Index). These covariates directly relate to the better life domains of the Organisation for Economic Co-operation and Development (OECD), which are essential metrics for human well-being [246]. This shows that the more positive the conditions for human well-being the higher people value food. This might be contra-intuitive, as people who desperately rely on external support for food and are undernourished would value food much higher. These regions, however, are not captured by the available data sets. I also found that the religious confession influence monetary values. Particularly in major Hindu sites significant lower values for food can be identified. Although, the dietary standards of Hindus vary in time and place, most of them do not eat fish. Except Hinduism the majority of the world religions are predominantly non-vegetarian [247].

Economy: With increasing subsidies in agricultural sector the value for food provision decreases. Subsidies distort markets by promoting the production of agricultural commodities beyond market demand, thus, they encourage farmers and fishermen to rely on them instead of consumer wants [248].

Application of value transfer function: Spatial extrapolation of values shows for food the highest uncertainties and lowest values are in India and parts of Africa (Fig 3.4). On contrary, most certain and highest values are in China, South-East Asia, USA, Brazil, Mexico, EU-member states and parts of the Russian Federation. It is striking that these areas match regions where a high consumption of fish and fish products as well as high capture rates occur [245].

3.3.2.2 Water provision

Available input data: For water provision one of the smallest datasets was available (26 valuation studies). Most of the valuation studies were conducted in climate sensitive lower latitudes (63%). Climate change is affecting the hydrologic cycle and directly impacts the water resource base, usage, and management, in particular in lower latitudes [249].

Model uncertainty: The value transfer function for water provision shows the highest uncertainties and explains 18% of the variance (Fig 3.3). Confidence intervals of transferred values illustrate that only 70% of the terrestrial earth surface is covered by low and medium uncertainty classes (1 to 26 Int.-$-2007 per ha).

Importance of covariates: Most influential are ecosystem-based covariates that indicate biodiversity and water availability (67%), followed by type of biome (3%). Further important are covariates of social and economic indicators (22%).

Ecology and society: Areas of high biodiversity threat and conservation value are positively correlated with monetary values and explain 21% of the variance. Biodiversity and water supply are strongly interrelated [250; 251]. Drivers leading to biodiversity loss, such as pollution or river fragmentation, are the same that causing water security problems [252]. Sites with high biodiversity show high human populations and substantially higher human population growth rates than that for the entire world [253; 254]. Therefore, increasing population drives the value for water (8%). These patterns can also be found in the spatial results of the value transfer functions (Fig 3.4), see below. Furthermore, in conservation areas the sensitivity of beneficiaries for the protection of common goods is more pronounced. Further drivers which put water provision under pressure and influenced the value transfer function could be identified. First, a higher risk of erosion leads to higher values

(12%). Second, increasing anthropogenic altered habitats due to land use change and harvest of primary production (8%, HANPP >15%, pasture area >5km^2 per grid cell), in particular, agricultural frontier areas of cropland foster high values for water provisioning (4%, crop area between 3 and 20km^2 per grid cell). Third, deforestation explains 3% of the variance and is positively correlated with water values. Water availability, moreover, depends on the spatial (3%) and temporal allocation of water resources (2%). The more unequal rivers and lakes are distributed in an area the higher is the value for water provision. Seasonal variability or long-term climatic changes cause extended periods of droughts or water abundance. The type of biome explains 3% of the variance. However, the applied land use classification system differs from the actual biome type of the valuation studies. Taking valuation study based classification into account coastal wetlands and freshwater (rivers/lakes) show highest values, confirming [231; 55; 232].

Economy: The portion of privately owned forests is positively correlated with water provision value (5%). This confirms that weak ownerships might affect valuation of other common goods negatively [255]. Similarly, there is a strong relationship of higher tax revenues which leads to lower values of water services (12%) pointing out to the fact, that with higher economic activities, more technical solution which can provide access to water are more likely to implement, because technical substitution is affordable [252]. I further found negative correlation between values and renewable energy production (2%).

Application of value transfer function: Spatial extrapolation of values shows the most certain and highest values in areas of high population growth and increasing pressures on water security, for instance in China, India, Java, eastern USA, south Mexico and Western Central America, south coast of Western Africa, and Mediterranean Europe (Fig 3.4). Transferred values with the highest uncertainties coincide with the lowest values and appear in areas where almost no valuation studies are available. Most of these areas represent the big deserts of the earth (Sahara, Kalahari, Namib, Australian, Arabian, Thar, Dasht-e Lut, Karakum, North American), eastern central Africa, Siberia, Greenland and Canada.

3.3.2.3 Climate regulation

Available input data: From a total of 36 valuation studies (69 monetary values), carbon sequestration was most frequently examined (68%), followed by other greenhouse gases (<2%) or remain unspecified (24%). The majority of studies were carried out in tropical and temperate forests (25%) as well as inland and coastal wetlands (45%). These biomes are seen as regions highly suitable for carbon sequestration [256; 257]. Moreover, most studies are located in climate sensitive, lower latitudes (72%), similarly to the ES mentioned before.

Model uncertainty: With 38% of variance explained in monetary values the transfer model for climate regulation represents the third best prediction performance (Fig 3.3). For most of the terrestrial earth surface (81%) confidence intervals could be calculated that show low to medium uncertainty (1 to 21 Int.-$-2007 per ha).

Importance of covariates: The most important covariates are ecosystem-based variables of nature threats (49%). Also relevant but explaining less of the variance are covariates indicating input measures of climate sensitive economic sectors (20%) and other economic variables (6%), followed by scale (7%), methods (6%) and social variables (4%),

Ecology and economy: Covariates of nature threats show that high values are associated with areas of high risk that unique biodiversity will soon be lost (30%) and high risk of erosion (19%). Covariates indicating input measures of climate sensitive economic sectors (e.g. energy production and water business) are positively correlated with monetary values for climate regulation. Most important covariates are: proportion of electricity production from hydroelectric sources (12%), annual mean of solar radiation (6%) and the water storage capacity of dams per country (2%). Values are high, for instance, in areas of lower latitudes where up to 99% of electricity is produced by hydroelectric power plants and where big artificial constructed water reservoirs (dams with capacity of < 3000 km^3) exist. Furthermore, the economic covariate inequality of income (6%) shows that the more unequal income is distributed the higher the value for climate regulation.

Scale and valuation method: Spatial extents of investigation areas as well as valuation methods applied in the studies explain respectively 7% and 6% of the variance. With a greater spatial extent monetary values decrease. These diminishing returns may occur because of declining marginal utility for beneficiaries. The majority of studies based on benefit transfer (60% of valuation studies), followed by direct market prices (16%) and avoided costs (11%). For direct market prices the highest values and for benefit transfer and replacement costs the lowest ones can be observed.

Society: Social covariates of relevance are population density per country (2%) or the age of population (2%). Population density is negative correlated with monetary values. Surprisingly, valuation studies in countries with on average older population report higher values of climate regulation. One might hypothesize older people may have made in their lifetime perceiving changes in climatic conditions and associated consequences, thus, valuing climate regulation service higher than younger persons. This might be an indication for the 'shifting-baseline' hypothesis, i.e. shifts of the reference points of human perception for estimating changes [258].

Application of value transfer function: Applying the value transfer function shows that the most certain and highest values are computed for areas under threat of habitat alteration due to climate change or other land degradation processes. Examples are areas like the Sahel Zone, tropical islands and mountains, Mediterranean ecosystems, Eastern USA and parts of Europe (Fig 3.4). On contrary, abandoned areas with the highest suitability of soil for carbon sequestration, such as Canadian and Siberian Tundra and boreal forests cover most uncertain and lowest values. This is due to a lack of valuation studies in such regions.

3.3.2.4 Prevention of extreme events

Available input data: The majority of valuation studies (82%) were conducted in areas of high vulnerability to extreme events and sites which are increasingly exposed to extreme events due to climate change [259-261]. In 42% flood prevention was considered, followed by unspecific extreme event prevention (30%), storm prevention (20%) and fire prevention (3%).

Model uncertainty: The value transfer function for prevention of extreme events represents medium prediction performance and explains 21% of the variance in monetary values (Fig 3.3). Transferred values of low and medium uncertainties (1 to 26 Int.-$-2007 per ha) are calculated for 82% of the terrestrial earth surface.

Importance of covariates: The impact of extreme events depends on both ecological conditions and societal vulnerability. I found that with 64% the highest explanatory power is represented by covariates showing the inherent conditions of ecosystems, followed by socio-economic characteristics (33%) and covariates dealing with the spatial and temporal scale (3%).

Anthropogenic pressure on the ecosystem: Extreme event prevention is valued high in areas with advanced anthropogenic alteration of ecosystems characterized by highly changed biomass (HANPP 13%), high agricultural induced soil erosion rates (10%), degraded freshwater resources and riverine biodiversity (10%), dense infrastructure (5% market access), dense settlements with major markets (4% Anthromes) and high population density (3%). Hence, the risk awareness to weather extremes and natural hazards increases with number of people potentially effected and higher level of land-use and degradation. The more risk aware a society is, the more weight it places on strategies that preserve or build ecosystem resilience, and the higher the value it would allocate to ecosystem configurations that are more robust [262]. This is further emphasized by the findings that monetary values are high in nations seeking for sustainable political governance, i.e. protect ecosystems and manage productive natural resources efficient for both economic growth and for supporting human well-being, while reducing environmental harm (2% adjusted net savings, 1% Environmental Performance Index, 1% Happy Planet Index).

Species richness and unemployment: I also found that areas with high species richness (4%) and high level of conservation priority (3%) show high valuation for extreme event prevention. These areas are characterized by high population, the highest population growth rates globally [253; 254] and economically poorest societies [263]. In nations, moreover, with a high unemployment rate (11%) extreme event prevention is valued high. Societal vulnerability to extreme events arises from the inability of people to withstand adverse impact from extreme events. Poor people have little adaptive capacities due to limited technological mitigation options, such as building codes and disaster preparedness [264]. This increases their exposure to severe adverse consequences of extreme events; particularly in areas with anthropogenic altered extreme event buffers. A variety of species may provide valuable insurances against severe disruptions [265].

Application of the benefit transfer function: Using the value transfer model for spatial estimations of extreme event prevention show that the most certain and highest valuations are situated in densely populated areas with advanced anthropogenic altered environments (Fig 3.4). The largest uncertainties are associated with low values and are shown in low populated areas where valuation studies are missing. Similarly to the findings from water provision, these areas are the big deserts of the earth (Sahara, Kalahari, Namib, Australian, Arabian, Thar, Dasht-e Lut, Karakum, North-American deserts), eastern central Africa, Siberia, and Greenland.

3.3.2.5 Recreation service

Available input data: The database for the ES recreation services captures with 96 the most valuation studies. The majority of studies were conducted in major non-religious and Christian sites (73%) as well as lower latitudes (77%). Studies in developing countries (Human Development Index < 0.6, gross domestic product (GDP) < 4024 US-$) are underrepresented (26%). Subcategories of recreation services investigated are tourism (41%), hunting (<1%), ecotourism (<1%) and unspecific recreation (47%).

Model uncertainty: The value transfer function for recreation services is with 33% variance explained the fourth most certain model (Fig 3.3). Confidence intervals show that low to medium uncertainty (1 to 26 Int.-$-2007 per ha) could be extrapolated for 91% of the terrestrial earth surface.

Importance of covariates: With 32% ecosystem-based covariates are the most influential group. In comparison with other value transfer functions, however, this is the lowest value (Fig 3.3). Further important covariates are those representing the spatial extent of investigation (25%), socio-economic variables (22%) and methods used (2%). The spatial extent of investigation is the most important variable in the transfer model and negatively correlated with monetary values.

Ecology: More homogeneous environments receive lower values for recreation. The value transfer function shows that areas are low valued with intensive agricultural use (6%), a high number of people living on degraded land (2%) and low number of terrestrial protection areas (4%) and biodiversity (2%) as well as low ethnic diversity (1%). Surprisingly there is a negative effect of marine protection areas (4%) and length of coastlines (1%). This is due to the low number of valuation studies carried out in coastal areas (17%) and marine protection areas (16%). Furthermore, covariates on land use/land cover types explain 9% of the variance and show that wetlands and freshwater areas (river/lakes) are highest valued. The most important climatic covariates are solar radiation (3%) and soil moisture (2%). The latter one is strongly correlated with precipitation. Highest monetary values are shown for areas with 100 to 190 W/m^2 and a soil moisture index of 1 to 1.6. This corresponds to areas in the (sub-) tropics, see Fig 3.4. Climate effect human's psychological perspective as the beneficiary enjoys, for instance, sunshine/cloudiness, hours of daylight, UV radiation (health, suntan) [266]. Covariates, however, confirm too less or too much radiation or humidity can also reduce attractiveness, e.g. short day length (depression, vitamin deficiency) or very high UV radiation (sunburn, allergies).

Economy and society: Economic covariates show that recreation is highly valued in wealthy countries. These countries are characterized by high market access (3%), low GDP growth (3%), low consumer prices (2%), positive trade balance and a high level of export to import ratio (3%). In wealthy countries the access to a greater share of ES and substitutes is provided, thus, the basis for recreation given. However, in areas with a high unemployment rate (6%) recreation values are high, too. I hypothesize these are sites where tourism is already established and an important economic factor. With increasing portion of privately owned forests the value for recreation is higher (1%). This shows that with the granting of property rights the valuation of common goods might be positively affected [255] and emphasize findings I made for food provision.

Application of value transfer function: Applying the value transfer function shows that the most certain and highest values are in the USA, most of the Mediterranean area, Caribbean islands, and Colombia (Fig 3.4). These areas coincide with most attractive tourist places mentioned by the World Tourism Organization [267]. Highest uncertainties and simultaneously lowest values are in the Russian Federation, African regions along the Sahel Zone, Indonesia and parts of Australia.

3.3.2.6 Habitat service

Available input data: The database for habitat service contains one of the smallest numbers of valuation studies (23 valuation studies, Fig 3.3) and highest variances in monetary values (Fig 3.2). In the majority of valuation studies (96%) the provision of habitats for young species (nursery) was conducted. Furthermore, most studies (92%) took place in climate sensitive lower latitudes. Habitat services are highly responsive to climate change and substantial alterations expected [268; 269].

Model uncertainty: The resulting value transfer function of the small and highly varying data set shows moderate uncertainty and explains 27% of the variance in the data. For 90% of the terrestrial earth surface values could be extrapolated with medium to low uncertainty (1 to 14 Int.-$-2007 per ha).

Importance of covariates: The group of ecosystem-based covariates contributes with 90% to the value transfer function (Fig 3.3). These are climate covariates (42%), followed by soil (24%) and water variables (24%), as well as biota (7%). Furthermore, social covariates (4%) and the spatial extent of the investigation area are relevant (3%). Social variables such as ethnicity are also relevant, but influence the value transfer function with <1% only slightly. I assume this is caused by the small number of monetary values.

Ecology and society: Habitat services are valued less in marginal areas, i.e. harsh growing conditions due to low soil quality (24%), arid climate zones with high drought potential (16%) and high UV exposure (26%). Marginal areas are mostly sparsely populated (1%) and characterized by low market access (3%). Also those areas are the home of poor people [270; 271] with little awareness of biodiversity [272] and subsistence economy prevails [271]. Consequently, land management is prioritized in order to meet basic needs, such as food provision or use of raw material. This is supported by the findings that in countries with high proportions of privately forests values for wildlife habitats are low (12%). On contrary, humid areas with increasing soil carbon content representing enhanced habitat quality and high species richness (4%) are positively correlated with monetary values of habitat services. This shows the direct link between habitat function for wildlife and food provisioning. Furthermore it emphasizes the importance to conserve habitat areas as a prerequisite for food and other ES. European studies even show that habitats under conservation (for example in protected areas) provide more regulating and cultural ES than other habitats [273; 274].

Application of value transfer functions: Spatial extrapolation shows the most certain values in low valued marginal areas like the highlands and drylands of Asia and sub-Saharan Africa, transition zones of the grassland to deserts of Australia as well as southern Latin Americas Andes Mountains, and the highlands and drylands of North America (Fig 3.4).

3.4 Discussion

Although ‘money’ is seen as a well-known and easily understandable indicator, monetary valuation of ES is ambiguous and shows only a fraction of the multiple characteristics that give utility to the beneficiary [275]. Applying benefit transfer and mapping a variety of ecosystems, social preferences and economics constraint to a single monetary value is an aggregation in which information is lost. To compare and transfer values in a reliable and valid manner I determined three major sources of uncertainty: (i) the availability and quality of input data; (ii) the performance and suitability of the estimated transfer model and (iii) the spatial application of the transfer model in order to estimate global ES value maps; see Fig 3.5.

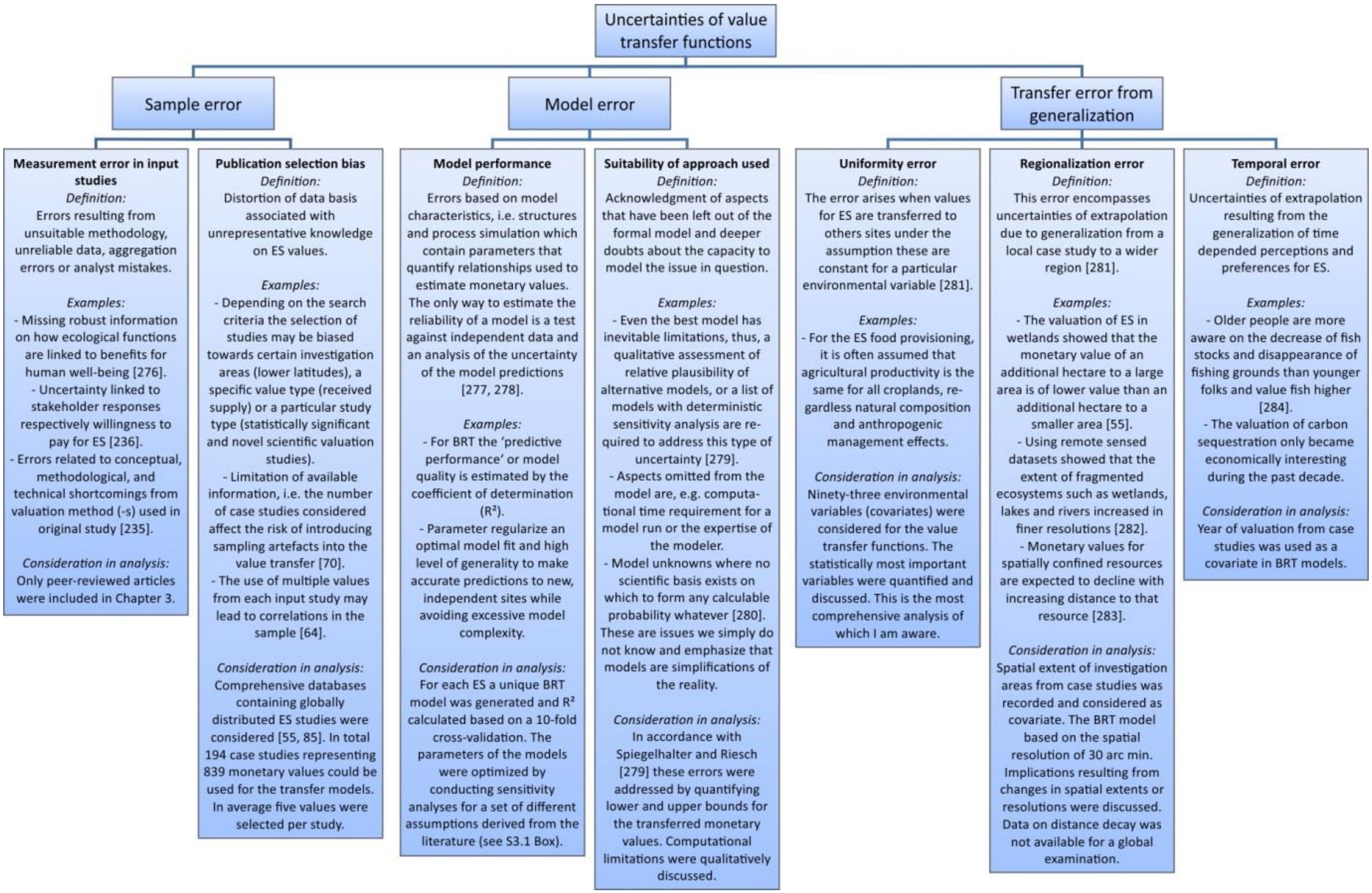


Fig 3.5: Overview of uncertainties in modelling global value transfer functions. The boxes denote uncertainties, which I either considered directly in the model design or discussed qualitatively.

The data availability and the quality of input studies determine the sampling error. I only included valuation studies that were reviewed by experts as a minimal assurance of study quality. Although the peer review approach is often criticized it is also appreciated as an efficient method that increased the scientific progress over the past decades [285]. The majority of valuation studies were conducted in lower latitudes (81% of studies), in areas characterized by a high population density and market accessibility above global average (92%) as well as high threats of degradation (71%). In situations of declining natural capital and continuing high demand, beneficiaries are sensitive to changes in natural capital [181], which might lead to overestimation. I thus assume that the global maps of monetary valued ES, illustrated by Fig 3.4, represent an upper estimate of ES values, particularly for transferred values in more pristine areas. Furthermore, only 7% of studies were conducted in countries with a per capita income smaller than 1,045 International-$-2005. Thus, there is a major research gap in the poorest countries [213] where people use the environment in a more direct way than richer ones and dependence on as well as preferences for ES are likely to be different compared to developed countries [217]. Results of the BRT models confirm that transferred values in poorest areas are associated with high uncertainties (Fig 3.4).

Another concern with respect to the input data refers to the aggregation of the monetary values. In order to create a comparable data base for spatially explicit value transfer modelling, monetary values need to be disentangled. Only values measured under marginal changes in the socio-ecological system were considered [181]. I utilized units expressed in 'estimate per unit area value', in contrast to 'estimate per beneficiary' which are often used for cultural services [286]. The first unit represents supply rather than demand aspects. Specifically, the potential supply rather than the received service is reflected for a given time period. Thus, the values cannot be utilized to identify societal urgent needs [287]. Accordingly, highest valued regions in Fig 3.4 (and S3.1 Fig) do not represent areas with potentially highest supply of ES nor the societal most important ES. The maps in Fig 3.4 may not be used to prioritize the most worthy ecosystems for human welfare, as suggested in [231; 232].

Utilizing BRT for spatially explicit, meta-analytic value transfer functions have inherent causes of error, too. Although this method is acclaimed to be one of the most sophisticated approaches for benefit transfer [288; 232] the evaluation with R-squared (cross-validated) revealed that none of the value transfer functions explain more than 44% of the variance in the data. Reasons for the comparably low explanatory power are the small number of valuation studies (Fig 3.3) as well as computational limitations. A finer resolution than 30 arc min or categorical predictors with a high number of categories could not be employed in the statistical analysis. Higher spatial resolution data might provide better results, but the limiting factor of model performance is the small number of valuation studies. Further a model fitting the data with a high R-square (postdiction context) may not generalize well (prediction context). Thus using new modelling techniques (BRT, random forests, etc.) should complement a search for more data.

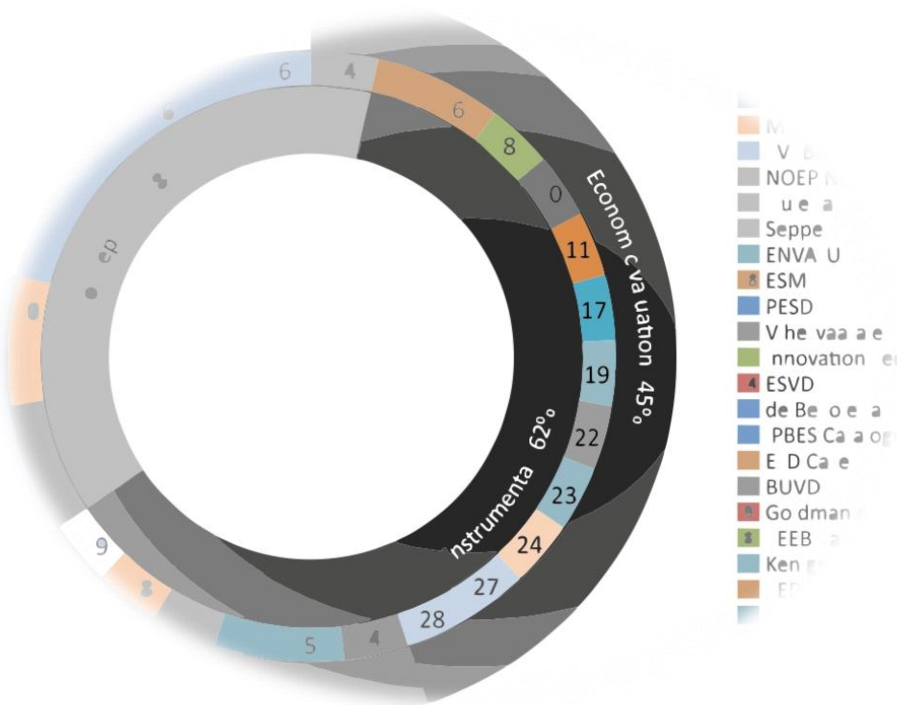
The spatial application of the value transfer functions in unsampled areas generates transfer errors from generalization, which are determined by uniformity, spatial extent and resolution (regionalization error) as well as temporal aspects [281; 217]. I found that ecosystem related uniformity errors are the key source of potential error in benefit transfer. Uniformity error occur if values for ES are transferred under the assumption that important covariates are constant [281]. For food provisioning, for instance, it is often assumed that agricultural productivity is the same for all croplands. The consideration of biophysical heterogeneity in ecosystems is particularly important for transferring values of habitat service, where ecological indicators contribute with 90% to the value transfer function. By utilizing more than 93 covariates I sought after the best possible solution to minimize uniformity error.

Regionalization error encompasses extrapolation errors due to generalization from a local case study to a wider region [281]. All value transfer functions are prone to errors according to different dimensions of scales [289]. The spatial extent of the investigation area showed high variation in the explanatory power of the analysis (1-26%). Most of the ES, except erosion and soil fertility, indicate diminishing returns to the spatial extent for ES values. The monetary value of an additional hectare to a large area is of lower value than an additional hectare to a smaller area, as reported for wetlands [55]. Further, resolution of data sets (granularity) determined explanatory values [282]. This was particularly striking for land use/land cover types according to the History Database of the Global Environment (HYDE). In eight out of twelve ES land use/land cover types change fundamentally depending on the level of resolution. For lower-resolution HYDE (10 arc min) the ES recreation, for instance, showed the highest values in tropical forests and grasslands, however, according to the finer-resolution of study site description from the valuation studies coastal wetlands, partly inland wetlands and freshwater areas are the most worthwhile land use/land cover types, which confirms several preceding publications [231; 55; 232]. Missing indicators are, for instance, those that reflect how the value for spatially confined resources is expected to decline with increasing distance to that resource. Transfer values without accounting for distance decay may result in overestimations [283].

The major achievement of this Chapter 3 is, first, to clearly distinguish between major sources of uncertainties and to quantify patterns in the influence of different study- and site-characteristics that affect value transfer functions and predicted ES values. Secondly, regions were identified for which sufficient knowledge on our natural capital is available, i.e. a statistically defensible benefit transfer model can be applied in combination with uncertainty values. Thirdly, global maps of the ‘white spots’ on our knowledge on accounting natural capital and ES were developed. These ‘white spots’ provide guidance for future analysis and concerted action on the assessment of natural capital and ES within the work program of IPBES [290] and the Aichi Biodiversity Targets [201]. Fourthly, a conceptual basis was developed for the establishment of a more standardized reporting of uncertainties in benefit transfer.

The integration of the presented value transfer functions in a fully automated spatial benefit transfer tool, such as the Ecosystem Valuation Toolkit [291], would be a next exciting step. Predefined automatic processes would reduce the time effort for model building and improve the model performance by constantly updating the data basis with both unconsidered covariates and valuation studies.

4 Using ecosystem service databases for the evaluation of effectiveness and efficiency of ecosystem service study outcomes



4.1 Introduction

Which kind of ES-based measures are most efficient to slow resource overexploitation? What are best practices for simultaneously protecting habitats and reducing poverty? Do ES-based approaches lead to more effective decision support? Only little is known yet about the answers to these questions, but finding answers is crucial to reduce the global decline of ES and biodiversity [20]. If any progress is to be made in improving decision support and stemming the global decline of ES and biodiversity, the field of ES research must adopt evaluation approaches to determine what works, where and when.

The number of ES studies is increasing substantially over the last decades [34]. Also aspirations for assessing research outcome and impact in society are being deployed more often to justify and prioritize public investment in research [292; 19; 185; 59]. However, there is also evidence that most of studies are designed in a way that permits an evaluation of its outcomes [293; 294]. Recommendations on how to improve study designs are given in literature [295; 296]. However, evaluation approaches are quite diverse [82; 83] and the principles on which the evaluation process should be based are not always clear [84]. In General, all evaluation efforts are grounded on a comparison between different groups, for instance impact evaluation of interventions requires a counterfactual comparison group that shows the outcome that would have happened if there had been no intervention [293].

Databases aim to bring together information from individual ES studies in a consistent way that facilitates the detection of similarities and differences prevailing across ES studies and thus enables to identify comparable ES studies. Databases use variables that collate evidence on characteristics of ES studies, which are promising to derive indicators and regularities for their evaluation. Although the number of ES databases is growing their secondary use for evaluation purposes is neglected. ES databases hold the potential to provide insights on how to improve evaluation of ES study outcomes.

The evaluation of ES study outcomes implies a systematic determination and judgement of a studies' worth or merit using criteria governed by a set of standards [297]. Besides sustainability and fairness [79], criteria such as effectiveness and efficiency are often used in ES community. While effectiveness is well-received as a normative judgment criterion whether an outcome can be deemed as 'good', efficiency becomes more prominent in measuring performance and progress in ES research and practice [80; 81]. Both effectiveness and efficiency are goal-relative criteria, i.e. the definition of clear objectives and measurable targets determine the scope within effectiveness and efficiency can be analyzed and applied as evaluation criteria respectively. Examples for general objectives of ES studies vary between [57]:

(1) Instrumental, aims at the correction of market and policy failure through the provision of ES knowledge that is directly applied in decision-making to generate actions based on specific recommendations or alternative options for policies, plans or programs;
(2) Strategical, aims to support a specific intervention, promote new policy options, or justify previously held beliefs and values;
(3) Conceptual, aims to broaden and deepen understanding of topics, and shape the way people think about human-nature interactions and policies.

Measurement of effectiveness and efficiency is highly sensitive to the data sets being used. For instance, international comparisons of effectiveness and efficiency of public spending suffer from conceptually varying data sets [298]. In this example data reflect the different organizations and traditions of government and therefore are not fully comparable between countries. Vartiainen [84] concludes the more similar the conceptual design of data the more reliable and concrete the evaluation findings. However, this homogeneity of data design is rarely given, due to missing standardization of terminologies and methods used for monitoring and evaluation of effectiveness and efficiency in ES research [86-89]. Measuring effectiveness and efficiency of ES study outcomes is complex, as the objectives change different indicators are important to consider, for instance, for evaluating the effectiveness of changed land-use practices to reduce soil erosion and remove sediment loads from streams that causes costs for hydro-power generation, the indicator sedimentation rates is monitored [157]. This indicator, however, is of little help for the evaluation of effective landscapes for psychological recovery and spiritual inspiration [299; 300]. Furthermore, study outcomes that have an impact over long timescales are difficult to observe, let alone measure [301; 292]. Due to these constraints, findings from effectiveness and efficiency assessments are interpreted in various ways [298].

For a more standardized evaluation of effectiveness and efficiency of ES study outcomes a better understanding of basic principles is required. ES databases provide insights into common patterns across different ES studies and contain indicators that are promising for the usage of evaluating effectiveness and efficiency. Against this background, the research questions arise: Which indicators for the evaluation of effectiveness and efficiency of ES study outcomes exist in ES databases and which basic principles can be derived to facilitate a more standardized evaluation?

In this Chapter 4, I conducted a review of ES databases variables and there suitability as indicators for the evaluation of effectiveness and efficiency of ES study outcomes. Firstly, I developed a hierarchical framework for a systematic analysis of effectiveness and efficiency indicators. Secondly, I identified indicators that contribute to the evaluation of effectiveness and efficiency based on a review of major ES databases variables. Thirdly, I synthesized findings across indicators to derive basic principles for the evaluation of effectiveness and efficiency of ES study outcomes. I then discussed methodical implications for the evaluation of effectiveness and efficiency on the basis of the four principles. I end with conclusions of the work.

4.2 Methods

4.2.1 Framework for the identification of effectiveness and efficiency indicators

For the identification of indicators for the evaluation of effectiveness and efficiency I developed a comparison framework. The comparison framework formulates an ideal evaluation model based on hierarchical organized indicators that constitute different notions of effectiveness and efficiency. This framework forms a concept of the features of effectiveness and efficiency, which can be compared with variables used in ES databases to manage information on ES studies. I formalized indicators of the comparison framework in accordance with the most generic definitions of effectiveness and efficiency. Indicators for effectiveness are (i) the accuracy and (ii) completeness with which an ES study achieved an objective. Efficiency was determined according to the effort of an ES study or project measured by the (iii) resources used to (iv) achieve an objective. Using generic indicator ordered in a hierarchical framework enables to place broad boundaries around what does - and does not – qualify as an indicator for effectiveness and efficiency. Also, it maintains the flexibility to include more specific indicators used in different application contexts and facilitates comparisons by organizing specific indicators consistently under the same generic banner. The hierarchical organized framework ensured that specific indicators were extracted by the overarching definitions which matter most, not simply the ones that are easiest to measure.

The effectiveness indicator 'accuracy' and 'completeness' with which a desired result is achieved refers to the quality of ES study outcomes. Accuracy is determined by the estimation of systematic and random errors of outcomes [302] as well as the potential suitability of the methods applied in ES studies to the context under analysis [303; 279]. While errors of outcome are conditional to the method setting, potential suitability of the methods applied in ES studies requires the estimation of the confidence to measure the issue in question and the evidence underlying the ES-based approach [304]. Completeness of achieving an objective is determined by the extent to which outcomes of ES studies are of sufficient breadth, depth, and scope for the task at hand [305]. Assessment of completeness relies upon the presence of a reference standard, which may be drawn from contacting experts or comparing ES study outcomes with alternate trusted measures and sources [306; 294].

The efficiency indicators 'resources used' to 'achieve an objective' represent the relation between inputs and outputs of ES studies under consideration of feasible output levels [298]. Therefore, also the assessment of efficiency requires a reference standard, which can be derived from the comparison of information about time and costs used for conducting ES studies. Temporal requirements to achieve the objectives are for instance the study duration or the periodicity of the assessment in case of monitoring [289]. Costs are not limited to monetary units, but include all other required means such as methods and people involved. Methods reflect the means that were used to collect or analyze ES and indicate data requirements, complexity of measurements or specific activities applied to achieve the objective [307]. People involved encompass the expertise, the number of persons and stakeholder engaged in ES-based measures [308]. The achieved objective represents the actual output, outcome and impact of an ES study. It refers to positive and negative environmental or socio-economic change (-s) directly caused by an ES study, for instance, the co-production of scientific knowledge by designing and applying methods for ES assessments [309; 310] or improvement of ES delivery through investments in restoration and conservation of ES [311].

Since effectiveness and efficiency are goal-relative criteria I differentiated between distinct objectives of ES databases and also considered contextual conditions to avoid incommensurability between various database entries. The magnitude of the effectiveness and efficiency from ES studies is likely to be affected by contextual conditions, which are often outside of scientists' control. Contextual conditions include local conditions about the institutions, governance, culture of places etc. where ES studies were conducted.

4.2.2 Review of indicators in ecosystem service databases

ES databases selected in Chapter 2 were used to identify indicators for the evaluation of effectiveness and efficiency of ES study outcomes (Table 4.1). The databases contain information about globally distributed ES studies. Databases can generally be looked at as being a collection of variables organized in a table for a specific objective. The tables store data entries in cells, with multiple cells represented in a system of rows and columns. For instance, data entries in a database that aims at assessing the quality of ES studies include how uncertainties have been taken into account (column) for each ES study (row) [85]. Columns define the data in a table, while rows populate data into the table. Hence, column headers contain clear defined and measurable indicators that are used to assess to what extent objectives are being met. These indicators follow a built-in formal reporting protocol used in the database to ensure the provision of consistent information on ES studies and facilitate the identification of comparable studies. I analyzed the presence of column headers suitable for the usage as indicators for the evaluation of effectiveness and efficiency of study outcomes. Also, I quantified how many data entries were available for the identified indicators in order to compare ES studies and determine effective and efficient ES study outcomes.

Table 4.1. Databases considered for the review of effectiveness and efficiency indicators. The gray bar plots illustrate the total number of columns and rows (log) per database respectively.

Database name	Number of columns	Number of rows
Innovation Seeds	379	89
ReefLink Database	289	13,894
Goldman et al., 2008	173	121
EVCBN	162	507
ESML	112	2,301
ESB	80	207
SGA	72	32
ValuES Cases	69	65
EM	50	960
IPBES Catalogue	47	242
Seppelt et al., 2011	42	155
Cardinale et al., 2012	42	315
Envalue	35	235
EVRI	34	3,611
Vihervaara et al., 2010	29	353
ESVD	27	1,310
Keniger et al., 2013	26	82
IIED Watershed Markets	25	75
BUVD	21	4,284

(Table continues...)

de Bello et al., 2010	19	548
PESD	15	364
NOEP Non-Market	14	753
TEEB Cases	13	120
ValuES Methods	12	19
ARIES Cases	11	17
ELD Cases	10	1,223
ESID	10	295
MESP	9	1,059
Liu et al., 2010	6	703

4.2.3 Quantification of indicators of effectiveness and efficiency

I quantified indicators for the evaluation of effectiveness and efficiency of ES study outcomes ($M_{s,\mathrm{t}}$) by reviewing whether columns (n) and data entries (m) of ES databases can be assigned to the five generic indicators (t) of the comparison framework and for specific objectives (s) of databases. With t being accuracy, and completeness for effectiveness, resources used (input) and achieved objective (output) for efficiency as well as contextual conditions. First, I counted the number of column headers ($C_{i,k}$) of ES databases that thematically overlap with t for each s. For the counting of relevant $C_{i,k}$ all columns of each ES database ($n_k = \{n_1, \ldots, n_{29}\}$) and all ES databases ($k = 1, \ldots, 29$) were reviewed.

$$C_{i,k} := \begin{cases} 1\ , relevant\ for\ s\ and\ t \\ 0\ , not\ relevant\ for\ s\ and\ t \end{cases} \tag{5}$$

$$M_{s,t} = \sum_{\mathrm{k}=1}^{29} \sum_{i=1}^{n_k} C_{i,\mathrm{k}} \tag{6}$$

For instance, in the database Seppelt et al. [85] a column header referred to the topic how uncertainties have been taken into account in ES studies. This column header matches with the effectiveness indicator accuracy and was counted as one relevant indicator for the evaluation of effectiveness of ES study outcomes.

Second, I counted the number of data entries ($C_{i,j,k}$) of relevant $C_{i,k}$ for all rows of each ES database ($m_k = \{m_1, \ldots, m_{29}\}$).

$$C_{i,j,k} := \begin{cases} 1\ , relevant\ for\ s\ and\ t \\ 0\ , not\ relevant\ for\ s\ and\ t \end{cases} \tag{7}$$

$$\widehat{M}_{s,t} = \sum_{k=1}^{29} \sum_{j=1}^{m_k} \sum_{i=1}^{n_k} C_{i,j,k} \tag{8}$$

For instance, in the database Seppelt et al. [85] the column header “uncertainties” contains in 155 rows the same amount of data entries which represent information on systematic and random errors of study outcomes. These data entries populate information into the effectiveness indicator and provide a basis for the determination of effective ES study outcomes.

4.3 Results

None of the reviewed databases were created with the intention of evaluating effectiveness or efficiency. The majority of databases aimed at instrumental goals (62%) and intended to support decision-making, followed by conceptual goals (38%), see Fig 4.1. For instance, the database EVRI was used for governmental action plans and environmental stewardship. PESD triggered debates on payment for ES on different policy levels. A few others were considered for broadening and deepening understanding on ES in research initiatives beyond their original project (SGA, IPBES Catalogue, ESVD, EVRI, ReefLink Database) and for capacity building in university courses or workshops for practitioners and federal employees (ValuES Cases, ValuES Methods, EVRI, EM). More specifically databases aimed at the following objectives (Fig 4.1):

(1) Economic valuation, i.e. recognition of ES and their economic significance for policy decisions about the management of ecosystems (45% of databases)
(2) Application of ES concept in practice, i.e. support of practitioners to apply the ES concept for decision-making by assembling (good) practice examples of indicators, processes and methods (35%)
(3) Understanding of relationships; i.e. broadening and deepening understanding on interlinkages between ecological components of nature, ES, and human well-being (10%)
(4) Evolution and Education, i.e. broadening and deepening understanding about historical evolution of ES research as well as for teaching, learning and scholarly communication in general (10%)

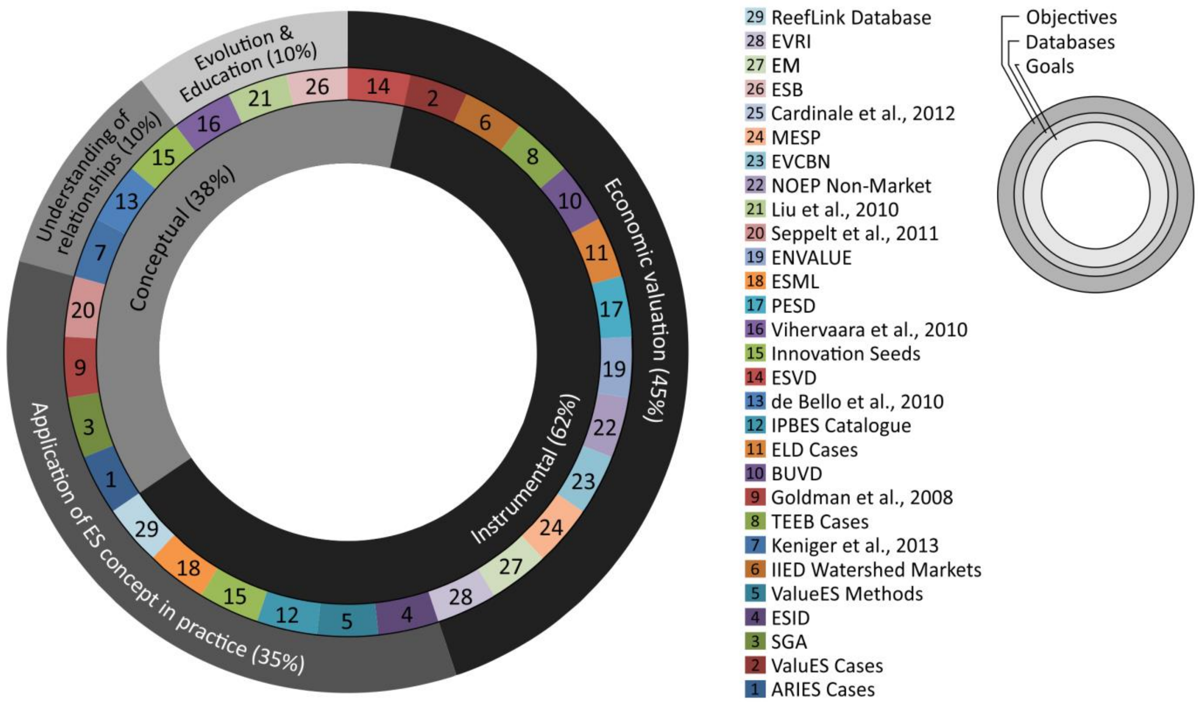


Fig 4.1. Visualization of databases' objectives. The ring charts illustrate the goals (inner ring) and objectives (outer ring) of 29 ES databases (middle ring) in percentage values. Goals represent general targets while objectives determine more specific targets towards the databases are directed (S4.1 to S4.2 Table).

Across all objectives I found 1,193 column headers in ES databases that provided information relevant for the evaluation of effectiveness or efficiency of ES study outcomes (S4.1 Table and S4.3 Table). Column headers are hereinafter referred to as indicators for the evaluation of effectiveness and efficiency of ES study outcomes. From these indicators 47% were thematically related to efficiency and 19% to effectiveness (Fig 4.2). The remaining 34% indicated contextual conditions in which ES studies have been carried out. Most indicators were documented for the following objectives: application of the ES concept in practice (59%), followed by economic valuation (17%), understanding of relationships (12%), and evolution and education (12%). The number of available indicators for the evaluation of efficiency and effectiveness of ES study outcomes shifted slightly with the objective of the databases (Fig 4.2). The efficiency indicator resources used / input played a major role for the application of the ES concept in practice (19%) and education and evolution (5%). In economic valuation the indicator achieved objective / output (6%) was more frequently documented than resources used / input (5%). For the objective understanding of relationships efficiency indicators were of less importance (3% resources used / input, 1% achieved objective / output) than the effectiveness indicator accuracy (4%). The effectiveness indicator completeness of achieving an objective is documented in none database.

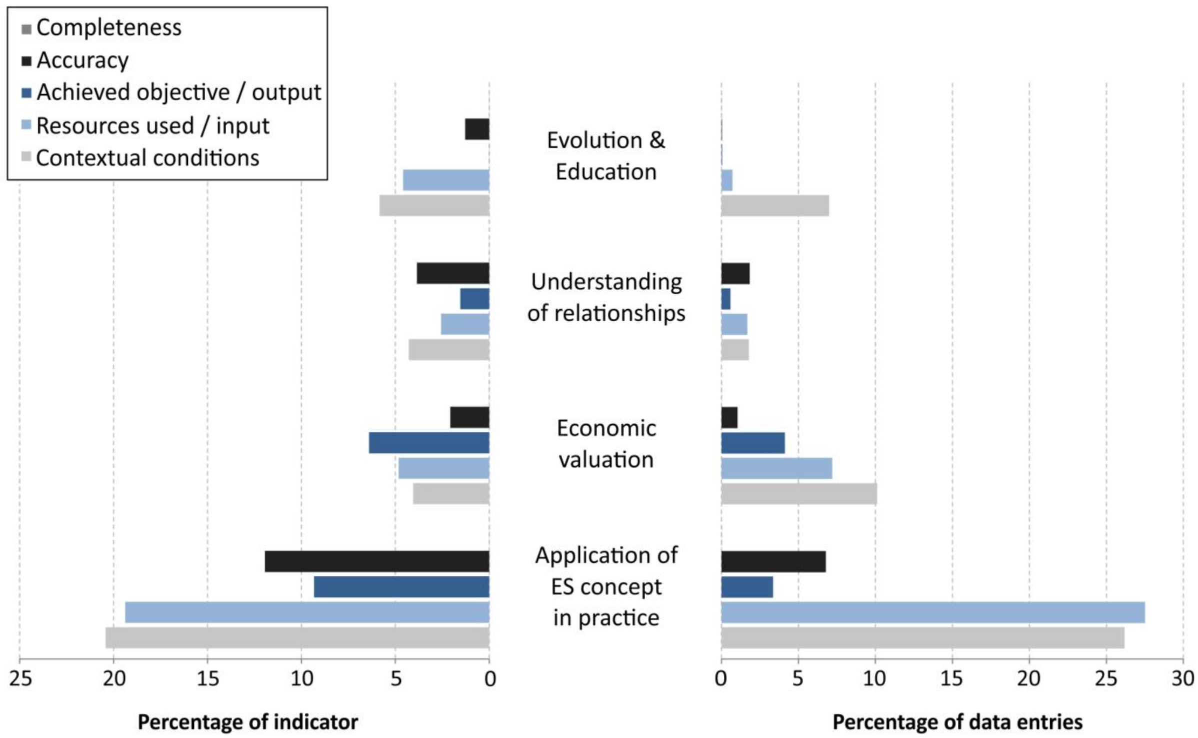


Fig 4.2. Indicators for the evaluation of effectiveness and efficiency of ES study outcomes for major objectives. The bar charts visualize the number of effectiveness and efficiency indicators (left) as well as available information for those in database entries (right), in percentage values. The effectiveness and efficiency indicators and data entries refer to the four major objectives of the reviewed 29 databases (center).

Taking additionally account of the number of data entries which were available for each indicator of effectiveness and efficiency emphasized the low number of information for evaluating effectiveness of ES study outcomes (10% of data entries), see Fig 4.2 (S4.1 Table and S4.4Table). Particularly, for the objectives economic valuation (1%) and evolution and education (<1%) indications of effectiveness were neglected. Data entries for indicators of contextual conditions that may influence effectiveness and efficiency of ES study outcomes were most often available in databases (45%).

Table 4.2. Examples of specific indicators for the evaluation of effectiveness and efficiency of ES study outcomes. The table lists examples of the 1,193 specific indicators from ES databases that can be assigned to generic effectiveness (accuracy) and efficiency indicators (resources used / input, achieved objective / output) for four major objectives.

Objective	**Indicator**				**Source**
	Accuracy	**Resources used / input**	**Achieved objective / output**	**Contextual conditions**	
Application of ES concept in practice	• Level of technical maturity of the method including whether and how qualitative or quantitative uncertainties are considered.	• Cost of applying the method. • Time needed for using the method. • Data needed to apply the method. • Level of expertise or training required for applying the method.	• Output and data results produced by methods. Short descriptions on what information does the method provide.	• Potential context of application. Description on situations in which the method can be carried out.	ValuES Meth-ods [135]
Economic valuation	• Estimated monetary value of ES including different uncertainty measures, for instance confidence intervals of economic models or standard error of means etc.	• Information about data input used for the economic valuation of ES such as households considered in survey or data points included for benefit transfer etc.	• Estimated monetary value of ES.	• Characteristics of population in valuation area, such as ethnicity, profession, age, etc. • Environmental Stressor affecting the valuation area. • Extent of environmental change in air, water, land, animals, plants and micro-organisms. • Availability of substitutes and substitute sites relevant for ES valuation.	EVRI [109]
Understanding of relationships	• Criticism/ observation: Expert-based evaluation of inadequacies and errors in methodological procedure.	• Information about data input used for the analysis of benefits from human interactions with nature such as participants considered in survey or environmental observations (e.g. proximity to greenspace, size of nearest greenspace) etc.	• Central findings and outcomes. Description of benefits from human interactions with nature.	• Description of local setting of investigation area and geographic location.	Keniger et al. 2013 [112]
Evolution and education	• Number of studies focusing on the topic uncertainty.	• Number of studies focusing on specific methods for selected topics such as economic valuation, ecological assessment, policy, management and incentive mechanisms.	-	• Specific geographic locations of ES applications.	ESB [117]

The numerous amounts of indicators for efficiency (Fig 4.2) can be attributed to the high number of databases which focused on study design and methodological approaches used for the objectives: application of the ES concept in practice or economic valuation. There are many different ways to reach an objective when an interdisciplinary framework such as the ES concept has been applied. For instance the monitoring of water availability can be done by analyzing satellite images, measuring a river's streamflow or by doing surveys with water users. In order to transparently document the manifold approaches, various indicators were used across databases that provide insights into inputs and outputs of ES methods. These indicators can be adapted for the evaluation of efficiency. For instance, specific indicators of temporal requirements, monetary costs, data needs, and expertise or training required for applying different ES methods were available in ES databases aiming at the application of the ES concept in practice (Table 4.2).

Although a high number of both indicators and data entries were available for the evaluation of efficiency of ES study outcomes, the determination of most efficient ES study outcomes was not possible. I found a lack of information to determine if different ES studies were conducted under similar conditions. This appears contradictory according to findings that show a high number of specific indicators as well as data entries for contextual conditions. In fact, specific indicators and data entries for contextual conditions were often condensed and lacking in detail, for instance 18% of specific indicators of contextual conditions provide general information such as country and biome names in which ES studies were conducted.

The effectiveness indicator accuracy of achieving an objective was most often documented for the objective: application of ES concept in practice (Fig 4.2). Examples for specific indicators of accuracy were exemplified in Table 4.2. Quantified, numeric values for the accuracy were rare (14% of data entries for accuracy) and only available in four database (ESML, EVRI, ELD, Cardinale et al., 2012). In the database ESML that focused on ES models a systematic differentiation of uncertainty types had been made in order to provide more transparency in ES modelling and increase the level of confidence in applying ES models. This differentiation is unique across all considered databases. For instance, the following types of uncertainties are documented: (i) model calibration refers to the adjustment of selected model variables to best fit a set of local observations, prior to model use; (ii) operational validation that represents a statistical comparison of model predictions with independent data; (iii) sensitivity analysis that quantifies how a given amount of variation in one or more predictor variables is reflected in variation of model response; and (iv) propagation of uncertainties refers to the evaluation of how predictor variable uncertainties propagate into the response variable estimates of the model.

The determination of most effective ES study outcomes was primarily not possible due to a lack of completeness indicators, but also due to the small number of accuracy indicators and condensed indicators for contextual conditions (similar to efficiency).

4.4 Discussion

At the time of this analysis, the reviewed ES databases contained more than 2,100 column headers. From these about 57% contained information that were assigned to indicators relevant for the evaluation of effectiveness and efficiency of ES study outcomes; according to the comparison framework and definitions used in this analysis. Even though I could identify effectiveness and efficiency indicators, for the determination of most effective and efficient ES study outcomes information was missing. Synthesizing findings across all indicators and data entries enables to better understand basic principles of evaluating effectiveness and efficiency of ES study outcomes. I derived four basic principles and discussed methodical implications for the evaluation of effectiveness and efficiency of ES study outcomes. The four principles run as follows:

(1) Determination of the objective of evaluation
(2) Selection of indicators for evaluation
(3) Consideration of reference standards
(4) Conceptual comprehension

4.4.1 Determination of the objective of evaluation

For the evaluation of effectiveness and efficiency of ES study outcomes the determination of objectives is crucial. The objective of the evaluation limits the examination scope within effectiveness and efficiency analysis can be conducted. For instance, assuming evaluation objectives based on objectives of reviewed ES databases shows that for a set of four clusters the evaluation can be conducted. These are the objectives: (i) the application of the ES concept in practice, (ii) economic valuation, (iii) understanding of relationships, and (iv) evolution and education. Directly linked to the determination of specific objectives of the evaluation is the consideration of contextual conditions and their effects on ES study outcomes. Taking contextual conditions into account ensures that ES studies are conducted under similar circumstances. For instance, ES studies aiming at the application of the ES concept in practice tend to be more effective when they are mandated by governments. IPBES [188] showed that such ES studies were generally more closely aligned with the needs of decision-makers, and thus had a kind of ‘receiving environment’ for the findings. Most of reviewed database entries available for the evaluation of effectiveness and efficiency of ES study outcomes addressed contextual conditions. However, these data entries were often condensed and lacking in detail, thus information on whether alternative approaches aiming at the same objectives were applied under similar conditions was not sufficient. Consequently, both the specification of clear objectives of the evaluation and consideration of contextual conditions are important prerequisites to determine comparable ES studies and provide an enabling framework for the evaluation of effectiveness and efficiency of ES study outcomes.

4.4.2 Selection of the indicators for evaluation

The indicators for an evaluation represent the means to carry out the evaluation of effectiveness and efficiency. In this review, for instance, indicators for the evaluation of effectiveness and efficiency based upon different notions of effectiveness and efficiency. Indicators are accuracy and completeness for effectiveness as well as resources used / input and achieved objective / output for efficiency. Challenges of the selection of suitable indicators arise from the diversity of specific application contexts of studies considered for the evaluation. As the diversity of application contexts of studies increases, it becomes increasingly difficult to find indicators for the evaluation [84]. This challenge stems from the increasing level of abstraction that is needed to enable the comparison of different studies. Optimal preconditions for the identification and application of indicators for the evaluation exists, when the application context of ES studies are as similar as possible.

Another challenge addresses the level of aggregation of indicators used for the evaluation of effectiveness and efficiency. Whether specific characteristics of effectiveness and efficiency are outside of control or directly considered by the indicators of evaluation depends on the level of aggregation of the indicators used. A high level of aggregation means that information is composed from a multitude or combination of other more individual information, which leads to information loss and can conceal inefficiency [312]. For instance, aiming at the identification of cost-efficient ES assessment tools at a more aggregated level the monetary costs may only consider the purchase price for the tools, while data acquisition and labor costs for applying the tool by experts would be taken for granted. In this analysis aggregation levels of effectiveness and efficiency indicators varied considerably within similar objectives, and thereby impeded the determination of effective and efficient ES study outcomes.

4.4.3 Consideration of reference standards

In an ideal situation the evaluation of effectiveness and efficiency of ES study outcomes based upon case control or reference standards. This requires ES studies which are designed in a way that allows the comparison of alternative approaches in the same context within a single study [294]. However, such comparative studies are rare [294], usually comparing small numbers of alternative approaches and not necessarily consider all influencing factors [296]. A more pragmatic approach would be to build upon checklists of evaluation that provide highly characterized and validated specification criteria for different application contexts [313-315]. Even though these checklists are not comprehensive for all methodological approaches and application contexts, they raise attention on common problems in evaluation efforts. For instance, Mupepele and Dormann [304] provided a guideline for evidence assessment of ES studies outcomes based upon a synthesis of 30 published quality checklists for ES studies from different scientific disciplines. This guideline includes criteria that reflect the extent to which all aspects of conducting an ES study can be shown to protect against bias and inferential errors. The criteria can be used as a baseline for the formalization of a feasible concept for the documentation and evaluation of the effectiveness indicator completeness of achieving an objective. In other words, criteria could be used to develop an ideal evaluation model with specified standard levels against which ES study outcomes are compared. For instance, Castellini et al. [316] used an evaluation model with eight evaluation criteria that specified standard levels against which completeness of outcome reporting of clinical trials were compared.

Developing reference standards and using them for the comparison of alternative approaches might also contribute to a better understanding of how different ES studies not simply uncover but also construct values [317]. Choices of methodological approaches can bias information according to a particular disciplinary perspective, and potentially limiting of how interests of ES beneficiaries are reflected [63]. Recognizing and differentiating value-articulating effects of ES studies, invites us to critical reconsider the effectiveness of a particular measure that deals with value pluralism and the multidimensional nature of ES.

4.4.4 Conceptual comprehension

For the evaluation to be relevant, it is crucial that the concepts used for the purpose of evaluating effectiveness and efficiency are clearly defined so that different stakeholder groups will interpret and understand the concepts involved in the same way. The usage of different concepts may lead to difficulties in the interpretation and comparison of evaluation results [318]. The usage of a hierarchical approach to organize different objectives, contextual conditions, aggregates, and notion of effectiveness and efficiency implies the benefit that distinct concepts can be formalized, collected and interconnected. This is an important first step towards scrutinizing suitable concepts and discussing requirements to reach consensus on standards. Having agreed upon standards facilitates synthetic analysis, enables a closer collaboration across different domains, and contributes to the identification of a core set of indicators that have a high impact to detect effectiveness and efficiency and should have priority in designing, implementing and maintaining monitoring systems.

4.5 Conclusion

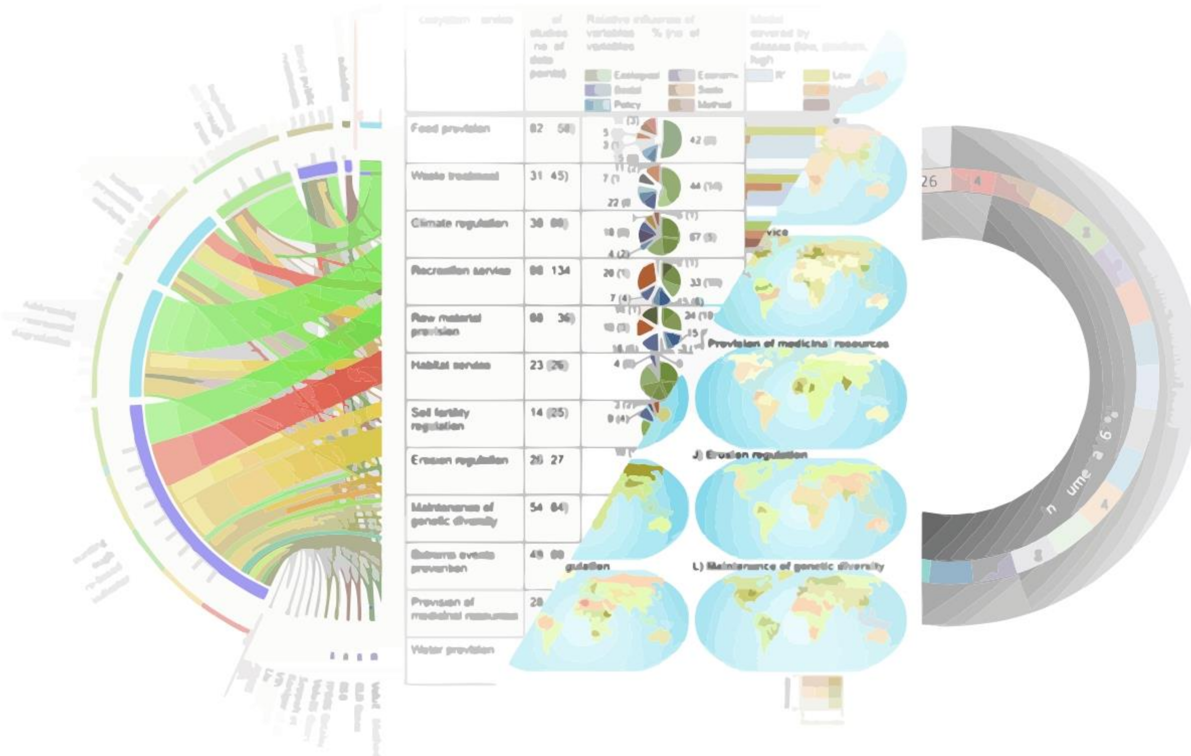
For the evaluation of effectiveness and efficiency of ES study outcomes basic principles have to be followed that pave the way for the identification of core indicators and enable the comparability across different sites. I suggested basic principles that help to structure efforts of evaluating effectiveness and efficiency of ES study outcomes. The principles highlight the importance of clearly determining the objectives of the evaluation, conditions for the selection of indicators for the evaluation, reference standards that set the bar for the evaluation, and conceptual comprehension.

The database review showed that although none of the ES databases aimed at monitoring or evaluation of effectiveness and efficiency of ES study outcomes they contain a broad set of indicators that provides insights into effectiveness and efficiency. However, after correcting for incommensurability through the application of the basic principles only a fraction of indicators remained. Either indicators or database entries for the indicators were too few for the determination of most effective and efficient ES study outcomes. In order to foster the development of a more consistently structured approach in which effectiveness and efficiency of ES study outcomes are readily comparable for the evaluation, I propose a standardized reporting tool. The reporting tool should be designed in a way that covers a full list of important aspects which are crucial to consider within the evaluation of effectiveness and efficiency of ES study outcomes. I recommend aligning the reporting tool with the four basic principles. Based on this tool a standardized formalization, collection and interconnection of indicators for effectiveness and efficiency of ES study outcomes can be conducted. This is an essential step forward towards scrutinizing a core set of indicators that have a high impact to detect effectiveness and efficiency and should have priority in designing, implementing and maintaining monitoring systems.

Improving monitoring and evaluation of effectiveness and efficiency of ES study outcomes through joining together of heterogeneous concepts, describing the relation between them and developing more standardized approaches brings great benefits. For instance, like a multilingual dictionary or a conversion table, the better understanding of relations facilitate the communication and collaboration within and between different domains and groups even when the commonality of concepts has not (yet) led to a consensus on standards. Further benefits address: (i) a more comprehensive understanding of the assumptions, options and limits of effectiveness and efficiency evaluation, (ii) more transparency in the utilization of resources and justification of results and impacts vis-à-vis the stakeholders, and (iii) improvements of future projects through the learning from experiences of successes and failures of ES studies.

Ultimately, agreeing upon standards in the evaluation of effectiveness and efficiency of ES study outcomes allows for learning and rewards for good performance, and contributes to both scientific and societal progress.

5 Synthesis of findings and perspectives



5.1 Ecosystem service databases' contributions to mainstreaming and standardization

Mainstreaming ES requires the identification of impediments for the incorporation of ES information into decision-making and finding strategies to tackle them. One impediment to a comprehensive adoption of ES information is the lack of standards that define terminology, acceptable data and methods, and reporting requirements for sharing consistent information on ES [39]. With the increasing popularity of the ES concept in a time of rapid advances in information technology, globalization, and increasing networking, a proliferation of terminologies, conceptual frameworks, methods and datasets caused a growing amount of inconsistent information and confusion on what determines good practice approaches. Results of this dissertation showed that databases organized large amounts of information in a consistent way that provides a baseline for standardization and mainstreaming of ES knowledge. However, comparisons across ES databases showed that they varied considerably in scope, standardization, size, usage, accessibility, and other characteristics. Commonly agreed reference collections – that set the bar for standardization in a community – were missing and only a few well-established standard protocols for archiving and retrieval of information across databases existed. These factors made the secondary usage of ES databases beyond their original purpose an ambitious and highly labor-intensive task. Within the dissertation, information contents of major ES database were reviewed for different application contexts and recommendations derived for guiding discussions on standards that facilitate the mainstreaming of ES information.

Firstly, analyzing ES databases and linking their contents to information demand from policy instruments that affect resource and land-use decisions showed that databases contain information for most of the policy instruments (Chapter 2). By synthesizing results across different policy instruments, common principles were derived that represent priority areas to formalize standards for the documentation of knowledge on ES. These priority areas are:

(1) Quantitatively recognize nature's value;
(2) Develop prioritization schemes based on ES valuation;
(3) Sensitive stakeholder engagement;
(4) Facilitate information access and capacity building to establish ES-based decision-making; and
(5) Evaluate long-term returns of interventions on ES.

Secondly, learning from ES databases and transferring their information for decision support assumes that information contained in databases is equally applicable and effective in another setting. Estimations of the transferability of ES database information represented by a set of monetary valued ES showed there were limitations (Chapter 3). Using meta-analytic value transfer functions as a basis for modelling benefit transfer provided insights into different sources of uncertainty. Results showed that value transfer functions explained from 18% (water provision) to 44% (food provision) of variance in monetary values. Based on these models statistically reliable value transfers were conducted for 70% (water provision) to 91% (food provision) of the terrestrial earth surface. Furthermore, through the synthesis of results across all value transfer functions a conceptual framework for the establishment of a more standardized reporting on uncertainties of benefit transfer was derived. This framework entails reporting requirements for three major sources of uncertainty:

(1) Sample errors that result from the availability and quality of input data;
(2) Model errors that represent the performance and suitability of the transfer model to analyze the task at hand;
(3) Transfer error from generalization which results from spatial and temporal consideration of environmental conditions for the extrapolation of ES values.

Thirdly, steering ES science towards improved decision advice and ultimately to ecological and social betterment requires gauging its achievements accordingly. Findings of the dissertation (Chapter 4) showed that databases contained consistent indicators that could be used as metrics for the evaluation of effectiveness and efficiency of ES study outcomes. However, for the determination of most effective and efficient ES study outcomes information was missing. Drawing conclusions on the results showed that four basic principles can be derived that contribute to improved reporting on effectiveness and efficiency of ES study outcomes and facilitate their evaluation in future endeavors. These basic principles relate to the:

(1) Determination of the objectives of evaluation;
(2) Selection of indicators for the evaluation;
(3) Consideration of reference standards; and
(4) Conceptual comprehension.

Organizing ES information based on results of this dissertation contributes to knowledge management tasks and facilitates debates on standardization. Reaching consensus on standards that codify agreement on good practices will accelerate the mainstreaming of ES information.

5.2 Methodological limitations of the dissertation

The methodological approach applied in this dissertation is denoted as ‘systematic review’. Systematic reviews differ from conventional literature reviews as they follow a strict methodological protocol and provide a comprehensive assessment of available empirical evidence [319]. Conducting systematic reviews includes the following analytical steps: (i) clearly formulate a research question, (ii) conduct a comprehensive literature search, (iii) define transparent database inclusion and exclusion criteria, (iv) conduct a synthesis of the included data, and (v) interpret the results. Each of the steps should be carried out thoroughly in order to avoid the introduction of errors and biases that entail implications for results and recommendations (Table 5.1).

Table 5.1. Limitations of systematic reviews. The table lists major errors and biases for different analytical steps in a systematic review including approaches on how to address, avoid or mitigate them.

Analytical step of review	**Source of error**	**Description**	**Approaches to address, avoid or mitigate errors and biases**
Clearly formulated research question	Integrity of research question	The usage of a holistic or reductionist approach to formulate the research question affects the review's relevance, utility and value. There is the risk that the research question becomes either too broad, complex or just impossible to answer [320] or that the external validity is limited [321].	Collaborative approaches to formulate the question with stakeholder and – if necessary – specification of sub-questions that are sufficiently well-structured to be amenable for a systematic review [322; 321; 323].
Comprehensive literature search	Selection bias	Risk that information that may be highly relevant for answering the research question is overlooked or not representative studies are included [288; 324; 325].	Different approaches for treating selection biases depending on the specific subtypes, for instance Leimu and Koricheva [326] or Rosenberger and Johnston [288].
Transparent database inclusion and exclusion criteria	Eligibility criteria bias	Risk of selective, subjective, or inconsistent inclusion of databases due to pre-specified search terms and eligibility criteria that can be interpreted in different ways. This failure can lead to inconsistent synthesis [327].	Increase reliability of inclusion or exclusion of databases by review teams of at least two reviewers. Each reviewer should apply search terms or eligibility criteria independently. Disagreements between reviewers should be resolved by consensus [328].
Synthesis of the data	Data extraction	Errors and biases due to inconsistent extraction or coding of data from database (or original studies) by reviewer [319].	Development of a standardized data extraction form for the documentation of decisions made regarding definitions of data coding criteria and data extraction [329].
	Model bias	Bias and errors resulting from the characteristics of the synthesis method. For instance, meta-regressions use statistical models to pool evidence from extracted data for answering the research question. Often model settings are determined by parameter for which subjective judgements are required [330].	Depending on method used various approaches are recommended for the mitigation of this bias, for instance narrative synthesis [331] and quantitative data synthesis [64].
	Generalization bias (external validity)	Bias and errors due to the extension of synthesis findings from a sample to the entire population without considering differences in contextual conditions such as ecological and social settings.	Meta-regression provides a vital tool for estimating the statistical influence of determinants of generalization bias [332].
	Suitability of approach used	Errors and bias due to aspects that have been left out of the formal synthesis and sources of unknowns where no scientific basis exists on which to form any calculable probability whatever [280].	Consideration of an external perspective of estimating the accuracy and robustness of the whole synthesis endeavor [333; 304].
Interpretation of the results	Reporting bias	Systematic error in the synthesis outcomes caused by selective (non-) reporting of results, for instance preferential reporting about only statistically significant results [334; 335].	The review team should explicitly acknowledge the variation in possible interpretations and simply present the evidence and limits of the analysis [332].
All steps	People involvement	Systematic error due to unbalanced engagement of different groups (e.g. funder, reviewer, practitioner) in the various analytical steps of the review process [170].	Critical appraisal of people engagement for different steps of systematic review [336].

5.2.1 Formulating a research question and databases selection process

Formulating a research question for a systematic review struggles with the compromise between taking a holistic approach, involving a large number of variables and increasing the number of relevant studies as well as a reductionist approach that limits the review's relevance, utility and value [337; 321]. The definition of the research question entails an implicit determination of those databases considered relevant. In order to reduce the risk of selective inclusion or exclusion of databases a wide range of information sources needs to be considered. Comprehensive literature searches should ensure that key evidence is not missed and as many databases as possible are identified [338]. However, such comprehensive searches tend to have low specificity, in other words poor discrimination of information that is truly irrelevant. Consequently, comprehensive searches are prone to return large numbers of irrelevant selections. Therefore, the challenge for conducting systematic reviews is to separate the evidence from the large amount of irrelevant information without introducing errors or biases.

Each systematic review (actually every analysis based on secondary data sources) can only be as good as the underlying primary study. When selecting ES databases that contain primary studies, there is the implicit assumption that the underlying body of information provides an unbiased sample of the population of empirical estimates. If this assumption is violated, the result will be systematic transfer biases [288]. Potential sources of selection biases are diverse [339; 340; 288]. However, their main concerns can be summarized and pertain to the risk that due to a selection process information that may be highly relevant for the reuse is overlooked or not representative studies are included. For instance, based on the three research questions of the dissertation, search terms were determined to collate ES databases that contain globally distributed ES studies. I chose simple and broad search terms such as 'ecosystem service' as well as eligibility criteria such as 'only databases containing globally distributed ES studies' to ensure a comprehensive literature search and unambiguous and transparent inclusion of databases for further analysis. Only 'global ES databases' were considered to minimize selection bias from local peculiarities and to increase the relevance of the review for a broader audience. Nevertheless, by using pre-defined search terms and eligibility criteria I limited the scope of the analysis, which in return led to sample selection bias. Results of the selection process showed that information for society's poorest nations was underrepresented (Chapter 2). Consequently, generalizations of assertions or the transferability of knowledge to developing countries should be treated carefully, since socio-economic and political situations vary considerably between developed and developing countries. Results from benefit transfer (Chapter 3) confirmed that transferred values in poorest areas are associated with high uncertainties.

Researchers should seek to make the potential impact of selection effects transparent, particularly where adjustments are infeasible or on which there is no widely accepted approach for mitigation. Diverse measures for correcting selection biases are suggested in literature [341; 288]. By additionally considering publications and databases – which do not literally refer to ES, but implicitly contain information that can be linked to estimate the value of nature, its benefits to humans or what a good life encompasses – the above mentioned lack of information may be attenuated. Other secondary data sources, such as the Equator Initiative's Nature-Based Solutions

Databases [342], provide best practices on nature-based actions in developing countries and could be included to complement good practice examples in poor areas with little or no data.

Another selection bias stems from poor quality of primary studies (low internal validity). Random errors and research judgments on data collection, analysis and presentation of results can affect the outcomes of primary studies. This dissertation showed that there is a limited availability of information on the quality of primary studies in ES databases (Chapter 4). Incomplete or insufficient information compromises the reuse of ES databases for other purposes. Expressing uncertainties of information contained in ES databases requires common approaches on how to report on the quality of the underlying evidence. Suggestions are given for instance by Spiegelhalter and Riesch [279], who recommend an approach that structures potential systematic and random errors of studies. Guidelines are missing that provide recommendations on how to proceed when information on the quality of primary studies is limited. Meta-analysis may provide a viable tool for reducing the influence of low quality studies by considering a comprehensive set of studies with large variations in research design. For instance, in Rosenberger and Johnston [288] it is shown how these selection biases were washed out in results of benefit transfer based on a meta-analysis.

5.2.2 Synthesis of the data

Once relevant ES databases were selected data extraction as a part of the synthesis of the data is prone to different biases and errors, too. Data extraction is the process of coding and describing information about the selected ES databases and their variables in a consistent and transparent way, so that information of the ES databases can be placed in context and synthesized. Data coding ensures that the data extracted is relevant to the research questions. Based upon data coding criteria (meta-data), relevant characteristics of selected ES databases such as objective of databases or functionality, and database variables such as results of ecological or socio-economic valued ES are recorded. In other words, a list of vital 'ingredients' (ontology) are sought and extracted that provides both insights into a better understanding of the casual powers compiled in ES databases and means by which the research questions can be answered. When deciding on data coding conceptual comprehension (Chapter 4) is a major source of error. Ambiguously defined data coding criteria lead to the introduction of selective, subjective, or inconsistent information. In fact, even if the data coding criteria are clearly defined, the extraction of information from ES databases is prone to bias. ES databases use different conceptual approaches for the documentation of database variables that require a translation and assignment to the data coding criteria. Missing descriptions and contextual information of database variables may lead to misinterpretation and misclassification in relation to the data coding criteria (Chapter 4). Also, the level of aggregation of data coding criteria is critical for data extraction. Whether specific content-related aspects of the research question are outside of control or directly considered by the data coding criteria depends on the level of aggregation of the criteria used (Chapter 4). A high level of aggregation means that information is composed from a multitude or combination of other more individual information, which leads to information loss and can result in misleading recommendations derived from the synthesis [312]. In this dissertation, tables for data coding and extraction were developed to allow repeatability of data extraction and maintain transparency in decisions made for extracting data. The tables contain prompts to record all relevant information necessary to address the research question, plus any additional information required for critical appraisal of errors and biases, and any contextual information that were required for writing the synthesis (S2.3 Table, S3.2 Table, S4.1 to S4.4 Table).

For the synthesis of the extracted data various methods can be used [343]. Depending on the method chosen different biases and errors might be introduced. The methodological approach should be justified due to the contents and heterogeneity of extracted data. When numerical contents are too few or the heterogeneity is too high, narrative syntheses are used instead of quantitative data synthesis approaches. Nonetheless, narrative syntheses, such as content analysis, include descriptive statistics to visualize findings [331]. Content analysis was used in Chapter 2 and Chapter 4 to pool the disparate information contained across different ES databases and characterize the evidence base. Applying content analysis means, categories were developed a priori based on the coding from data extraction, and frequencies of these categories were determined. Therefore, all data, including qualitative information contents of ES databases, was transformed into quantitative measures such as frequencies. Limitations of this approach for the synthesis include that '[…] it is inherently reductive and tends to diminish complexity and context' [343]. Similar to the above mentioned aggregation of data coding criteria, information get lost when qualitative information is reduced to quantitative categories. Due to this information loss counting of the frequencies may fail to reflect the structure or importance of the underlying phenomenon. For instance, the absence of database variables could be treated as evidence of non-reporting due to missing knowledge or evidence of no importance because of irrelevance for a specific purpose. Thus, there is the risk that the synthesis considers only what is easy to classify and count, rather than what is truly important, resulting in oversimplified findings. In order to minimize errors and biases for the narrative synthesis in this dissertation, I used transparent and systematic approaches to determine categories and count frequencies. Categories to synthesize the research question 1: '*How can ES databases facilitate mainstreaming ES and the development of standards in specific application contexts?*' (Chapter 2), were determined based on a systematic review of information demand of decision-makers including governmental and policy documents as well as surveys on information demand of decision-makers. Categories for the research question 3: '*Which indicators for the evaluation of effectiveness and efficiency of ES study outcomes exist in ES databases and which basic principles can be derived to facilitate a more standardized evaluation?*' (Chapter 4), were determined based on an ideal evaluation model that hierarchically organized indicators which constitute different notions of effectiveness and efficiency. This ideal evaluation model ensured that specific information was extracted by the overarching definitions which matter most, not simply the ones that are easiest to classify and count. Tables developed in the analytical step of data extraction can be used to follow decisions made for classification and counting in the narrative synthesis.

Quantitative data synthesis such as meta-regression was conducted in Chapter 3. Meta-regression includes statistical methods that pool evidence from multiple studies to detect effects and effect modifiers which describe the causal power of a study [344]. I used the meta-regression approach called boosted regression trees (BRT) to better understand the effects of ecological and socio-economic determinants on the variance of monetary values of ES. Although BRT are highly sophisticated approaches for synthesis [237], the method has inherent errors, too. With a BRT a statistical model of relationships is hypothesized based on input variables (dependent, independent variables) and model parameter that characterize model settings (learning rate, tree complexity etc.). For the determination of model parameter subjective judgements are involved that influence the reliability and robustness of findings. In this dissertation, model parameters were optimized by conducting sensitivity analyses for a set of different assumptions derived from the literature.

In the synthesis of ES databases also the external validity is crucial to consider [319]. External validity refers to the extent to which results from the synthesis can be generalized [345]. For instance, in benefit transfer context (Chapter 3), transfer errors from generalization might occur when values are transferred from the source case (location of valuation) to the target case (unsampled area) without fully accounting for scales (e.g. spatial and temporal) and environmental conditions (including ecological and social settings). The usage of meta-regression approaches, such as BRT, allows the investigation of transfer errors from generalization. In this dissertation I conducted comprehensive analyses of transfer errors from generalization and discussed major reasons.

Also deeper doubts about the suitability of the approach to synthesize the issue in question constitute a source of error. This kind of error source represents unknowns where no scientific basis exists on which to form any calculable probability whatever [280]. To acknowledge a precautionary hedge against unspecified limitations in the synthesis approach, different options can be considered, for instance for the meta-regression (Chapter 3) I estimated upper and lower probabilities for extrapolated values by providing reasonable predictive performance over a wide range of possible scenarios for the BRT parameter. Another approach to consider unknown limitations is an external perspective of estimating the accuracy and robustness of the whole synthesis endeavor. Hereby, qualitative measures of confidence are conducted based on judgments of the quality of the evidence underlying the estimates [333; 304].

5.2.3 Reporting and interpretation of results

Reporting bias relates to pitfalls surrounding the interpretation of findings from the data synthesis and the unwittingly introduction of bias due to conclusions drawn from inconclusive evidence rather than pointing out the limits of information and methods considered. When reviews are inconclusive due to missing evidence, '[…] it is important not to confuse 'no evidence of an effect' with 'evidence of no effect' [336]. The former may only provide a basis for drawing conclusions concerning the need for further research, whereas the latter could have considerable consequences for current science and practice. Also, review authors may be tempted to reach conclusions that go beyond the evidence that is reviewed or suppress information that was not considered sufficiently important for the publication. These kinds of selective conclusions introduce biased outcomes that would not have been observed when all the evidence from the synthesis had been considered. Also there is the risk that end-users with different backgrounds and purposes consider one and the same evidence from the review for different decisions. Review authors should explicitly acknowledge the variation in possible interpretations and ideally present the types of errors and bias that are potentially introduced with each analytical step of a systematic review. In this dissertation, different sources of error were identified and comprehensively discussed (Chapter 3). Findings of the discussion in Chapter 3 provided a conceptual basis for the establishment of a more standardized reporting of sources of error in benefit transfer context. Furthermore, within this Chapter 5, steps are presented that contribute to a more balanced reporting and interpretation of findings from this dissertation. By critical appraising the different analytical steps of the systematic reviews applied in this dissertation, a guiding framework is provided that increases the transparency and repeatability of the dissertation.

5.2.4 General limitations

In the process from formulating specific research questions to interpreting results of the synthesis, the integration of different groups plays a major role. For instance, to ensure independence of conduct and avoid conflicts of interest, the funder or commissioner of the review, the author that conducts the review and the stakeholder that might have a stake in the formulation of the question (and findings of the review) would not be a single individual person. Examples in literature show how an unbalanced engagement of different groups can affect results of studies [346]. In this dissertation, it was ensured that any individual considered for the formulation of the research question was not a member of more than one of these groups. Moreover, funders were declared (Acknowledgment) along with any other conflicts of interest that might have arose (Declaration under oath).

5.3 Towards optimized exploitation of ecosystem service information

In the era of knowledge-centric views and increased global networking where vast amounts of information are placed in the hands of researcher and decision-makers, it seems logical to use a database approach to manage the proliferation of information. However, this dissertation showed that ES databases contained a broad range of data semantic concepts, data types and structures (Chapter 2). Furthermore, commonly agreed reference collections were missing and only a few well-established standard protocols for archiving and retrieval of information across databases existed. These factors made the discovery and integration of ES information into decision-making an arduous task. Mechanisms are required that facilitate: i) access to databases by clarifying multiple semantic concepts used, and ii) processing of information through greater levels of automation of querying steps, data transformation, summarization, and integration tasks.

Knowledge representation techniques such as ontologies represent one enabling mechanism that is promising for unifying databases of ES, facilitating access to database contents and enable greater levels of automation. Ontologies capture semantic subtleties of ES database structure, contents and interrelationships among data variables in a logical way that can be interpreted by both human and computer applications [198; 347]. The first step to develop an ontology is to identify terms, concepts and their relationships that represent the knowledge contained in databases (Box 5.1). For instance, ES have multiple interpretations [14; 33; 16] and by formally defining these different usages a basis is provided to discuss these differences and agree upon rigorously defined and scientific sound terms and relationships. Therefore, an ontology contributes to define a common vocabulary for people who need to share information. Second, the ontology concept needs to be mapped to data entries in databases (Box 5.2). This process is often referred to as 'semantic annotation' and needs to provide information about the characteristics of database entries, which are often hidden or accompanied with meta-data. Through such annotations, ontologies improve data visibility to search engines and enable automation processes for unit conversion, semantic resolution, dataset merging, summarization of contextual information, and statistical modeling [203; 200].

Box 5.1. Using ontologies to specify ES

Ontologies are formal models of terms and concepts interrelated through logic systems of inferences analogous to mathematical set theory. According to Madin et al. [200] in an ontology, terms or concepts (i.e. sets) denote a collection of 'instances' that share common characteristics. Relationships between terms and concepts describe how they are associated and interact. For instance, the 'is-a' relationship states that the sub-concept 'Food' is also a member of the super-concept 'Ecosystem Service' (Fig 5.1). Other commonly used relationships are part-whole or disjoint relationships. Part-whole relationships, such as 'part-of' or inverse 'has-part' describe that instances of one concept are components of another concept, e.g. 'Haunch' is a part of a 'Deer' or 'Organism' are partly used as 'Food'. These relationships are constraint by the number of instances enabled in the relationship using cardinality restrictions, e.g. a 'Haunch' can only be 'part-of' one 'Deer'. The relationship 'disjoint' denotes that two concepts are mutually exclusive. Relationships and cardinality restrictions are inherited through 'is-a' relationships, e.g. instances of the concept 'Plant' have at least two or more instances of 'Biological Parts'.

Various modeling languages exist that can capture ontologies such as Web Ontology Language (OWL) [347]. OWL is used to describe here represented ontologies.

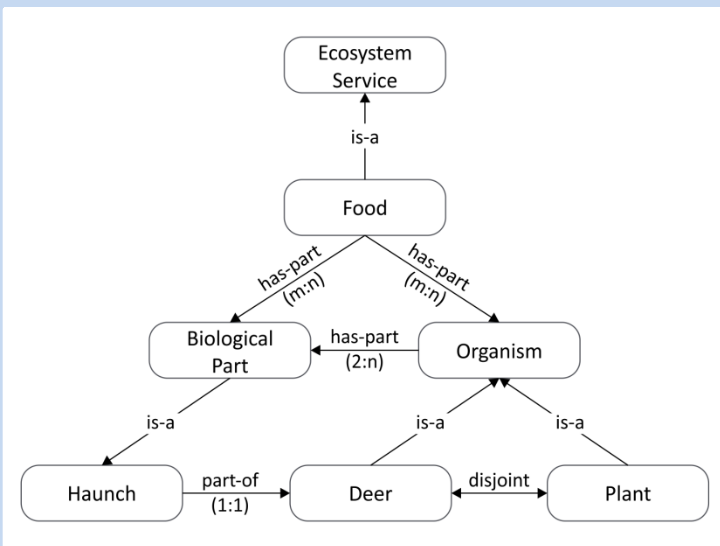


Fig 5.1. Ontology fragment for ES. The ontology fragment illustrates terms and concepts in ellipses, relationships in arrows, and cardinality restrictions are shown in parentheses. For example, some instances of 'Biological Parts' or 'Organism' are used as 'Food': A 'Haunch' is a part of one instance (1:1) of a 'Deer', conversely, an instance of 'Deer' has at least two or more (2:n) parts that are instances of 'Biological Part', because 'has-part' relationships and cardinality are inherited from super-concepts. This ontology represents only one interpretation of the ES food, where other interpretations can similarly be described and possibly interrelated using different ontologies.

The usage of ontologies would optimize semantic-based queries by broaden the capability for understanding or interpreting the content and relevance of the data from multiple disciplinary perspectives. The flexibility of the annotation approach enables multiple interpretations of data entries. For instance, different scientist can provide different annotations of the same dataset to make it simultaneously useful for separate inquiries (e.g. using pollination as a measure of intermediate service like reproduction of plants or final service such as crop yield) or to capture differences of perspectives and opinions about what the data represent (e.g. measure of productivity, biodiversity or effectiveness of a land-use intervention). In Madin et al. [203] the

Extensible Observation Ontology (OBOE) is presented that aims to capture the semantics of generic scientific observations and measurements, and allows for extensions by domain-specific vocabulary representing terminology used in specialized scientific disciplines or communities. Such ontologies facilitate transdisciplinary work on the one side and enable to better discuss standards for specific application contexts on the other side.

Also ontologies can support statistical analysis and modeling tools, for instance workflow-automation systems, which provide graphical environments for tracking data provenance, running analyses and visualizing results [348]. For instance, using ontologies for benefit transfer would facilitate and accelerate the scientific workflow shown in Chapter 3 (Fig 3.1). In this scientific workflow, each analytical step is recorded that is required to take input data (synthesize databases on monetary values and compile covariates) and produce an output product (transferred monetary values and their uncertainties). By determining semantic annotations for data sources relevant for benefit transfer, semantic compatible datasets could be identified (Box 5.2) and workflow steps executed by software applications such as the Kepler system [348] or SERVES [291]. Examples for automatized workflow steps reach from finding relevant valuation studies, translate ES types and convert units from different dataset (Box 5.2) to dataset merging and summarization of contextual information such as how, where and when valuation studies were conducted.

Box 5.2. Mainstreaming and finding data by using ontologies

Ontologies help to more powerfully discover, interpret, reuse and integrate information. For instance, in separate databases the column labels 'ValueD', 'Estimate' and 'Val' refer all to a valuation of the ES provisioning of 'Deer' as food, but this information is missing in the column labels and not described in a uniform or consistent way by meta-data. Hidden or inherent meaning of data can be clarified by semantically annotating data with concepts from ontologies (Fig 5.2 colored arrows). This enables automation processes to construct more precise queries and help to identify a greater number of relevant search results.

Assuming an ontology exists that has been built on the basis of priority areas for mainstreaming ES information (e.g. 'Recognize Nature's Value', 'Prioritization Scheme'; Fig 5.2) identified in Chapter 2. Within this ontology 'Valuation' is defined as a super-concept of 'Biophysical Measure' and 'Socio-Economic Value'. Also, 'Valuation' is a part of 'Prioritization', which is determined by the sub-concepts 'Magnitude Of Change' and 'Number of Beneficiaries'. The valuation of ES in biophysical and socio-economic terms, their magnitude of change and number of affected beneficiaries are crucial information to support decision-makers in better recognizing nature's value and prioritizing ES to identify need of action. While a conventional keyword search as 'valuation' would return only those datasets with variables directly labeled 'valuation' or whose meta-data contains this term, by annotating data to ontology concepts searching for 'valuation' would also find variables annotated with 'biophysical measure' or 'socio-economic value'. Using ontologies and semantical annotations enable to automatically expand a search by inferring relationships between terms and also allow more complex, application case-specific queries. For instance, rather than searching simply for 'valuation', a user can search via a combination of explicit ontology concepts such as 'valuation of prioritization of deer in Germany'. This query represents a multiple concept definition built from other concepts ('Valuation', 'Deer', 'Prioritization', 'Germany') and relationships (e.g. 'part-of' or 'located-in') which can be further expanded (e.g. to include 'Biophysical Measure') by an ontology-enabled

(Box continues…)

search engine [349]. If the contextual variables and semantic nature of data have been sufficiently described (including measurement standards and units; Fig. 5.2), compatible parts of resulting datasets could be automatically merged through ontology reasoning systems [203].

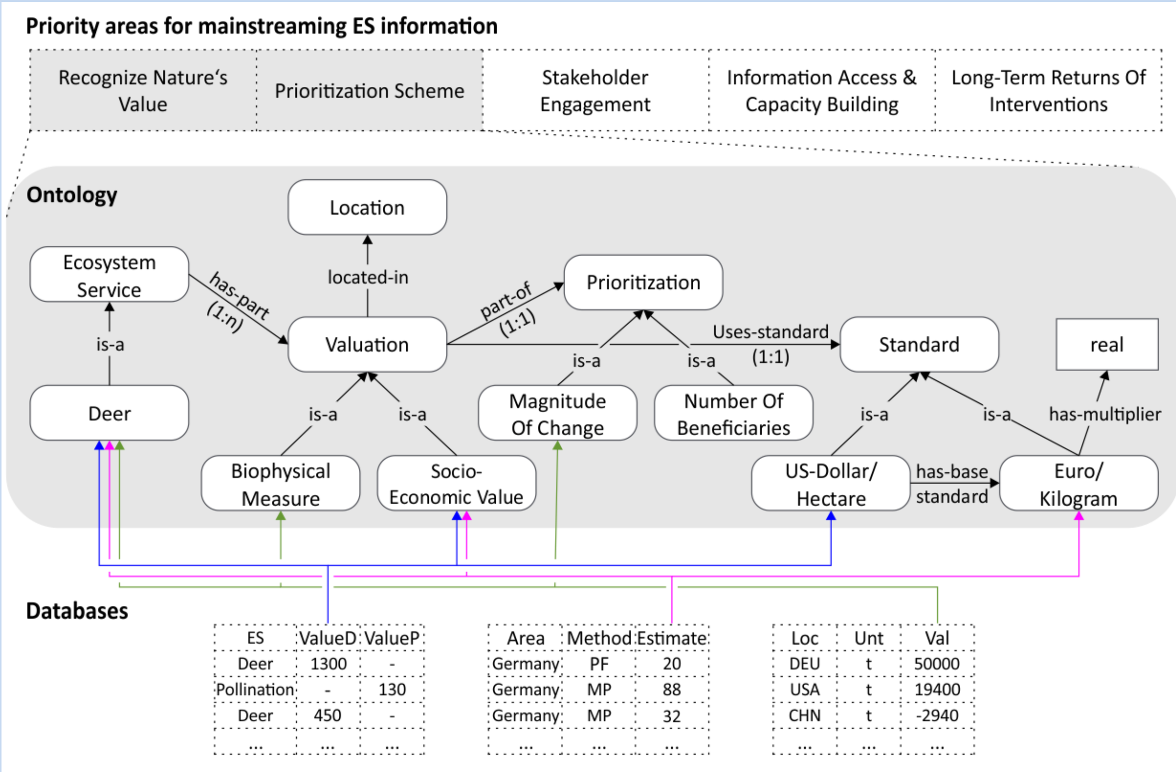


Fig 5.2. Ontology fragment and semantic annotations representing ES information for priority areas to mainstream ES information. For the priority areas (from Chapter 2): 'Recognize Nature's Value' and 'Prioritization Scheme', an ontology is visualized. Terms and concepts of the ontology semantically annotate data entries in columns of different databases (colored arrows). For instance, the blue arrows show that the dataset 'ValueD' (left database) is associated with the following three concepts: 'Deer' (the ES valued), 'Socio-Economic Value' (the value of the ES) and 'US-Dollar/Hectare' (the standard used to value ES). The purple arrows show similar annotations for the dataset in the middle. The green arrows additionally interlink data entries (right database) that contain 'Biophysical Measures' that explicitly represent the 'Magnitude Of Change' of 'Deer'. By traversing relationships in the ontology (e.g. 'is-a', 'has-part', and 'part-of'), a query for 'ecosystem service valuation' could now find data from all three databases. Moreover, information is provided to transform and merge compatible data entries from different databases exemplified by conversion of valuation units from US-Dollar/hectare to Euro/Kilogram.

Within this dissertation an empirically based taxonomy of knowledge demand on ES is identified (Chapter 2) 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 build an early prototype of a demand-driven ontology that takes full advantage of the growing ES databases on the Internet. The relevance and legitimacy of such a prototype for mainstreaming ES information could by iteratively improved by a further engagement of stakeholders and application contexts. Ontologies will be most effective when they are developed through a community-based effort involving researchers, information managers and decision-makers, and shared among a broad community of potential users [350]. Community-driven development and endorsement of ontologies are crucial to become standardized, commonly accepted and applied information-management architectures. The development of a demand-driven 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.

5.4 Conclusions

For mainstreaming ES information, more standards are needed that define terminology, acceptable data and methods, and reporting requirements for sharing consistent information on ES. This dissertation showed that there is a large amount of information on ES available in databases which provide a baseline for discussions on standards. By reviewing ES databases and matching information contents with information demand from policy instruments that affect resource and land-use decisions, common principles can be derived that represent priority areas to formalize standards for the documentation of knowledge on ES. Synthesizing ES databases for benefit transfer enabled the deduction of a conceptual foundation for a more standardized reporting on the transferability of monetary valued ES and associated uncertainties. Furthermore, applying ES database information contents to the evaluation of effectiveness and efficiency of ES study outcomes facilitated the understanding of basic principles required for a more standardized evaluation.

However, the usage of ES databases for standardization and mainstreaming ES information had limitations. Major concerns were related to various sources of error and bias from the process of reviewing and transferring database's information to different application contexts. Sources of error and bias were estimated and mitigated by different approaches shown in the dissertation. For instance, in benefit transfer meta-regressions were used to take several sources of error into account and estimate their impacts (e.g. model error, transfer error from generalization). However, mitigation approaches do not exist for all sources of error and bias. In this case researchers should seek to make the potential impacts of errors and bias as transparent as possible.

Furthermore, conceptual comprehension across ES databases is a major challenge. Even though within databases consistent information was provided, across databases different concepts were used. These differences in the organization of database entries made the data discovery, complementation of information across different databases and processing of information for answering the research questions of this dissertation an arduous task.

There is a need for more systematic reviews and the development of ontologies that help to collect, formalize and interconnect distinct concepts used in ES databases and beyond, in different ES studies and application contexts. Joining together of heterogeneous concepts, describing the relation between them and developing more standardized approaches brings great benefits. For instance, like a multilingual dictionary or a conversion table, the better understanding of relations facilitate the communication and collaboration within and between different domains and groups even when the commonality of concepts has not (yet) led to a consensus on standards.

References

1. Naisbitt J. 1982. Megatrends: Ten new directions transforming our lives. Nr. 158. Warner Books. New York. ISBN: 9780446512510
2. Björk B-C, Roos A, Lauri M. 2008. Global annual volume of peer reviewed scholarly articles and the share available via different open access options. ELPUB2008. 178-186. Accessed Mai/2018. Available from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.161.9806&rep=rep1&type=pdf.
3. National Science Board. 2010. Science and engineering indicators 2010. Arlington, USA: National Science Foundation (NSB 10-01). Accessed Mai/2018. Available from: http://www.ictliteracy.info/rf.pdf/Science-Engineering-Indicators2010.pdf
4. Grimm V, Wissel C. 1997. Babel, or the ecological stability discussions: An inventory and analysis of terminology and a guide for avoiding confusion. Oecologia 109 (3): 323-334. doi: 10.1007/s004420050090
5. Solow RM. 1973. Is the end of the world at hand? Challenge 16 (1): 39-50. doi: 10.1080/05775132.1973.11469961
6. Clawson M. 1959. Methods of measuring the demand for an value of outdoor recreation. Resources for the Future.
7. Krutilla JV. 1967. Conservation reconsidered. American Economic Review 57 (4): 777-786
8. Ridker RG, Henning JA. 1967. The determinants of residential property values with special reference to air pollution. The Review of Economics and Statistics 49 (2): 246-257. doi: 10.2307/1928231
9. Turner RK, Pearce DW, Bateman I. 1993. Environmental economics: An elementary introduction. Johns Hopkins University Press. ISBN: 9780801848636
10. Ehrlich PR, Ehrlich AH. 1981. Extinction: the causes and consequences of the disappearance of species. Random House. ISBN: 9780394513126
11. Gomez-Baggethun E, de Groot R, Lomas PL, Montes C. 2010. The history of ecosystem services in economic theory and practice: From early notions to markets and payment schemes. Ecological Economics 69 (6): 1209-1218. doi: 10.1016/j.ecolecon.2009.11.007
12. Daily GC, Polasky S, Goldstein J, Kareiva PM, Mooney HA, Pejchar L, Ricketts TH, Salzman J, Shallenberger R. 2009. Ecosystem services in decision making: Time to deliver. Frontiers in Ecology and the Environment 7 (1): 21-28. doi: 10.1890/080025
13. Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: Synthesis. Island Press. Washington, DC. ISBN: 1597260401
14. Haines-Young R, Potchin M. 2010. Proposal for a Common International Classification of Ecosystem Goods and Services (CICES) for integrated environmental and economic accounting (V1). Fifth Meeting of the UN Committee of Experts on Environmental-Economic Accounting EEA/BSS/07/007 30
15. TEEB. 2010. The Economics of Ecosystems and Biodiversity: Ecological and economic foundations. Earthscan. London, Washington. ISBN: 9781849712125

16. Landers DH, Nahlik AM. 2013. Final Ecosystem Goods and Services Classification System (FEGS-CS). Washington, DC: U.S. Environmental Protection Agency, EPA/600/R-13/ORD-004914. Accessed October/2017. Available from: https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=257922
17. Waage S, Hwang L, Armstrong K. 2012. The quiet (r)evolution in expectations of corporate environmental performance emerging trends in the uptake of ecosystem services. BSR's Ecosystem Services Working Group. Accessed April/2018. Available from: https://www.bsr.org/reports/Quiet_Revolution_Env_Performance.pdf
18. Albert C, Hauck J, Buhr N, von Haaren C. 2014. What ecosystem services information do users want? Investigating interests and requirements among landscape and regional planners in Germany. Landscape Ecology 29 (8): 1301-1313. doi: 10.1007/s10980-014-9990-5
19. Guerry AD, Polasky S, Lubchenco J, Chaplin-Kramer R, Daily GC, Griffin R, Ruckelshaus M, Bateman IJ, Duraiappah A, Elmqvist T, Feldman MW, Folke C, Hoekstra J, Kareiva PM, Keeler BL, Li SZ, McKenzie E, Ouyang ZY, Reyers B, Ricketts TH, Rockstrom J, Tallis H, Vira B. 2015. Natural capital and ecosystem services informing decisions: From promise to practice. Proceedings of the National Academy of Sciences of the United States of America 112 (24): 7348-7355. doi: 10.1073/pnas.1503751112
20. UNEP. 2016. Summary of the sixth Global Environment Outlook GEO-6 Regional Assessments: Key findings and policy messages. UNEP/EA.2/INF/17. Nairobi, Kenya: United Nations Environment Programme (UNEP). Accessed April/2018. Available from: https://europa.eu/capacity4dev/unep/blog/geo-6-global-environment-outlook-all-regional-assessments
21. UNEP. 2012. Catalogue of assessments on biodiversity and ecosystem services. Accessed April/2018. Available from: http://catalog.ipbes.net/
22. TEEB. 2014. The Economics of Ecosystems and Biodiversity - case studies. United Nations Environmental Programme (UNEP), Helmholtz Centre for Environmental Research – UFZ, Leipzig. Accessed April/2018. Available from: http://www.teebweb.org/resources/case-studies/
23. IPBES. 2017. Intergovernmental Platform on Biodiversity and Ecosystem Services - website. Accessed August/2017. Available from: https://www.ipbes.net/
24. WAVES. 2014. List of supporters. World Bank. Accessed August/2017. Available from: http://www.wavespartnership.org/sites/waves/files/documents/NCA%20supporters%20060314.pdf
25. The Natural Capital Declaration. 2012. The Natural Capital Declaration. Accessed April/2018. Available from: www.naturalcapitaldeclaration.org
26. Porras I, Grieg-Gran M, Neves N. 2008. All that glitters - a review of payments for watershed services in developing countries. London: International Institute for Environment and Development. Accessed April/2017. Available from: http://pubs.iied.org/pdfs/13542IIED.pdf
27. Schaefer M, Goldman E, Bartuska AM, Sutton-Grier A, Lubchenco J. 2015. Nature as capital: Advancing and incorporating ecosystem services in United States federal policies and

programs. Proceedings of the National Academy of Sciences 112 (24): 7383-7389. doi: 10.1073/pnas.1420500112

28. Bouwma I, Schleyer C, Primmer E, Winkler KJ, Berry P, Young J, Carmen E, Špulerová J, Bezák P, Preda E, Vadineanu A. 2017. Adoption of the ecosystem services concept in EU policies. Ecosystem Services. doi: 10.1016/j.ecoser.2017.02.014
29. Kinzig AP, Perrings C, Chapin FS, Polasky S, Smith VK, Tilman D, Turner BL. 2011. Paying for ecosystem services-promise and peril. Science 334 (6056): 603-604. doi: 10.1126/science.1210297
30. Lant CL, Ruhl JB, Kraft SE. 2008. The tragedy of ecosystem services. BioScience 58 (10): 969-974. doi: 10.1641/b581010
31. Helming K, Diehl K, Geneletti D, Wiggering H. 2013. Mainstreaming ecosystem services in European policy impact assessment. Environmental Impact Assessment Review 40 82-87. doi: 10.1016/j.eiar.2013.01.004
32. Sitas N, Prozesky HE, Esler KJ, Reyers B. 2014. Opportunities and challenges for mainstreaming ecosystem services in development planning: perspectives from a landscape level. Landscape Ecology 29 (8): 1315-1331. doi: 10.1007/s10980-013-9952-3
33. Nahlik AM, Kentula ME, Fennessy MS, Landers DH. 2012. Where is the consensus? A proposed foundation for moving ecosystem service concepts into practice. Ecological Economics 77 27-35. doi: 10.1016/j.ecolecon.2012.01.001
34. McDonough K, Hutchinson S, Moore T, Hutchinson JMS. 2017. Analysis of publication trends in ecosystem services research. Ecosystem Services 25 (Supplement C): 82-88. doi: 10.1016/j.ecoser.2017.03.022
35. Hofer BK. 2000. Dimensionality and disciplinary differences in personal epistemology. Contemporary Educational Psychology 25 (4): 378-405. doi: 10.1006/ceps.1999.1026
36. Fazey I, Evely AC, Reed MS, Stringer LC, Kruijsen J, White PCL, Newsham A, Jin LX, Cortazzi M, Phillipson J, Blackstock K, Entwistle N, Sheate W, Armstrong F, Blackmore C, Fazey J, Ingram J, Gregson J, Lowe P, Morton S, Trevitt C. 2013. Knowledge exchange: a review and research agenda for environmental management. Environmental Conservation 40 (1): 19-36. doi: 10.1017/s037689291200029x
37. Jax K. 2006. Ecological units: Definitions and application. Quarterly Review of Biology 81 (3): 237-258. doi: 10.1086/506237
38. Pickett STA, Kolasa J, Jones CG. 2007. Ecological understanding: The nature of theory and the theory of nature. Ecological Understanding (Second Edition). Academic Press. San Diego. ISBN: 978-0-12-554522-8. doi: 10.1016/B978-012554522-8.50003-0
39. Polasky S, Tallis H, Reyers B. 2015. Setting the bar: Standards for ecosystem services. Proceedings of the National Academy of Sciences of the United States of America 112 (24): 7356-7361. doi: 10.1073/pnas.1406490112
40. Hoehne WE. 1978. Standards for meteorology. Bulletin of the American Meteorological Society 59 (9): 1156-1158. doi: 10.1175/1520-0477(1978)059<1156:sfm>2.0.co;2
41. Finkbeiner M, Inaba A, Tan RBH, Christiansen K, Kluppel HJ. 2006. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. International Journal of Life Cycle Assessment 11 (2): 80-85. doi: 10.1065/lca2006.02.002

42. Prusak L. 2001. Where did knowledge management come from? Ibm Systems Journal 40 (4): 1002-1007. doi: 10.1147/sj.404.01002
43. Peterseil J, Magagna B, Schentz H, van der Werf B, Kertész M, Bertrand N, Kuitunen P, van Daele T, Frenzel M, Borovec J, Lieskovský J, Adamescu M, Aszalós R, Karasti H, Boussard H, Blankman D. 2009. A Long-term Biodiversity, Ecosystem and Awareness Research Network: Basic set of domain ontologies. Vienna: 3.I6.D1. Accessed February/2018. Available from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.113.180&rep=rep1&type=pdf
44. Nativi S, Craglia M, Pearlman J. 2013. Earth science infrastructures interoperability: The brokering approach. Ieee Journal of Selected Topics in Applied Earth Observations and Remote Sensing 6 (3): 1118-1129. doi: 10.1109/jstars.2013.2243113
45. Hey T, Tansley S, Tolle K. 2009. The fourth paradigm data-intensive scientific discovery. Redmond: Microsoft Research. Accessed April/2018. Available from: http://www.immagic.com/eLibrary/ARCHIVES/EBOOKS/M091000H.pdf
46. Dwivedi YK, Venkitachalam K, Sharif AM, Al-Karaghouli W, Weerakkody V. 2011. Research trends in knowledge management: Analyzing the past and predicting the future. Information Systems Management 28 (1): 43-56. doi: 10.1080/10580530.2011.536112
47. Nativi S, Mazzetti P, Santoro M, Papeschi F, Craglia M, Ochiai O. 2015. Big Data challenges in building the Global Earth Observation System of Systems. Environmental Modelling & Software 68 1-26. doi: 10.1016/j.envsoft.2015.01.017
48. Helen G. 1998. Knowledge management. Work Study 47 (5): 175-177. doi: 10.1108/00438029810229318
49. IPBES. 2016. Preliminary guide regarding diverse conceptualization of multiple values of nature and its benefits, including biodiversity and ecosystem functions and services (deliverable 3 (d)). Kuala Lumpur: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES-4-INF-13_EN. Accessed March/2018. Available from: http://www.ipbes.net/sites/default/files/downloads/IPBES-4-INF-13_EN.pdf
50. Olander L, Characklis GW, Comer P, Effron M, Gunn J, Holmes T, Johnston R, Kagan J, Lehman W, Loomis J, McPhearson T, Neale A, Patterson L, Richardson L, Ross M, Saah D, Sifleet S, Stockmann K, Urban D, Wainger L, Winthrop R, Yoskowitz D. 2016. Data and modeling infrastructure for national integration of ecosystem services into decision making: Expert summaries. Durham: National Ecosystem Services Partnership, NESP WP 16-02. Accessed April/2018. Available from: https://nicholasinstitute.duke.edu/sites/default/files/publications/nesp_wp_16-02_0.pdf
51. IPBES. 2014. Decision IPBES-2/5: Work programme for the period 2014-2018. Bonn. Accessed August/2017. Available from: https://www.ipbes.net/system/tdf/downloads/Decision%20IPBES_2_5.pdf?file=1&type=node&id=14655
52. Tallis H, Mooney H, Andelman S, Balvanera P, Cramer W, Karp D, Polasky S, Reyers B, Ricketts T, Running S, Thonicke K, Tietjen B, Walz A. 2012. A global system for monitoring ecosystem service change. BioScience 62 (11): 977-986. doi: 10.1525/bio.2012.62.11.7
53. Becerra-Fernandez I, Sabherwal R. 2010. Knowledge management: Systems and processes. M.E. Sharpe. Armonk (N.Y.), London. ISBN: 9780765628572

54. McComb G, Lantz V, Nash K, Rittmaster R. 2006. International valuation databases: Overview, methods and operational issues. Ecological Economics 60 (2): 461-472. doi: 10.1016/j.ecolecon.2006.05.009
55. de Groot R, Brander L, van der Ploeg S, Costanza R, Bernard F, Braat L, Christie M, Crossman N, Ghermandi A, Hein L, Hussain S, Kumar P, McVittie A, Portela R, Rodriguez LC, ten Brink P, van Beukering P. 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosystem Services 1 (1): 50-61. doi: 10.1016/j.ecoser.2012.07.005
56. Sangha KK, Russell-Smith J, Morrison SC, Costanza R, Edwards A. 2017. Challenges for valuing ecosystem services from an Indigenous estate in northern Australia. Ecosystem Services 25 167-178. doi: 10.1016/j.ecoser.2017.04.013
57. McKenzie E, Posner S, Tillmann P, Bernhardt JR, Howard K, Rosenthal A. 2014. Understanding the use of ecosystem service knowledge in decision making: Lessons from international experiences of spatial planning. Environment and Planning C-Government and Policy 32 (2): 320-340. doi: 10.1068/c12292j
58. Ruckelshaus M, McKenzie E, Tallis H, Guerry A, Daily G, Kareiva P, Polasky S, Ricketts T, Bhagabati N, Wood SA, Bernhardt J. 2015. Notes from the field: Lessons learned from using ecosystem service approaches to inform real-world decisions. Ecological Economics 115 11-21. doi: 10.1016/j.ecolecon.2013.07.009
59. Saarikoski H, Primmer E, Saarela S-R, Antunes P, Aszalós R, Baró F, Berry P, Blanko GG, Goméz-Baggethun E, Carvalho L, Dick J, Dunford R, Hanzu M, Harrison PA, Izakovicova Z, Kertész M, Kopperoinen L, Köhler B, Langemeyer J, Lapola D, Liquete C, Luque S, Mederly P, Niemelä J, Palomo I, Pastur GM, Peri PL, Preda E, Priess JA, Santos R, Schleyer C, Turkelboom F, Vadineanu A, Verheyden W, Vikström S, Young J. 2017. Institutional challenges in putting ecosystem service knowledge in practice. Ecosystem Services. doi: 10.1016/j.ecoser.2017.07.019
60. Förster J, Barkmann J, Fricke R, Hotes S, Kleyer M, Kobbe S, Kübler D, Rumbaur C, Siegmund-Schultze M, Seppelt R, Settele J, Spangenberg JH, Tekken V, Václavík T, Wittmer H. 2015. Assessing ecosystem services for informing land-use decisions: A problem-oriented approach. Ecology and Society 20 (3). doi: 10.5751/ES-07804-200331
61. Boyd J, Banzhaf S. 2007. What are ecosystem services? The need for standardized environmental accounting units. Ecological Economics 63 (2-3): 616-626. doi: 10.1016/j.ecolecon.2007.01.002
62. Sagoff M. 2011. The quantification and valuation of ecosystem services. Ecological Economics 70 (3): 497-502. doi: 10.1016/j.ecolecon.2010.10.006
63. Martin-Lopez B, Gomez-Baggethun E, Garcia-Llorente M, Montes C. 2013. Trade-offs across value-domains in ecosystem services assessment. Ecological Indicators 37 220-228. doi: 10.1016/j.ecolind.2013.03.003
64. Nelson J, Kennedy P. 2009. The use (and abuse) of meta-analysis in environmental and natural resource economics: An assessment. Environmental & Resource Economics 42 (3): 345-377. doi: 10.1007/s10640-008-9253-5

65. Johnston RJ, Rosenberger RS. 2010. Methods, trends and controversies in contemporary benefit transfer. Journal of Economic Surveys 24 (3): 479-510. doi: 10.1111/j.1467-6419.2009.00592.x

66. Rosenberger R, Phipps T. 2007. Correspondence and convergence in benefit transfer accuracy: Meta-analytic review of the literature. Environmental Value Transfer: Issues and Methods The Economics of Non-Market Goods and Resources Volume 9 pp 23-43

67. Plummer ML. 2009. Assessing benefit transfer for the valuation of ecosystem services. Frontiers in Ecology and the Environment 7 (1): 38-45. doi: 10.1890/080091

68. Boyle KJ, Bergstrom JC. 1992. Benefit transfer studies - myths, pragmatism, and idealism. Water Resources Research 28 (3): 657-663. doi: 10.1029/91wr02591

69. Bennett J. 2006. Introduction. Rolfe J, Bennett J editors. Choice modelling and the transfer of environmental values Cheltenham, UK: Edward Elgar, 1-9. ISBN: 978-1-84376-684-1. doi: 10.1093/erae/jbm030

70. Rosenberger RS, Stanley TD. 2006. Measurement, generalization, and publication: Sources of error in benefit transfers and their management. Ecological Economics 60 (2): 372-378. doi: 10.1016/j.ecolecon.2006.03.018

71. Eshet T, Baron MG, Shechter M. 2007. Exploring benefit transfer: Disamenities of waste transfer stations. Environmental & Resource Economics 37 (3): 521-547. doi: 10.1007/s10640-006-9047-6

72. McCauley DJ. 2006. Selling out on nature. Nature 443 (7107): 27-28. doi: 10.1038/443027a

73. Kosoy N, Corbera E. 2010. Payments for ecosystem services as commodity fetishism. Ecological Economics 69 (6): 1228-1236. doi: 10.1016/j.ecolecon.2009.11.002

74. Norgaard RB. 2010. Ecosystem services: From eye-opening metaphor to complexity blinder. Ecological Economics 69 (6): 1219-1227. doi: 10.1016/j.ecolecon.2009.11.009

75. Fisher JA, Brown K. 2014. Ecosystem services concepts and approaches in conservation: Just a rhetorical tool? Ecological Economics 108 257-265. doi: 10.1016/j.ecolecon.2014.11.004

76. Silvertown J. 2015. Have ecosystem services been oversold? Trends in Ecology & Evolution. doi: 10.1016/j.tree.2015.08.007

77. Miteva DA, Pattanayak SK, Ferraro PJ. 2014. Do biodiversity policies work? The case for conservation evaluation 2.0. Nature in the Balance. Oxford: Oxford University Press. ISBN: 9780199676880. doi: 10.1093/acprof:oso/9780199676880.003.0012

78. Kontogianni A, Luck GW, Skourtos M. 2010. Valuing ecosystem services on the basis of service-providing units: A potential approach to address the ‘endpoint problem’ and improve stated preference methods. Ecological Economics 69 (7): 1479-1487. doi: 10.1016/j.ecolecon.2010.02.019

79. Liu S, Costanza R, Farber S, Troy A. 2010. Valuing ecosystem services theory, practice, and the need for a transdisciplinary synthesis. Limburg K, Costanza R editors. Ecological Economics Reviews. Malden: Wiley-Blackwell, 54-78. ISBN: 0077-8923

978-1-57331-766-5. doi: 10.1111/j.1749-6632.2009.05167.x

80. Abson DJ, von Wehrden H, Baumgärtner S, Fischer J, Hanspach J, Härdtle W, Heinrichs H, Klein AM, Lang DJ, Martens P, Walmsley D. 2014. Ecosystem services as a boundary object for sustainability. Ecological Economics 103 (0): 29-37. doi: 10.1016/j.ecolecon.2014.04.012

81. Turnhout E, Neves K, de Lijster E. 2014. 'Measurementality' in biodiversity governance: knowledge, transparency, and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). Environment and Planning A 46 (3): 581-597. doi: 10.1068/a4629
82. House ER. 1978. Assumptions underlying evaluation models. Educational Researcher 7 (3): 4-12. doi: 10.3102/0013189x007003004
83. Stufflebeam DL, Webster WJ. 1980. An analysis of alternative approaches to evaluation. Educational Evaluation and Policy Analysis 2 (3): 5-20. doi: 10.2307/1163593
84. Vartiainen P. 2002. On the principles of comparative evaluation. Evaluation 8 (3): 359-371. doi: 10.1177/135638902401462484
85. Seppelt R, Dormann CF, Eppink FV, Lautenbach S, Schmidt S. 2011. A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. Journal of Applied Ecology 48 (3): 630-636. doi: 10.1111/j.1365-2664.2010.01952.x
86. Engel S, Pagiola S, Wunder S. 2008. Designing payments for environmental services in theory and practice: An overview of the issues. Ecological Economics 65 (4): 663-674. doi: 10.1016/j.ecolecon.2008.03.011
87. Laycock HF, Moran D, Smart JCR, Raffaelli DG, White PCL. 2011. Evaluating the effectiveness and efficiency of biodiversity conservation spending. Ecological Economics 70 (10): 1789-1796. doi: 10.1016/j.ecolecon.2011.05.002
88. Armsworth PR, Acs S, Dallimer M, Gaston KJ, Hanley N, Wilson P. 2012. The cost of policy simplification in conservation incentive programs. Ecology Letters 15 (5): 406-414. doi: 10.1111/j.1461-0248.2012.01747.x
89. Galler C, von Haaren C, Albert C. 2015. Optimizing environmental measures for landscape multifunctionality: Effectiveness, efficiency and recommendations for agri-environmental programs. Journal of Environmental Management 151 243-257. doi: 10.1016/j.jenvman.2014.12.011
90. Ranganathan J, Raudsepp-Hearne C, Lucas N, Irwin F, Zurek M, Bennett K, West P. 2008. Ecosystem services - a guide for decision makers. World Resource Institute, 2007941147. Accessed April/2018. Available from: http://pdf.wri.org/ecosystem_services_guide_for_decisionmakers.pdf
91. Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: Opportunities and challenges for business and industry. Washington, DC.: World Resources Institute. Accessed April/2018. Available from: http://www.millenniumassessment.org/documents/document.353.aspx.pdf
92. COP. 2010. Report of the tenth meeting of the Conference of the Parties to the Convention on Biological Diversity. Nagoya: 27. Accessed October/2017. Available from: http://www.cbd.int/cop10/doc/
93. PRI & UNEP FI. 2011. Universal Ownership - why environmental externalities matter to institutional investor. Trucost, Principles for Responsible Investment, United Nations Environment Programme Finance Initiative. Accessed April/2018. Available from: http://www.unepfi.org/fileadmin/documents/universal_ownership_full.pdf

94. Bartelmus P. 2014. Environmental-economic accounting: Progress and digression in the SEEA revisions. Review of Income and Wealth 60 (4): 887-904. doi: 10.1111/roiw.12056

95. IPIECA. 2016. Biodiversity and ecosystem services fundamentals - guidance document for the oil and gas industry. IPIECA, International Association of Oil and Gas Producers, 554. Accessed April/2018. Available from: http://www.ipieca.org/resources/good-practice/biodiversity-and-ecosystem-services-fundamentals/

96. Natural Capital Coalition. 2016. Natural Capital Protocol. Accessed October/2017. Available from: www.naturalcapitalcoalition.org/protocol

97. Hauck J, Schweppe-Kraft B, Albert C, Görg C, Jax K, Jensen R, Fürst C, Maes J, Ring I, Hönigová I, Burkhard B, Mehring M, Tiefenbach M, Grunewald K, Schwarzer M, Meurer J, Sommerhäuser M, Priess JA, Schmidt J, Grêt-Regamey A. 2013. The promise of the ecosystem services concept for planning and decision-making. GAIA - Ecological Perspectives for Science and Society 22 (4): 232-236. doi: 10.14512/gaia.22.4.6

98. Weichselgartner J, Kasperson R. 2010. Barriers in the science-policy-practice interface: Toward a knowledge-action-system in global environmental change research. Global Environmental Change-Human and Policy Dimensions 20 (2): 266-277. doi: 10.1016/j.gloenvcha.2009.11.006

99. van den Hove S, Chabason L. 2009. The debate on an Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) - exploring gaps and needs. Paris: Institute for Sustainable Development and International Relations (IDDRI), 01/2009. Accessed October/2017. Available from: http://www.iddri.org/Publications/Collections/Idees-pour-le-debat/Id_090104_gap_analysis-4Feb.pdf

100. Laurans Y, Rankovic A, Bille R, Pirard R, Mermet L. 2013. Use of ecosystem services economic valuation for decision making: Questioning a literature blindspot. Journal of Environmental Management 119 208-219. doi: 10.1016/j.jenvman.2013.01.008

101. Guo J, Kildow J. 2015. The gap between science and policy: Assessing the use of nonmarket valuation in estuarine management based on a case study of US federally managed estuaries. Ocean & Coastal Management 108 20-26. doi: 10.1016/j.ocecoaman.2014.09.017

102. Ash N, Blanco H, Brown C, Garcia K, Henrichs T, Lucas N, Raudsepp-Hearne C, David Simpson DR, Scholes R, Tomich TP, Vira B, Zurek M. 2010. Ecosystems and human well-being: A manual for assessment practitioners. Island Press. Washington, Covelo, London. ISBN: 9781597267113

103. Seppelt R, Fath B, Burkhard B, Fisher JL, Gret-Regamey A, Lautenbach S, Pert P, Hotes S, Spangenberg J, Verburg PH, Van Oudenhoven APE. 2012. Form follows function? Proposing a blueprint for ecosystem service assessments based on reviews and case studies. Ecological Indicators 21 145-154. doi: 10.1016/j.ecolind.2011.09.003

104. Kosmus M, Renner I, Ullrich S. 2012. Integrating ecosystem services into development planning - a stepwise approach for practitioners based on the TEEB approach. Eschborn: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). Accessed April/2018. Available from: https://www.cbd.int/doc/case-studies/inc/giz-2012-en-integr-ecosys-serv-in-dev-planning.pdf

105. DEFRA. 2015. What nature can do for you - a practical introduction to making the most of natural services, assets and resources in policy and decision making. Deparment for Environment, Food and Rural Affairs (DEFRA). Accessed April/2018. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/396840/pb13897-nature-do-for-you.pdf

106. Fienberg SE. 1994. Sharing statistical data in the biomedical and health sciences: Ethical, institutional, legal, and professional dimensions. Annual Review of Public Health 15 1-18. doi: 10.1146/annurev.pu.15.050194.000245

107. ICPSR. 2012. Guide to social science data preparation and archiving: Best practice throughout the data life cycle. Ann Arbor: Inter-university Consortium for Political and Social Research (ICPSR). Accessed April/2018. Available from: https://www.icpsr.umich.edu/files/deposit/dataprep.pdf

108. NSB. 2005. Long-lived digital data collections: Enabling research and education in the 21st century. National Science Board of the National Science Foundation of United States, NSB-05-40. Accessed April/2018. Available from: https://www.nsf.gov/pubs/2005/nsb0540/nsb0540.pdf

109. EVRI. 2016. Environmental Valuation Reference Inventory (EVRI) – online database for benefit transfer. Economic Analysis Directorate, Environment Canada, Canada. Accessed February/2016. Available from: http://www.evri.ca/

110. ARIES. 2017. ARtificial Intelligence for Ecosystem Services case studies. Accessed April/2018. Available from: http://www.ariesonline.org/

111. BUVD. 2001. Beneficial use values database. Accessed April/2018. Available from: http://buvd.ucdavis.edu/

112. Keniger L, Gaston K, Irvine K, Fuller R. 2013. What are the benefits of interacting with nature? International Journal of Environmental Research and Public Health 10 (3): 913. doi: 10.3390/ijerph10030913

113. Goldman RL, Tallis H, Kareiva P, Daily GC. 2008. Field evidence that ecosystem service projects support biodiversity and diversify options. Proceedings of the National Academy of Sciences of the United States of America 105 (27): 9445-9448. doi: 10.1073/pnas.0800208105

114. US EPA. 2017. EcoService Models Library (ESML). United States Environmental Protection Agency (US EPA). Accessed April/2018. Available from: https://esml.epa.gov/epf_l/

115. UNEP. 2015. Ecosystem Service Indicator Database (ESID). United Nations Environmental Programme (UNEP). Accessed February/2015. Available from: n.a.

116. Van der Ploeg S, Wang Y, Gebre Weldmichael T, De Groot RS. 2010. The TEEB valuation database – a searchable database of 1310 estimates of monetary values of ecosystem services. Wageningen: Foundation for Sustainable Development. Accessed April/2018. Available from: https://www.es-partnership.org/wp-content/uploads/2016/06/ESVD.-TEEB_Database_Report.pdf

117. University of Minnesota. 2013. Ecosystem Services Bibliography. University of Minnesota. Accessed April/2018. Available from: https://wayback.archive-it.org/338/20101229034335/http://blog.lib.umn.edu/polasky/ecosystem/

118. NOEP. 2017. Environmental & recreational (non-market) values - valuation studies search. National Ocean Economics Program (NOEP). Accessed February/2017. Available from: http://www.oceaneconomics.org/nonmarket/NMsearch2.asp

119. Cost Benefit Group. 2017. Environmental valuation & cost-benefit news - supporting rational evaluation over preconception by facilitating comprehensive quantification. Accessed April/2018. Available from: http://www.envirovaluation.org/

120. NSW EPA. 2004. Envalue - Environmental Valuation Database, a searchable environmental valuation database. New South Wales Environmental Protection Agency (NSW EPA). Accessed April/2018. Available from: http://www.environment.nsw.gov.au/envalueapp/Default.asp?ordertype=MEDIUM

121. Vihervaara P, Ronka M, Walls M. 2010. Trends in ecosystem service research: Early steps and current drivers. Ambio 39 (4): 314-324. doi: 10.1007/s13280-010-0048-x

122. Innovation Seeds. 2017. The eco-innovation knowledge portal for researchers, policy-makers and business. Accessed April/2018. Available from: http://www.innovationseeds.eu/

123. Cardinale BJ, Duffy JE, Gonzalez A, Hooper DU, Perrings C, Venail P, Narwani A, Mace GM, Tilman D, Wardle DA, Kinzig AP, Daily GC, Loreau M, Grace JB, Larigauderie A, Srivastava DS, Naeem S. 2012. Biodiversity loss and its impact on humanity. Nature 486 (7401): 59-67. doi: 10.1038/nature11148

124. de Bello F, Lavorel S, Diaz S, Harrington R, Cornelissen JHC, Bardgett RD, Berg MP, Cipriotti P, Feld CK, Hering D, da Silva PM, Potts SG, Sandin L, Sousa JP, Storkey J, Wardle DA, Harrison PA. 2010. Towards an assessment of multiple ecosystem processes and services via functional traits. Biodiversity and Conservation 19 (10): 2873-2893. doi: 10.1007/s10531-010-9850-9

125. Duke University. 2017. MESP - Marine Ecosystem Service Partnership. Accessed April/2018. Available from: http://marineecosystemservices.org/explore

126. Ecosystem Marketplace. 2017. Ecosystem Marketplace - A Forest Trends initiative. Accessed April/2018. Available from: http://www.ecosystemmarketplace.com/ecosystem-services/

127. OAS. 2008. Payment for ecosystem services database. Organization of America States (OAS). Accessed February/2017. Available from: http://www.oas.org/dsd/PES/Database.htm#

128. IIED. 2012. Payment for watershed markets - information from schemes in developing countries. International Institute for Environment and Development (IIED). Accessed April/2018. Available from: http://www.watershedmarkets.org/index.html

129. US EPA. 2016. ReefLink Database - a decision support tool for linking coral reefs and society through systems thinking, developed by the United States Environmental Protecion Agency. United States Environmental Protection Agency (US EPA). Accessed April/2018. Available from: https://archive.epa.gov/ged/coralreef/web/html/index.html

130. Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: Multiscale assessments. Island Press. Washington, DC. ISBN: 9781559631853

131. UNEP. 2005. Sub-Global Assessments and Working Group. United Nations Environmental Programme (UNEP). Accessed April/2018. Available from: http://www.millenniumassessment.org/en/Multiscale.html

132. ELD Initiative. 2017. ELD Case Studies, developed by The Economics of Land Degradation (ELD). Accessed April/2018. Available from: http://www.eld-initiative.org/index.php?id=70
133. ELD Initiative. 2013. The rewards of investing in sustainable land management. Interim report for the Economics of Land Degradation Initiative: A global strategy for sustainable land management. Bonn. Accessed April/2018. Available from: http://www.eld-initiative.org/fileadmin/pdf/ELD-Interim_Report_web.pdf
134. ValuES. 2016. ValuES Case Studies: Experiences with ecosystem service assessment processes, in ValuES: Methods for integrating ecosystem services into policy, planning, and practice. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Helmholtz-Centre for Environmental Research - UFZ, Leipzig. Accessed April/2018. Available from: http://aboutvalues.net/case_studies/
135. ValuES. 2016. ValuES Methods Database : Finding suitable methods for assessing ecosystem services, in ValuES: Methods for integrating ecosystem services into policy, planning, and practice. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Helmholtz-Centre for Environmental Research - UFZ. Accessed April/2018. Available from: http://aboutvalues.net/method_database/
136. TEEB. 2011. The Economics of Ecosystems and Biodiversity in national and international policy making. Earthscan. London, Washington. ISBN: 9781849712507
137. Schmidt S. 2018. Information content of global ecosystem service databases and their suitability for decision advice - data repository. Figshare. Accessed April/2018. doi: 10.6084/m9.figshare.6210872
138. UNDP. 2014. Human Development Report 2014. Sustaining human progress: Reducing vulnerabilities and building resilience. Tokyo: United Nations Development Programme. Accessed November/2017. Available from: http://hdr.undp.org/en/content/human-development-report-2014
139. Nelson GC, Bennett E, Berhe AA, Cassman KG, Defries R, Dietz T, Dobson A, Dobermann A, Janetos A, Levy M, Marco D, Nakicenovic N, O'Neill B, Norgaard R, Held P, Ojima D, Pingali P, Watson R, Zurek M, Carpenter SR, Pingali PL, Bennett EM, Zurek MB. 2005. Chapter 7: Drivers of change in ecosystem condition and services. Ecosystems and human well-being: Scenarios, volume 2. Washington, DC: Island Press. ISBN: 9781559633901
140. European Commission. 2017. Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. The EU Environmental Implementation Review: Common challenges and how to combine efforts to deliver better results. Brussels: European Commission, Directorate-General for Environment. Accessed April/2018. Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017DC0063
141. Jack BK, Kousky C, Sims KRE. 2008. Designing payments for ecosystem services: Lessons from previous experience with incentive-based mechanisms. Proceedings of the National Academy of Sciences of the United States of America 105 (28): 9465-9470. doi: 10.1073/pnas.0705503104

142. FAO. 2011. Payments for ecosystem services and food security. Rome: Food and Agriculture Organization (FAO) of the United Nations. Accessed April/2018. Available from: http://www.fao.org/docrep/014/i2100e/i2100e.pdf

143. Shine C. 2005. Using tax incentives to conserve and enhance biodiversity in Europe. 143. Nature and Environment. Council of Europe Publishing. ISBN: 978-92-871-5780-5

144. Anon. 2008. The project snow leopard. New Delhi: Ministry of Environment & Forests, Government of India. Accessed April/2018. Available from: http://www.snowleopardnetwork.org/actionplans/India_PSL.pdf

145. Bergsma E. 2000. Incentives of land users in projects of soil and water conservation, the weight of intangibles. GeoJournal 50 (1): 47-54. doi: 10.1023/a:1007146008246

146. Popp D. 2009. Abschlussbericht: Effizienzsteigerung des Prüfzeichens für das Biosphärenreservat Schorfheide-Chorin. Haundorf: FUTOUR Regionalberatung. Accessed October/2017. Available from: n.a.

147. Remme RP, Edens B, Schroter M, Hein L. 2015. Monetary accounting of ecosystem services: A test case for Limburg province, the Netherlands. Ecological Economics 112 116-128. doi: 10.1016/j.ecolecon.2015.02.015

148. OECD. 2005. Environmentally harmful subsidies: Challenges for reform. Paris: Organisation for Economic Co-operation and Development (OECD). Accessed April/2018. Available from: https://www.oecd-ilibrary.org/docserver/9789264012059-en.pdf?expires=1524763491&id=id&accname=oid013681&checksum=9DE438D32085FCF32383A7FC6EA9F1DD

149. Ulibarri CA, Seely HS, Willis DB. 1998. Farm profitability and BUREC water subsidies: An LP look at a region. Contemporary Economic Policy 16 (4): 442-451. doi: 10.1111/j.1465-7287.1998.tb00532.x

150. OECD. 1996. Subsidies and environment: Exploring the linkages. Paris: Organisation for Economic Co-operation and Development (OECD); Washington, D.C.: OECD Publications and Information Center. Accessed November/2017. Available from: Not open source

151. Bocker T, Finger R. 2016. European pesticide tax schemes in comparison: An analysis of experiences and developments. Sustainability 8 (4): 22. doi: 10.3390/su8040378

152. Yandle T, Dewees CM. 2008. Consolidation in an individual transferable quota regime: Lessons from New Zealand, 1986-1999. Environmental Management 41 (6): 915-928. doi: 10.1007/s00267-008-9081-y

153. Carroll N, Fox J, Bayon R. 2012. Conservation and biodiversity banking: A guide to setting up and running biodiversity credit trading systems. Taylor & Francis. ISBN: 9781849770842

154. Rosa JCS, Novachi G, Sánchez LE. 2016. Offsetting and compensating biodiversity and ecosystem services losses in mining. Annual Conference of the International Association for Impact Assessment. 1-6. Accessed June/2018. Available from: https://www.researchgate.net/profile/Luis_Sanchez39/publication/306248675_Offsetting_and_compensating_biodiversity_and_ecosystem_services_losses_in_mining/links/57b45a6108aeaab2a1038a69.pdf.

155. Barnes JI. 1996. Changes in the economic use value of elephant in Botswana: The effect of international trade prohibition. Ecological Economics 18 (3): 215-230. doi: 10.1016/0921-8009(96)00035-3

156. European Commission. 2004. Environmental Liability Directive. Accessed July/2017. Available from: http://ec.europa.eu/environment/legal/liability/

157. Pasha R, Asmawan T, Leimona B, Setiawan E, Wijaya CI. 2012. Commoditized or co-invested environmental services? Working paper nr 148. DOI: 10.5716/WP12051.PDF. Bogor, Indonesia: World Agroforestry Centre - ICRAF, SEA Regional Office, p27. doi: 10.5716/WP12051.PDF

158. Federal Register Presidential Documents, Executive Order 13158 of May 26, 2000 National Oceanic and Atmospheric Administration (NOAA),. Sect. (2000).

159. Gray NJ, Campbell LM. 2009. Science, policy advocacy, and marine protected areas. Conservation Biology 23 (2): 460-468. doi: 10.1111/j.1523-1739.2008.01093.x

160. Roberts CM, Bohnsack JA, Gell F, Hawkins JP, Goodridge R. 2001. Effects of marine reserves on adjacent fisheries. Science 294 (5548): 1920-1923. doi: 10.1126/science.294.5548.1920

161. Gjertsen H. 2005. Can habitat protection lead to improvements in human well-being? Evidence from marine protected areas in the Philippines. World Development 33 (2): 199-217. doi: 10.1016/j.worlddev.2004.07.009

162. Dixon JA, Sherman PB. 1990. Economics of protected areas: A new look at benefits and costs. Island Press. ISBN: 9781559630320

163. Dharmaratne GS, Yee Sang F, Walling LJ. 2000. Tourism potentials for financing protected areas. Annals of Tourism Research 27 (3): 590-610. doi: 10.1016/S0160-7383(99)00109-7

164. Aronson J, Milton SJ, Blignaut JN. 2007. Restoring natural capital: Definitions and rationale. Aronson J, Milton SJ, Blignaut JN editors. Restoring natural capital: Science, business and practice. Washington, D.C: Island Press, 3-8. ISBN: 978-1-59726-076-3

165. Reid J. 1999. Two roads and a lake, an economic analysis of infrastructure development in the Beni river watershed. Conservation Strategy Fund. Accessed April/2018. Available from: http://conservation-strategy.org/sites/default/files/field-file/tworoads_complete.pdf

166. Wittich A, Reid J, Malky A. 2014. Cost-benefit-analysis of the Bala dam proposal, Bolivia. Using economics to better show the overall expected impacts of a large infrastructure project. Gesellschaft für Internationale Zusammenarbeit (GIZ), Helmholtz Centre for Environmental Research - UFZ, Leipzig 1-3. Accessed April/2018. Available from: http://aboutvalues.net/data/case_studies/values_case_study_cost_benefit_analysis_bolivia.pdf

167. Landry CE, Hindsley P, Bin O, Kruse JB, Whitehead JC, Wilson K. 2011. Weathering the storm: Measuring household willingness-to-pay for risk-reduction in post-Katrina New Orleans. Southern Economic Journal 77 (4): 991-1013. doi: 10.4284/0038-4038-77.4.991

168. Hochrainer-Stigler S, Mechler R, Pflug G, Williges K. 2014. Funding public adaptation to climate-related disasters. Estimates for a global fund. Global Environmental Change 25 87-96. doi: 10.1016/j.gloenvcha.2014.01.011

169. Vogl A, Tallis H, Douglass J, Sharp R, Wolny S, Veiga F, Benitez S, León J, Game E, Petry P, Guimerães J, Lozano JS. 2016. Resource Investment Optimization System: Introduction &

theoretical documentation. Stanford: Natural Capital Project, Stanford University. Accessed April/2018. Available from: http://data.naturalcapitalproject.org/rios_releases/RIOSGuide_Combined_v1.1.16_30May2016.pdf

170. Durham E, Baker H, Smith M, Moore E, Morgan V. 2014. The BiodivERsA stakeholder engagement hand-book. Paris: BiodivERsA. Accessed April/2018. Available from: http://www.biodiversa.org/706/download

171. Hein L, van Koppen K, de Groot RS, van Ierland EC. 2006. Spatial scales, stakeholders and the valuation of ecosystem services. Ecological Economics 57 (2): 209-228. doi: 10.1016/j.ecolecon.2005.04.005

172. Pieters J. 2002. OECD workshop on environmentally harmful subsidies: What makes a subsidy environmentally harmful: Developing a checklist based on the conditionality of subsidies. Paris: Organisation for Economic Co-operation and Development (OECD). Accessed April/2018. Available from: http://www.oecd.org/site/agrehs/35219232.pdf

173. Jones HP, Schmitz OJ. 2009. Rapid recovery of damaged ecosystems. Plos One 4 (5): 6. doi: 10.1371/journal.pone.0005653

174. Innocenti D, Albrito P. 2011. Reducing the risks posed by natural hazards and climate change: The need for a participatory dialogue between the scientific community and policy makers. Environmental Science & Policy 14 (7): 730-733. doi: 10.1016/j.envsci.2010.12.010

175. Xuesong G, Jing Z, Liangji D, Shirong Z, Xiaolin H. 2011. The ecosystem service values of a farmland ecosystem with straw recycling. 2011 Second International Conference on Mechanic Automation and Control Engineering. 2698-2702. Accessed June/2018. Available from: http://ieeexplore.ieee.org/document/5987541/. doi: 10.1109/MACE.2011.5987541

176. TSMC. 2014. TSMC 2013 corporate responsibility report. Taiwan Semiconductor Manufacturing Company. Accessed April/2018. Available from: http://www.tsmc.com/download/csr/2014_tsmc_csr/english/files/e_all.pdf

177. Hejnowicz AP, Rudd MA. 2017. The value landscape in ecosystem services: Value, value wherefore art thou value? Sustainability 9 (5): 34. doi: 10.3390/su9050850

178. Jacobs S, Dendoncker N, Martín-López B, Barton DN, Gomez-Baggethun E, Boeraeve F, McGrath FL, Vierikko K, Geneletti D, Sevecke Katharina J, Pipart N, Primmer E, Mederly P, Schmidt S, Aragão A, Baral H, Bark Rosalind H, Briceno T, Brogna D, Cabral P, De Vreese R, Liquete C, Mueller H, Peh KSH, Phelan A, Rincón Alexander R, Rogers SH, Turkelboom F, Van Reeth W, van Zanten BT, Wam HK, Washbourne C-L. 2016. A new valuation school: Integrating diverse values of nature in resource and land use decisions. Ecosystem Services 22, Part B 213-220. doi: 10.1016/j.ecoser.2016.11.007

179. Polasky S, Carpenter SR, Folke C, Keeler B. 2011. Decision-making under great uncertainty: Environmental management in an era of global change. Trends in Ecology & Evolution 26 (8): 398-404. doi: 10.1016/j.tree.2011.04.007

180. Olander L, Polasky S, Kagan JS, Johnston RJ, Wainger L, Saah D, Maguire L, Boyd J, Yoskowitz D. 2017. So you want your research to be relevant? Building the bridge between ecosystem services research and practice. Ecosystem Services 26 170-182. doi: 10.1016/j.ecoser.2017.06.003

181. Farley J. 2008. The role of prices in conserving critical natural capital. Conservation Biology 22 (6): 1399-1408. doi: 10.1111/j.1523-1739.2008.01090.x

182. McCarthy DP, Donald PF, Scharlemann JPW, Buchanan GM, Balmford A, Green JMH, Bennun LA, Burgess ND, Fishpool LDC, Garnett ST, Leonard DL, Maloney RF, Morling P, Schaefer HM, Symes A, Wiedenfeld DA, Butchart SHM. 2012. Financial costs of meeting global biodiversity conservation targets: Current spending and unmet needs. Science 338 (6109): 946-949. doi: 10.1126/science.1229803

183. Parker C, Cranford M, Oakes N, Leggett M. 2012. The little biodiversity finance book. 3. Global Canopy Programme. Oxford

184. Reed MS. 2008. Stakeholder participation for environmental management: A literature review. Biological Conservation 141 (10): 2417-2431. doi: 10.1016/j.biocon.2008.07.014

185. Posner SM, McKenzie E, Ricketts TH. 2016. Policy impacts of ecosystem services knowledge. Proceedings of the National Academy of Sciences of the United States of America 113 (7): 1760-1765. doi: 10.1073/pnas.1502452113

186. Poolman M, Munamati M, Senzanje A. 2009. Stakeholder and conflict analysis. Accessed June/2018. Available from: http://www.smallreservoirs.org/full/toolkit/docs/I%2002%20Stakeholder%20and%20Conflict%20Analysis_MLA.pdf

187. Erbout N, De Cock L, De Boever M, Lauwers L. 2010. Best practice for stakeholder involvement at national level for research prioritisation. Belgium: Institute for Agricultural and Fisheries Research. Accessed October/2017. Available from: n.a.

188. IPBES. 2013. Critical review of the assessment landscape for biodiversity and ecosystem services. IPBES/1/INF/8. Bonn: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES/1/INF/8. Accessed February/2018. Available from: https://www.ipbes.net/ipbes1inf8-1

189. OECD. 2015. Scientific advice for policy making: The role and responsibility of expert bodies and individual scientists. Paris: OECD Science, Technology and Industry policy Papers. Accessed April/2018. Available from: https://www.oecd-ilibrary.org/docserver/5js33l1jcpwb-en.pdf?expires=1524642855&id=id&accname=guest&checksum=16C957F11B8604EFBFA26255290BE6BF

190. UN General Assembly. 2012. Report on the work of the Ad Hoc Working Group of the Whole on the Regular Process for global reporting and assessment of the state of the marine environment, including socioeconomic aspects, A/67/87. Accessed June/2017. Available from: https://documents-dds-ny.un.org/doc/UNDOC/GEN/N12/342/18/PDF/N1234218.pdf?OpenElement

191. Scholes RJ, Walters M, Turak E, Saarenmaa H, Heip CHR, Tuama EO, Faith DP, Mooney HA, Ferrier S, Jongman RHG, Harrison IJ, Yahara T, Pereira HM, Larigauderie A, Geller G. 2012. Building a global observing system for biodiversity. Current Opinion in Environmental Sustainability 4 (1): 139-146. doi: 10.1016/j.cosust.2011.12.005

192. Pickard BR, Daniel J, Mehaffey M, Jackson LE, Neale A. 2015. EnviroAtlas: A new geospatial tool to foster ecosystem services science and resource management. Ecosystem Services 14 45-55. doi: 10.1016/j.ecoser.2015.04.005

193. OPPLA. 2017. OPPLA - natural capital, ecosystem services, nature-based solutions. European Comission 7th Framework Programme for Research and Technical Development. Accessed April/2018. Available from: http://www.oppla.eu/

194. Eliasch J. 2008. Climate change: Financing global forests: The Eliasch Review. Earthscan. ISBN: 9781844077724

195. Bishop RC. 1978. Endangered species and uncertainty - economics of a safe minimum standard. American Journal of Agricultural Economics 60 (1): 10-18. doi: 10.2307/1240156

196. Margolis M, Naevdal E. 2008. Safe minimum standards in dynamic resource problems: Conditions for living on the edge of risk. Environmental & Resource Economics 40 (3): 401-423. doi: 10.1007/s10640-007-9162-z

197. Chapeyama O. 2012. Strengthening the protected area network (SPAN), PIMS3121, Final Evaluation, Final Report. Global Environmental Facility, United Nations Development Programme. Accessed April/2018. Available from: https://www.thegef.org/sites/default/files/project_documents/2492_3121_Namibia_BD_TE.pdf

198. Berners-Lee T, Hendler J, Lassila O. 2001. The Semantic Web - a new form of web content that is meaningful to computers will unleash a revolution of new possibilities. Scientific American 284 (5): 34-43. doi: 10.1038/scientificamerican0501-34

199. Gruber TR, Olsen GR. 1994. An ontology for engineering mathematics. Sandewall E, Torasso P editors. Principles of Knowledge Representation and Reasoning: Morgan Kaufmann, 258-269. ISBN: 10469567. doi: 10.1016/B978-1-4832-1452-8.50120-2

200. Madin JS, Bowers S, Schildhauer MP, Jones MB. 2008. Advancing ecological research with ontologies. Trends in Ecology & Evolution 23 (3): 159-168. doi: 10.1016/j.tree.2007.11.007

201. UNEP. 2010. Strategic Plan for Biodiversity 2011-2020 – provisional technical rationale, possible indicators and suggested milestones for the Aichi Biodiversity Targets UNEP/CBD/COP/10/27/Add.1. Nagoya, Japan. Accessed June/2018. Available from: https://www.cbd.int/doc/meetings/cop/cop-10/official/cop-10-27-add1-en.pdf

202. Geijzendorffer IR, Cohen-Shacham E, Cord AF, Cramer W, Guerra C, Martin-Lopez B. 2017. Ecosystem services in global sustainability policies. Environmental Science & Policy 74 40-48. doi: 10.1016/j.envsci.2017.04.017

203. Madin J, Bowers S, Schildhauer M, Krivov S, Pennington D, Villa F. 2007. An ontology for describing and synthesizing ecological observation data. Ecological Informatics 2 (3): 279-296. doi: 10.1016/j.ecoinf.2007.05.004

204. Ontolog. 2018. ONTOLOG collaborative work environment - historic archives. Accessed April/2018. Available from: http://ontolog.cim3.net/

205. OGC Working Group. 2018. Domain working groups. Accessed April/2018. Available from: http://www.opengeospatial.org/projects/groups/wg

206. SONet. 2018. Ontologies, markup languages, controlled vocabularies, and thesauri. Scientific Observation Network (SONet). Accessed April/2018. Available from: https://sonet.ecoinformatics.org/Resources/ontology

207. ESIP. 2018. Earth Science Ontology Portal (ESIP Portal). Federation of Earth Science Information Partners (ESIP). Accessed January/2018. Available from: http://semanticportal.esipfed.org/

208. Rueda C, Bermudez L, Fredericks J. 2009. The MMI Ontology Registry and Repository: A portal for marine metadata interoperability. OCEANS 2009. 1-6. Accessed April/2018. Available from. doi: 10.23919/OCEANS.2009.5422206

209. European Commission. 2018. INSPIRE Knowledge Base - infrastructure for spatial information in Europe. Accessed January/2018. Available from: https://inspire.ec.europa.eu/data-specifications/2892

210. Haddaway NR, Kohl C, Rebelo da Silva N, Schiemann J, Spök A, Stewart R, Sweet JB, Wilhelm R. 2017. A framework for stakeholder engagement during systematic reviews and maps in environmental management. Environmental Evidence 6 (1): 11. doi: 10.1186/s13750-017-0089-8

211. Barton T, Borrini G, de Sherbinin A, Warren P. 1997. Our people, our resources: Supporting rural communities in participatory action research on population dynamics and the local environment. Issues in Social Policy. IUCN - the World Conservation Union. Gland. ISBN: 2831703891

212. UNEP. 1999. Cultural and spiritual values of biodiversity. London: Intermediate Technology Publications. Accessed April/2018. Available from: http://staging.unep.org/pdf/Cultural_Spiritual_thebible.pdf

213. Christie M, Fazey I, Cooper R, Hyde T, Kenter JO. 2012. An evaluation of monetary and non-monetary techniques for assessing the importance of biodiversity and ecosystem services to people in countries with developing economies. Ecological Economics 83 67-78. doi: 10.1016/j.ecolecon.2012.08.012

214. OECD. 2001. Best practices in local development. Local Economic and Employment Development (LEED). OECD Publishing. Paris. ISBN: 9789264193369. doi: 10.1787/9789264193369-en

215. Schmidt S, Manceur AM, Seppelt R. 2016. Uncertainty of monetary valued ecosystem services - value transfer functions for global mapping. Plos One 11 (3): 22. doi: 10.1371/journal.pone.0148524

216. Kahn JR. 2005. Economic approach to environmental and natural resources 3rd. South-Western Publishers. Nashville, TN. ISBN: 0030314542

217. Pascual U, Muradian R, Brander L, Gómez-Baggethun E, Martín-López B, Verma M. 2010. The economics of valuing ecosystem services and biodiversity. Kumar P editor. The Economics of Ecosystems and Biodiversity Ecological and Economic Foundations. London and Washington: Earthscan. ISBN: 9781849775489

218. Downing M, Ozuna T. 1996. Testing the reliability of the benefit function transfer approach. Journal of Environmental Economics and Management 30 (3): 316-322. doi: 10.1006/jeem.1996.0021

219. Smith KV, Pattanayak SK. 2002. Is meta-analysis a Noah's Ark for non-market valuation? Environmental and Resource Economics 22 271–296. doi: 10.1023/A:1015567316109

220. Brander LM, Brauer I, Gerdes H, Ghermandi A, Kuik O, Markandya A, Navrud S, Nunes P, Schaafsma M, Vos H, Wagtendonk A. 2012. Using meta-analysis and GIS for value transfer and scaling up: Valuing climate change induced losses of European wetlands. Environmental & Resource Economics 52 (3): 395-413. doi: 10.1007/s10640-011-9535-1

221. Oteros-Rozas E, Martin-Lopez B, Gonzalez JA, Plieninger T, Lopez CA, Montes C. 2014. Socio-cultural valuation of ecosystem services in a transhumance social-ecological network. Regional Environmental Change 14 (4): 1269-1289. doi: 10.1007/s10113-013-0571-y

222. Stern N. 2008. The economics of climate change. American Economic Review: Papers & Proceedings 98 (2): 1-37. doi: 10.1017/CBO9780511817434

223. Hoegh-Guldberg O, Beal D, Chaudhry T, Elhaj H, Abdullat A, Etessy P, Smits M. 2015. Reviving the ocean economy: The case for action - 2015. Gland: WWF. Accessed April/2018. Available from: http://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/WWF-Report-Reviving-the-Ocean-Economy.pdf

224. SEEA. 2015. System of Environmental-Economic Accounting - website. Accessed November/2017. Available from: http://unstats.un.org/unsd/envaccounting/seea.asp

225. TEEB. 2015. The Economics of Biodiversity and Ecosystem Services - website. Accessed November/2018. Available from: http://www.teebweb.org/

226. WAVES. 2015. Wealth Accounting and the Valuation of Ecosystem Services - website. Accessed November/2018. Available from: http://www.wavespartnership.org/en

227. Miller DL. 2013. Federal Emergency Management Agency of the USA Mitigation Policy -FP-108-024-01, Consideration of Environmental Benefits in the Evaluation of Acquisition Projects under the Hazard Mitigation Assistance (HMA) Programs. Accessed August/2017. Available from: https://www.fema.gov/media-library-data/1406725991126-8fb4f01c1cbbc962638259f9f5716d20/FY13_Guidance_508.pdf

228. Hanson C, Ranganathan J, Iceland C, Finisdore J. 2012. The corporate ecosystem services review: Guidelines for identifying business risks & opportunities arising from ecosystem change. 2. World Resources Institute. Washington, DC. ISBN: 9781569737859

229. Elliot S, Duncan S, Malone N. 2014. New nature of business: How business pioneers support biodiversity and ecosystem services. Accessed April/2018. Available from: https://static.squarespace.com/static/534a63bde4b0dd67a16348ac/t/535f0c6ae4b09cd4e2b067e4/1398738026432/New_Nature_of_Business_Report.pdf

230. Iovanna R, Griffiths C. 2006. Clean water, ecological benefits, and benefits transfer: A work in progress at the U.S. EPA. Ecological Economics 60 (2): 473-482. doi: 10.1016/j.ecolecon.2006.06.012

231. Costanza R, dArge R, deGroot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, Oneill RV, Paruelo J, Raskin RG, Sutton P, vandenBelt M. 1997. The value of the world's ecosystem services and natural capital. Nature 387 (6630): 253-260. doi: 10.1038/387253a0

232. Costanza R, de Groot R, Sutton P, van der Ploeg S, Anderson SJ, Kubiszewski I, Farber S, Turner RK. 2014. Changes in the global value of ecosystem services. Global Environmental Change 26 (0): 152-158. doi: 10.1016/j.gloenvcha.2014.04.002

233. Brookshire DS, Eubanks LS, Randall A. 1983. Estimating option prices and existence values for wildlife resources. Land Economics 59 (1): 1-15. doi: 10.2307/3145871
234. Barbier EB. 2007. Valuing ecosystem services as productive inputs. Economic Policy (49): 178-229. doi: 10.1111/j.1468-0327.2007.00174.x
235. Kontoleōn A, Macrory R, Swanson TM. 2002. Individual preference-based values and environmental decision making: Should valuation have its day in court? Research in law and economics 20 177-214. doi: 10.1016/S0193-5895(02)20009-3
236. Akter S, Bennett J, Akhter S. 2008. Preference uncertainty in contingent valuation. Ecological Economics 67 (3): 345-351. doi: 10.1016/j.ecolecon.2008.07.009
237. De'ath G. 2007. Boosted trees for ecological modeling and prediction. Ecology 88 (1): 243-251. doi: 10.1890/0012-9658(2007)88[243:btfema]2.0.co;2
238. Breiman L, Friedman J, Stone CJ, Olshen RA. 1984. Classification and regression trees. Taylor & Francis. ISBN: 9780412048418
239. Friedman JH. 2001. Greedy function approximation: A gradient boosting machine. Annals of Statistics 29 (5): 1189-1232. doi: 10.1214/aos/1013203451
240. Ridgeway G. 2015. Generalized boosted regression models. Package "gbm": R Development Core Team
241. R Development Core Team. 2006. R: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing. Accessed April/2018. Available from: https://www.r-project.org/
242. Mendelsohn R, Dinar A, Williams L. 2006. The distributional impact of climate change on rich and poor countries. Environment and Development Economics 11 159-178. doi: 10.1017/s1355770x05002755
243. Jackson JBC, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, Bourque BJ, Bradbury RH, Cooke R, Erlandson J, Estes JA, Hughes TP, Kidwell S, Lange CB, Lenihan HS, Pandolfi JM, Peterson CH, Steneck RS, Tegner MJ, Warner RR. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293 (5530): 629-638. doi: 10.1126/science.1059199
244. Lotze HK, Lenihan HS, Bourque BJ, Bradbury RH, Cooke RG, Kay MC, Kidwell SM, Kirby MX, Peterson CH, Jackson JBC. 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 312 (5781): 1806-1809. doi: 10.1126/science.1128035
245. FAO. 2014. The state of world fisheries and aquaculture - opportunities and challenges. Rome: FAO, 978-92-5-108275-1. Accessed June/2018. Available from: http://www.fao.org/3/a-i3720e.pdf
246. OECD. 2013. How's life? 2013: Measuring well-being. OECD Publishing. Paris. ISBN: 9789264111615. doi: 10.1787/9789264201392-en
247. Srivastava J. 2007. Vegetarianism and meat-eating in 8 religions. Himalayan Academy. Accessed June/2018. Available from: http://www.hinduismtoday.com/modules/smartsection/item.php?itemid=1541
248. Hsu A, Emerson J, Levy M, de Sherbinin A, Johnson J, Malik O, Schwartz J, Jaiteh M. 2014. The 2014 Environmental Performance Index. New Haven: Yale Center for Environmental Law and Policy. Accessed April/2018. Available from:

http://sedac.ciesin.columbia.edu/downloads/data/epi/epi-environmental-performance-index-2014/2014-epi-full-report-final.pdf

249. Alavian V, Qaddumi HM, Dickson E, Diez SM, Danilenko AV, Hirji RF, Puz G, Pizarro C, Jacobsen M, Blankespoor B. 2009. Water and climate change: Understanding the risks and maling climate-smart investment decisions. Washington, DC: World Bank, 52911. Accessed April/2018. Available from: http://documents.worldbank.org/curated/en/2009/11/11717870/water-climate-change-understanding-risks-making-climate-smart-investment-decisions

250. Egoh B, Reyers B, Rouget M, Bode M, Richardson DM. 2009. Spatial congruence between biodiversity and ecosystem services in South Africa. Biological Conservation 142 (3): 553-562. doi: 10.1016/j.biocon.2008.11.009

251. Locatelli B, Imbach P, Wunder S. 2014. Synergies and trade-offs between ecosystem services in Costa Rica. Environmental Conservation 41 (1): 27-36. doi: 10.1017/s0376892913000234

252. Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Liermann CR, Davies PM. 2010. Global threats to human water security and river biodiversity. Nature 467 (7315): 555-561. doi: 10.1038/nature09440

253. Cincotta RP, Wisnewski J, Engelman R. 2000. Human population in the biodiversity hotspots. Nature 404 (6781): 990-992. doi: 10.1038/35010105

254. Balmford A, Moore JL, Brooks T, Burgess N, Hansen LA, Williams P, Rahbek C. 2001. Conservation conflicts across Africa. Science 291 (5513): 2616-2619. doi: 10.1126/science.291.5513.2616

255. Hardin G. 1968. The tragedy of the commons. Science 162 (3859): 1243-1248. doi: 10.1126/science.162.3859.1243

256. Malhi Y, Baldocchi DD, Jarvis PG. 1999. The carbon balance of tropical, temperate and boreal forests. Plant Cell and Environment 22 (6): 715-740. doi: 10.1046/j.1365-3040.1999.00453.x

257. Battin TJ, Luyssaert S, Kaplan LA, Aufdenkampe AK, Richter A, Tranvik LJ. 2009. The boundless carbon cycle. Nature Geoscience 2 (9): 598-600. doi: 10.1038/ngeo618

258. Pauly D. 1995. Anecdotes and the shifting baseline syndrome of fisheries. Trends in Ecology and Evolution 10 (10): 430. doi: 10.1016/S0169-5347(00)89171-5

259. Hoerling M, Kumar A. 2003. The perfect ocean for drought. Science 299 (5607): 691-694. doi: 10.1126/science.1079053

260. Emanuel K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. Nature 436 (7051): 686-688. doi: 10.1038/nature03906

261. Running SW. 2006. Is global warming causing more, larger wildfires? Science 313 (5789): 927-928. doi: 10.1126/science.1130370

262. Armsworth PR, Roughgarden JE. 2003. The economic value of ecological stability. Proceedings of the National Academy of Sciences of the United States of America 100 (12): 7147-7151. doi: 10.1073/pnas.0832226100

263. Baillie JEM, Bennun LA, Brooks TM, Butchart SHM, Chanson JS, Cokeliss Z, Hilton-Taylor C, Hoffmann M, Mace GM, Mainka SA, Pollock CM, Rodrigues ASL, Stattersfield AJ, Stuart SN. 2004. A global species assessment. 2. IUCN Red List of Threatened Species. IUCN. Gland, Cambridge. ISBN: 2-8317-0826-5

264. IFRC. 2006. World Disasters Report 2006 – Focus on neglected crises. Geneva: International Federation of Red Cross and Red Crescent Societies, 92-9139-122-0. Accessed June/2018. Available from: http://www.ifrc.org/en/publications-and-reports/world-disasters-report/wdr2006/

265. Lawton JH, Brown VK. 1993. Redundancy in ecosystems. Schulze ED, Mooney HA editors. Biodiversity and ecosystem function. Praktische Zahnmedizin Odonto-Stomatologie Pratique Practical Dental Medicine (Geology). Berlin, Heidelberg: Springer Verlag, 255-270. doi: 10.1007/978-3-642-58001-7_12

266. Gössling S, Scott D, Hall CM, Ceron J-P, Dubois G. 2012. Consumer behaviour and demand response of tourists to climate change. Annals of Tourism Research 39 (1): 36-58. doi: 10.1016/j.annals.2011.11.002

267. WTO. 2013. Yearbook of tourism statistics, data 2007 – 2011. United Nations World Tourism Organization. Madrid. ISBN: 9789284414888

268. Wilkinson CR. 1996. Global change and coral reefs: impacts on reefs, economies and human cultures. Global Change Biology 2 (6): 547-558. doi: 10.1111/j.1365-2486.1996.tb00066.x

269. Johnson WC, Millett BV, Gilmanov T, Voldseth RA, Guntenspergen GR, Naugle DE. 2005. Vulnerability of northern prairie wetlands to climate change. BioScience 55 (10): 863-872. doi: 10.1641/0006-3568(2005)055[0863:vonpwt]2.0.co;2

270. Fan S, Chan-Kang C. 2004. Returns to investment in less-favored areas in developing countries: Aa synthesis of evidence and implications for Africa. Food Policy 29 (4): 431-444. doi: 10.1016/j.foodpol.2004.07.003

271. Ruben R, Pender J, Kuyvenhoven A. 2007. Sustainable poverty reduction in less-favoured areas: Problems, options and strategies. Ruben R, Pender J, Kuyvenhoven A editors. Sustainable poverty reduction in less-favoured areas. Sustainable poverty reduction in less-favoured areas: problems, options and strategies: CABI, 464. ISBN: 9781845932770. doi: 10.1079/9781845932770.0001

272. Snaddon JL, Turner EC, Foster WA. 2008. Children's perceptions of rainforest biodiversity: Which animals have the lion's share of environmental awareness? Plos One 3 (7): e2579. doi: 10.1371/journal.pone.0002579

273. Eigenbrod F, Anderson BJ, Armsworth PR, Heinemeyer A, Jackson SF, Parnell M, Thomas CD, Gaston KJ. 2009. Ecosystem service benefits of contrasting conservation strategies in a human-dominated region. Proceedings of the Royal Society B-Biological Sciences 276 (1669): 2903-2911. doi: 10.1098/rspb.2009.0528

274. Maes J, Paracchini ML, Zulian G, Dunbar MB, Alkemade R. 2012. Synergies and trade-offs between ecosystem service supply, biodiversity, and habitat conservation status in Europe. Biological Conservation 155 (0): 1-12. doi: 10.1016/j.biocon.2012.06.016

275. Lancaster KJ. 1966. A new approach to consumer theory. Journal of Political Economy 74 132. doi: 10.1086/259131

276. Jackson LE, Pascual U, Hodgkin T. 2007. Utilizing and conserving agrobiodiversity in agricultural landscapes. Agriculture Ecosystems & Environment 121 (3): 196-210. doi: 10.1016/j.agee.2006.12.017

277. Kirchner JW, Hooper RP, Kendall C, Neal C, Leavesley G. 1996. Testing and validating environmental models. Science of the Total Environment 183 (1-2): 33-47. doi: 10.1016/0048-9697(95)04971-1
278. Bennett ND, Croke BFW, Guariso G, Guillaume JHA, Hamilton SH, Jakeman AJ, Marsili-Libelli S, Newham LTH, Norton JP, Perrin C, Pierce SA, Robson B, Seppelt R, Voinov AA, Fath BD, Andreassian V. 2013. Characterising performance of environmental models. Environmental Modelling & Software 40 1-20. doi: 10.1016/j.envsoft.2012.09.011
279. Spiegelhalter DJ, Riesch H. 2011. Don't know, can't know: Embracing deeper uncertainties when analysing risks. Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences 369 (1956): 4730-4750. doi: 10.1098/rsta.2011.0163
280. Keynes JM. 1937. The general theory of employment. The Quarterly Journal of Economics 51 (2): 209-223. doi: 10.2307/1882087
281. Eigenbrod F, Armsworth PR, Anderson BJ, Heinemeyer A, Gillings S, Roy DB, Thomas CD, Gaston KJ. 2010. Error propagation associated with benefits transfer-based mapping of ecosystem services. Biological Conservation 143 (11): 2487-2493. doi: 10.1016/j.biocon.2010.06.015
282. Konarska KM, Sutton PC, Castellon M. 2002. Evaluating scale dependence of ecosystem service valuation: A comparison of NOAA-AVHRR and Landsat TM datasets. Ecological Economics 41 (3): 491-507. doi: 10.1016/s0921-8009(02)00096-4
283. Bateman IJ, Day BH, Georgiou S, Lake I. 2006. The aggregation of environmental benefit values: Welfare measures, distance decay and total WTP. Ecological Economics 60 (2): 450-460. doi: 10.1016/j.ecolecon.2006.04.003
284. Saenz-Arroyo A, Roberts CM, Torre J, Carino-Olvera M, Enriquez-Andrade RR. 2005. Rapidly shifting environmental baselines among fishers of the Gulf of California. Proceedings of the Royal Society B-Biological Sciences 272 (1575): 1957-1962. doi: 10.1098/rspb.2005.3175
285. Jennings C. 2006. Quality and value: The true purpose of peer review. Nature 05032. doi: 10.1038/nature05032
286. Moeltner K, Johnston RJ, Rosenberger RS, Duke JM. 2009. Benefit transfer from multiple contingent experiments: A flexible two-step model combining individual choice data with community characteristics. American Journal of Agricultural Economics 91 (5): 1335-1342. doi: 10.1111/j.1467-8276.2009.01344.x
287. Heal GM. 2000. Nature and the marketplace: Capturing the value of ecosystem services. 1. Island Press. Washington DC. ISBN: 155963796X
288. Rosenberger RS, Johnston RJ. 2009. Selection effects in meta-analysis and benefit transfer: Avoiding unintended consequences. Land Economics 85 (3): 410-428. doi: 10.3368/le.85.3.410
289. Gibson CC, Ostrom E, Ahn TK. 2000. The concept of scale and the human dimensions of global change: a survey. Ecological Economics 32 (2): 217-239. doi: 10.1016/S0921-8009(99)00092-0
290. IPBES. 2014. Intergovernmental Platform on Biodiversity and Ecosystem Services - Deliverable 2(c): Global assessment on biodiversity and ecosystem services. Accessed

May/2014. Available from: http://www.ipbes.net/index.php/39-work-programme/488-deliverable-2c

291. Earth Economics. 2015. Ecosystem Valuation Toolkit (EVT). Accessed April/2018. Available from: http://www.eartheconomics.org/ecosystem-valuation-toolkit

292. Phillipson J, Lowe P, Proctor A, Ruto E. 2012. Stakeholder engagement and knowledge exchange in environmental research. Journal of Environmental Management 95 (1): 56-65. doi: 10.1016/j.jenvman.2011.10.005

293. Ferraro PJ, Pattanayak SK. 2006. Money for nothing? A call for empirical evaluation of biodiversity conservation investments. PLOS Biology 4 (4): e105. doi: 10.1371/journal.pbio.0040105

294. Smith RK, Dicks LV, Mitchell R, Sutherland WJ. 2014. Comparative effectiveness research: The missing link in conservation. Conservation Evidence 11 2-6

295. ADB. 2011. A review of recent developments in impact evaluation. Philippines: Asian Development Bank, 9789290922926. Accessed April/2018. Available from: https://www.adb.org/sites/default/files/publication/28622/developments-impact-evaluation.pdf

296. Miteva DA, Pattanayak SK, Ferraro PJ. 2012. Evaluation of biodiversity policy instruments: What works and what doesn’t? Oxford Review of Economic Policy 28 (1): 69-92. doi: 10.1093/oxrep/grs009

297. Scriven M. 1991. Evaluation thesaurus. 4. SAGE Publications. USA. ISBN: 9780803943643. doi: 10.1016/0020-7489(92)90035-F

298. Mandl U, Dierx A, Ilzkovitz F, European Commission. 2008. The effectiveness and efficiency of public spending. European Economy. Economic Papers 301. Brussels. Accessed April/2018. Available from: http://ec.europa.eu/economy_finance/publications/pages/publication11902_en.pdf

299. Fredrickson LM, Anderson DH. 1999. A qualitative exploration of the wilderness experience as a source of spiritual inspiration. Journal of Environmental Psychology 19 (1): 21-39. doi: 10.1006/jevp.1998.0110

300. Richardson EA, Mitchell R. 2010. Gender differences in relationships between urban green space and health in the United Kingdom. Social Science & Medicine 71 (3): 568-575. doi: 10.1016/j.socscimed.2010.04.015

301. In't Veld RJ, De Wit A. 2000. Clarifications. In't Veld RJ editor. Willingly and knowingly: The roles of knowledge about nature and the environment in policy processes. Lemma, Utrecht: RMNO, 147-157. ISBN: 9789072377869

302. ISO. 1994. Accuracy (trueness and precision) of measurement methods and results — Part 1: General principles and definitions. ISO 5725-1:1994. Accessed February/2018. Available from: https://www.iso.org/obp/ui/#iso:std:iso:5725:-1:ed-1:v1:en

303. Wynne B. 1992. Uncertainty and environmental learning: Reconceiving science and policy in the preventive paradigm. Global Environmental Change 2 (2): 111-127. doi: 10.1016/0959-3780(92)90017-2

304. Mupepele A-C, Dormann CF. 2014. Assessing the evidence of ecosystem services studies: A framework and its application. bioRxiv. doi: 10.1101/010140

305. Wang RY, Strong DM. 1996. Beyond accuracy: What data quality means to data consumers. J. Manage. Inf. Syst. 12 (4): 5-33. doi: 10.1080/07421222.1996.11518099

306. Weiskopf NG, Hripcsak G, Swaminathan S, Weng C. 2013. Defining and measuring completeness of electronic health records for secondary use. Journal of Biomedical Informatics 46 (5): 830-836. doi: 10.1016/j.jbi.2013.06.010

307. Bagstad KJ, Semmens DJ, Waage S, Winthrop R. 2013. A comparative assessment of decision-support tools for ecosystem services quantification and valuation. Ecosystem Services 5 (0): 27-39. doi: 10.1016/j.ecoser.2013.07.004

308. Whitlock EP, Lopez SA, Chang S, Helfand M, Eder M, Floyd N. 2010. AHRQ Series Paper 3: Identifying, selecting, and refining topics for comparative effectiveness systematic reviews: AHRQ and the Effective Health-Care program. Journal of Clinical Epidemiology 63 (5): 491-501. doi: 10.1016/j.jclinepi.2009.03.008

309. Sherrouse BC, Clement JM, Semmens DJ. 2011. A GIS application for assessing, mapping, and quantifying the social values of ecosystem services. Applied Geography 31 (2): 748-760. doi: 10.1016/j.apgeog.2010.08.002

310. Peh KSH, Balmford A, Bradbury RB, Brown C, Butchart SHM, Hughes FMR, Stattersfield A, Thomas DHL, Walpole M, Bayliss J, Gowing D, Jones JPG, Lewis SL, Mulligan M, Pandeya B, Stratford C, Thompson JR, Turner K, Vira B, Willcock S, Birch JC. 2013. TESSA: A toolkit for rapid assessment of ecosystem services at sites of biodiversity conservation importance. Ecosystem Services 5 E51-E57. doi: 10.1016/j.ecoser.2013.06.003

311. Ouyang Z, Zheng H, Xiao Y, Polasky S, Liu J, Xu W, Wang Q, Zhang L, Xiao Y, Rao E, Jiang L, Lu F, Wang X, Yang G, Gong S, Wu B, Zeng Y, Yang W, Daily GC. 2016. Improvements in ecosystem services from investments in natural capital. Science 352 (6292): 1455-1459. doi: 10.1126/science.aaf2295

312. Dogan M, Rokkan S. 1969. Quantitative ecological analysis in the social sciences. M.I.T. Press. doi: 10.2307/213356

313. OECD. 2007. DAC evaluation quality standards. Organisation for Economic Co-operation and Development (OECD) Development Assistance Committee (DAC). Accessed February/2018. Available from: http://www.oecd.org/development/evaluation/dcdndep/38686953.pdf

314. ADA. 2009. Guidelines for project and programme evaluations Vienna, Austria: Austrian Development Agency, Evaluation Unit. Accessed February/2018. Available from: https://www.oecd.org/development/evaluation/dcdndep/47069197.pdf

315. DeGEval. 2016. Standards für evaluation. Mainz, Germany: DeGEval – Gesellschaft für Evaluation. Accessed April/2018. Available from: https://www.degeval.org/fileadmin/Publikationen/DeGEval-Standards_fuer_Evaluation.pdf

316. Castellini G, Gianola S, Frigerio P, Agostini M, Bolotta R, Corbetta D, Gasparini M, Gozzer P, Guariento E, Li LD, Pecoraro V, Sirtori V, Turolla A, Moja L. 2015. Completeness of outcome description in studies for low back pain rehabilitation interventions: A survey of trials included in Cochrane reviews. Trials 16 3. doi: 10.1186/1745-6215-16-S1-P24

317. Vatn A, Bromley DW. 1994. Choices without prices without apologies. Journal of Environmental Economics and Management 26 (2): 129-148. doi: 10.1006/jeem.1994.1008

318. Cheetham J, Mullen EJ, Soydan H, Tengvald K. 1998. Evaluation as a tool in the development of social work discourse: National diversity or shared preoccupations? Reflections from a conference. Evaluation 4 (1): 9-24. doi: 10.1177/13563899822208356

319. Higgins JPT, Green S. 2008. Cochrane handbook for systematic reviews of interventions. 5. The Cochrane Collaboration and John Wiley & Sons Ltd. Chichester, UK. ISBN: 978-0-470-69951-5. doi: 10.1002/9780470712184

320. Stewart R, Liabo K. 2012. Involvement in research without compromising research quality. Journal of Health Services Research & Policy 17 (4): 248-251. doi: 10.1258/jhsrp.2012.011086

321. Pullin AS, Knight TM, Watkinson AR. 2009. Linking reductionist science and holistic policy using systematic reviews: Unpacking environmental policy questions to construct an evidence-based framework. Journal of Applied Ecology 46 (5): 970-975. doi: 10.1111/j.1365-2664.2009.01704.x

322. Booth A. 2006. Clear and present questions: Formulating questions for evidence based practice. Library Hi Tech 24 (3): 355-368. doi: 10.1108/07378830610692127

323. Wong G, Greenhalgh T, Westhorp G, Buckingham J, Pawson R. 2013. RAMESES publication standards: Realist syntheses. Bmc Medicine 11 14. doi: 10.1186/1741-7015-11-21

324. Song F, Parekh S, Hooper L, Loke YK, Ryder J, Sutton AJ, Hing C, Kwok CS, Pang C, Harvey I. 2010. Dissemination and publication of research findings: An updated review of related biases. Health Technology Assessment 14 (8): 1-236. doi: 10.3310/hta14080

325. Bayliss HR, Beyer FR. 2015. Information retrieval for ecological syntheses. Research Synthesis Methods 6 (2): 136-148. doi: 10.1002/jrsm.1120

326. Leimu R, Koricheva J. 2004. Cumulative meta-analysis: A new tool for detection of temporal trends and publication bias in ecology. Proceedings of the Royal Society B-Biological Sciences 271 (1551): 1961-1966. doi: 10.1098/rspb.2004.2828

327. Englund G, Sarnelle O, Cooper SD. 1999. The importance of data-selection criteria: Meta-analyses of stream predation experiments. Ecology 80 (4): 1132-1141. doi: 10.2307/177060

328. Sargeant JM, O'Connor AM. 2014. Conducting systematic reviews of intervention questions II: Relevance screening, data extraction, assessing risk of bias, presenting the results and interpreting the findings. Zoonoses and Public Health 61 39-51. doi: 10.1111/zph.12124

329. Frampton GK, Livoreil B, Petrokofsky G. 2017. Eligibility screening in evidence synthesis of environmental management topics. Environmental Evidence 6 (1): 27. doi: 10.1186/s13750-017-0102-2

330. Elith J, Leathwick JR, Hastie T. 2008. A working guide to boosted regression trees. Journal of Animal Ecology 77 (4): 802-813. doi: 10.1111/j.1365-2656.2008.01390.x

331. Snilstveit B, Oliver S, Vojtkova M. 2012. Narrative approaches to systematic review and synthesis of evidence for international development policy and practice. Journal of Development Effectiveness 4 (3): 409-429. doi: 10.1080/19439342.2012.710641

332. Borenstein M, Hedges L, Higgins JPT, Rothstein H. 2009. An introduction to meta-analysis. 19. John Wiley & Sons, Ltd. Cornwall, UK. ISBN: 9780470743386 doi: 10.1002/9780470743386

333. Guyatt GH, Oxman AD, Vist GE, Kunz R, Falck-Ytter Y, Alonso-Coello P, Schunemann HJ, Grp GW. 2008. GRADE: An emerging consensus on rating quality of evidence and strength of recommendations. British Medical Journal 336 (7650): 924-926. doi: 10.1136/bmj.39489.470347.AD
334. Card D, Krueger AB. 1995. Time-series minimum-wage studies: A meta-analysis. The American Economic Review 85 (2): 238-243
335. van Kooten GC, Eagle AJ, Manley J, Smolak T. 2004. How costly are carbon offsets? A meta-analysis of carbon forest sinks. Environmental Science & Policy 7 (4): 239-251. doi: 10.1016/j.envsci.2004.05.006
336. Collaboration for Environmental Evidence. 2018. Guidelines and standards for evidence synthesis in environmental management: Version 5.0. Project Report. Accessed Mai/2018. Available from: http://www.environmentalevidence.org/information-for-authors
337. Cottingham P, Maynard R, Stagner M. 2004. Synthesising evidence on the impacts of programmes and policies in education, crime and justice, and social welfare: Practical recommendations based on 14 test-bed reviews. Evaluation & Research in Education 18 (1-2): 28-53. doi: 10.1080/09500790408668307
338. Livoreil B, Glanville J, Haddaway NR, Bayliss H, Bethel A, de Lachapelle FF, Robalino S, Savilaakso S, Zhou W, Petrokofsky G, Frampton G. 2017. Systematic searching for environmental evidence using multiple tools and sources. Environmental Evidence 6 (1): 23. doi: 10.1186/s13750-017-0099-6
339. Sterling TD. 1959. Publication decisions and their possible effects on inferences drawn from tests of significance - or vice versa. Journal of the American Statistical Association 54 (285): 30-34. doi: 10.2307/2282137
340. Rosenthal R. 1979. The file drawer problem and tolerance for null results. Psychological Bulletin 86 (3): 638-641. doi: 10.1037/0033-2909.86.3.638
341. Stanley TD. 2008. Meta-regression methods for detecting and estimating empirical effects in the presence of publication selection. Oxford Bulletin of Economics and Statistics 70 (1): 103-127. doi: 10.1111/j.1468-0084.2007.00487.x
342. Equator Initiative. 2017. Nature-based solutions database. Accessed February/2017. Available from: http://www.revamping.equatorinitiative.org/knowledge-center/nature-based-solutions-database/
343. Dixon-Woods M, Agarwal S, Jones D, Young B, Sutton A. 2005. Synthesising qualitative and quantitative evidence: A review of possible methods. Journal of Health Services Research & Policy 10 (1): 45-53. doi: 10.1177/135581960501000110
344. Glass GV. 1976. Primary, secondary, and meta-analysis of research. Educational Researcher 5 (10): 3-8. doi: 10.2307/1174772
345. Avellar SA, Thomas J, Kleinman R, Sama-Miller E, Woodruff SE, Coughlin R, Westbrook TR. 2017. External validity: The next step for systematic reviews? Evaluation Review 41 (4): 283-325. doi: 10.1177/0193841x16665199
346. Bero L, Anglemyer A, Vesterinen H, Krauth D. 2016. The relationship between study sponsorship, risks of bias, and research outcomes in atrazine exposure studies conducted in

non-human animals: Systematic review and meta-analysis. Environment international 92-93 597-604. doi: 10.1016/j.envint.2015.10.011

347. McGuinness DL, van Harmelen F. 2004. OWL Web Ontology Language overview. W3C recommendation. Accessed Mai/2018. Available from: https://www.w3.org/TR/owl-features/

348. Ludäscher B, Altintas I, Berkley C, Higgins D, Jaeger E, Jones M, Lee EA, Tao J, Zhao Y. 2006. Scientific workflow management and the Kepler system. Concurrency and Computation: Practice and Experience 18 (10): 1039-1065. doi: 10.1002/cpe.994

349. Berkley C, Bowers S, Jones MB, Ludäscher B, Schildhauer M, Tao J. 2005. Incorporating semantics in scientific workflow authoring. In Proceedings of the 17th International Conference on Scientific and Statistical Database Management (SSDBM'05}. Accessed Mai/2017. Available from: https://pdfs.semanticscholar.org/8c72/003cb9579be7cd8e05c68b5c4e8fb1ef916c.pdf.

350. Uren V, Ciravegna F, Motta E, Cadas C. 2010. Lessons learned developing an ontology about aeroengines. Technical Report CS-11-02. Accessed Mai/2018. Available from: http://www.dcs.shef.ac.uk/intranet/research/public/resmes/CS1102.pdf

351. Eiswerth ME, Shaw WD. 1997. Adjusting benefits transfer values for inflation. Water Resources Research 33 (10): 2381-2385. doi: 10.1029/97WR01983

352. Friedman JH, Meulman JJ. 2003. Multiple additive regression trees with application in epidemiology. Statistics in Medicine 22 (9): 1365-1381. doi: 10.1002/sim.1501

353. Hastie T, Tibshirani R, Friedman JH. 2001. The elements of statistical learning: Data mining, inference, and prediction. Springer. ISBN: 9780387952840

354. Ridgeway G. 2009. Generalized boosted models: A guide to the gbm package. R Development Core Team. Accessed May/2015. Available from: http://bioconductor.wustl.edu/extra/vignettes/gbm/inst/doc/gbm.pdf

Supplementary material

Supplementary Material Chapter 2

S2.1 Table (see CD). References of review on information demand. The reference list shows literature that defined information demand or proposed guidance on how to implement ES into decision-making. Based on the contents of references indicators of information demand were identified and assigned to six policy instruments.

S2.2 Table. Design and impact of databases – indicator description. In the table six indicators are described that provided insights into databases' functionalities, characteristics and effects on situations or persons.

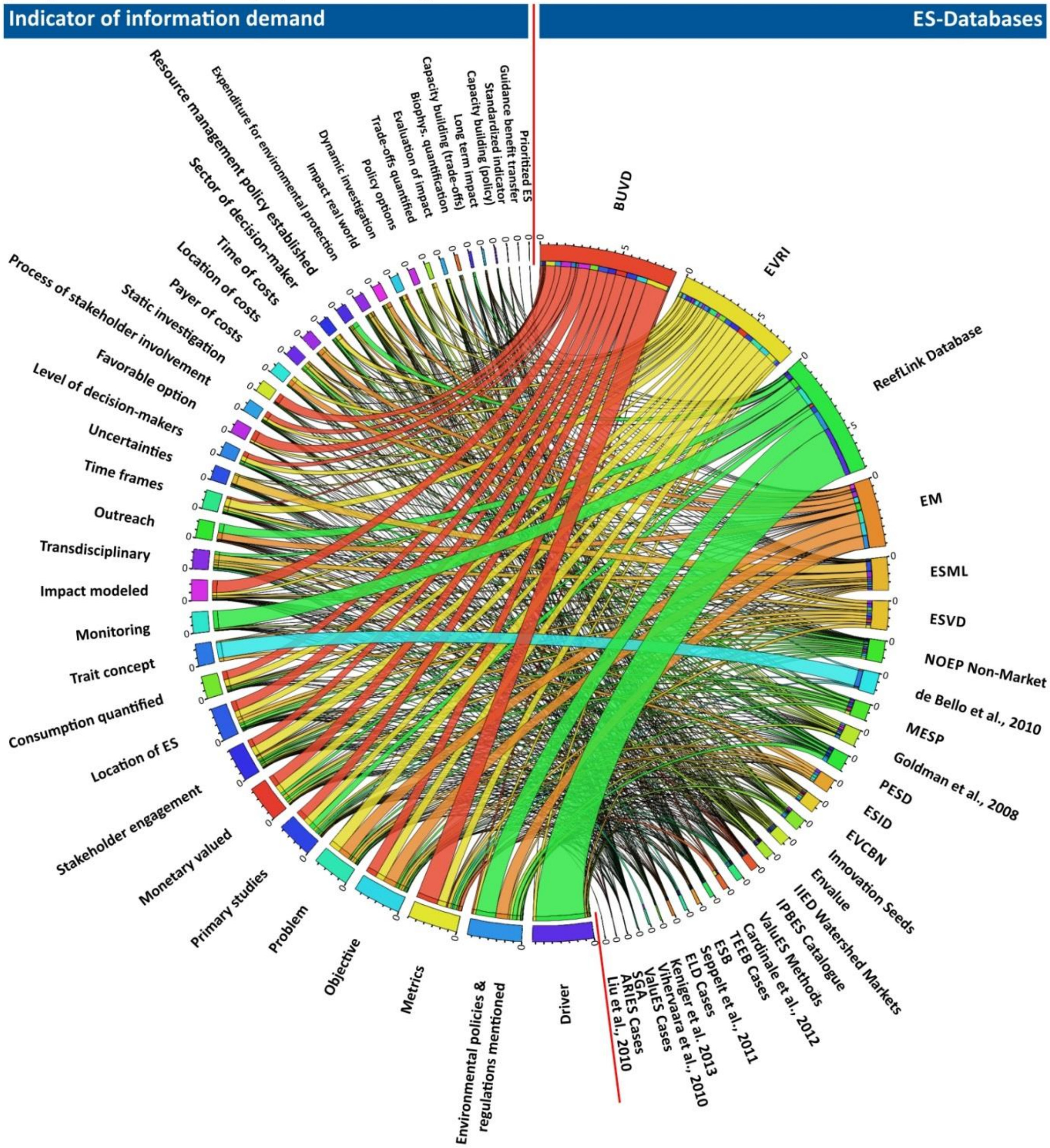
Indicator name	Description
Functional type	This indicator distinguishes between three functional types of databases defined by the National Science Board of the National Science Foundation of United States [108]. According to purpose, design, funding, and maintenance databases can be divided into 'research', '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. I 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 I directly contacted the developers of the databases.

S2.3 Table (see CD). Overview of policy instruments and indicators of information demand. In the table six policy instruments are listed ('Name') that contained descriptions and examples for 93 indicators of information demand. The column 'Description' defines specific topics of information needs required for a policy instrument. 'Examples from databases' relate to column headers or data entries of the databases considered for the analysis.

S2.4 Table. Quantitative matches between information supply provided by databases and information demand of policy-making instruments for safeguarding ES. This table is the addition to Fig 2.5 and shows the relative contributions of data entries provided by 29 databases (rows) to six policy instruments (columns).

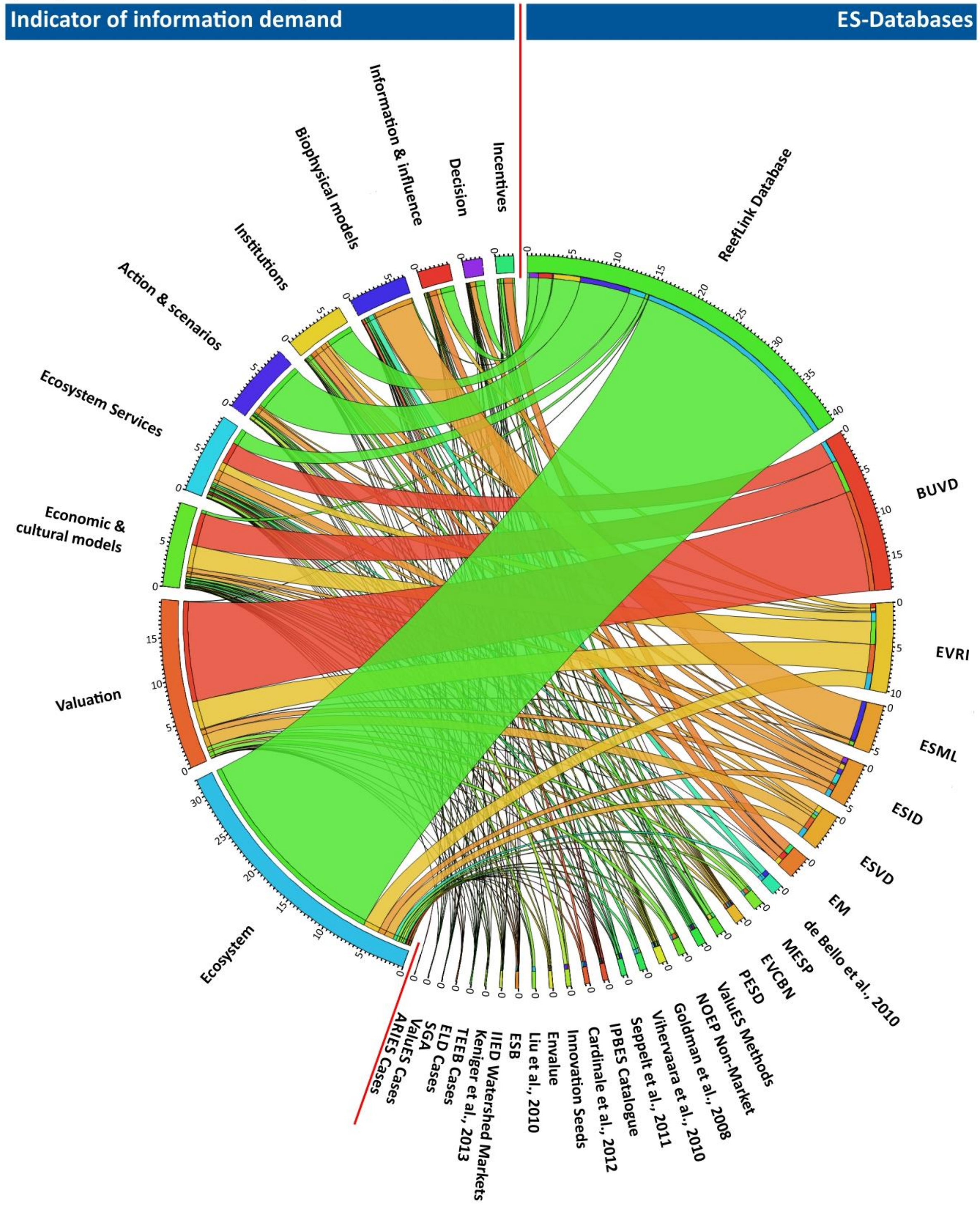
Databases	(A) Extending accounting systems through nature-based indicators	(B) Rewarding benefits through payments and markets	(C) Reforming environmentally harmful subsidies	(D) Addressing environmental degradation through regulation and pricing	(E) Regulating use through protected areas and recognition 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



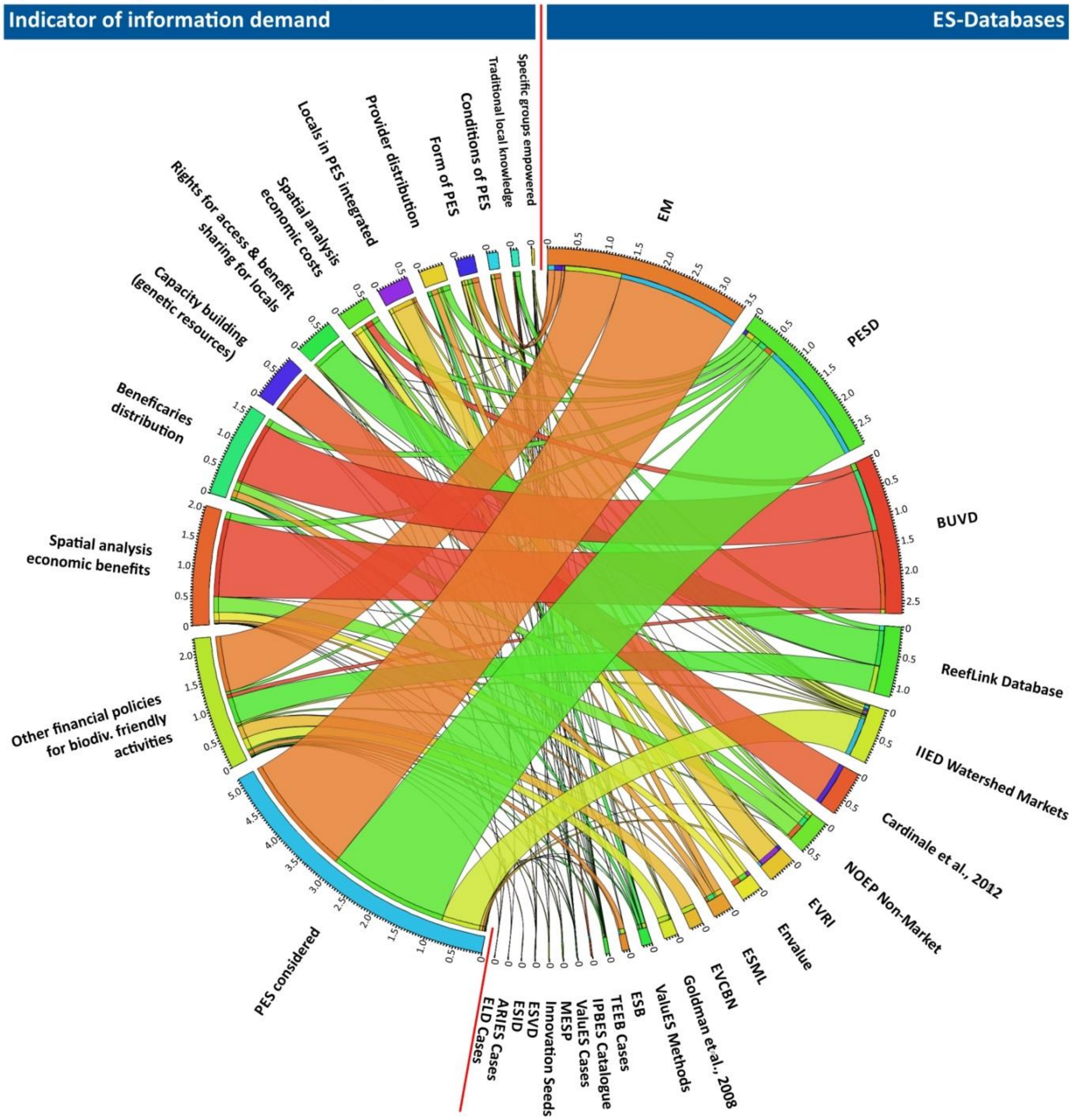
(Fig continues...)

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



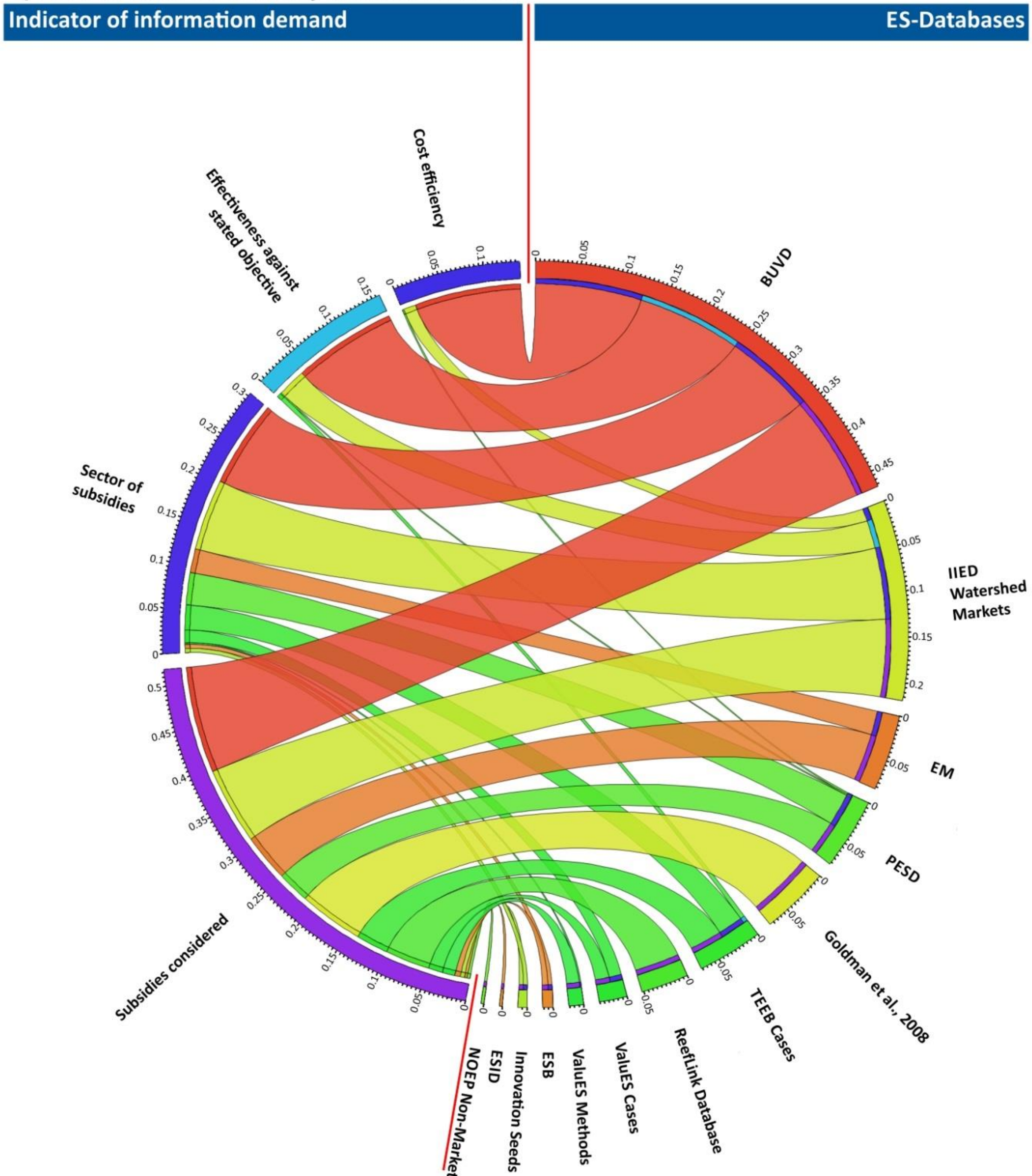
(Fig continues...)

B) Rewarding benefits through payments and markets



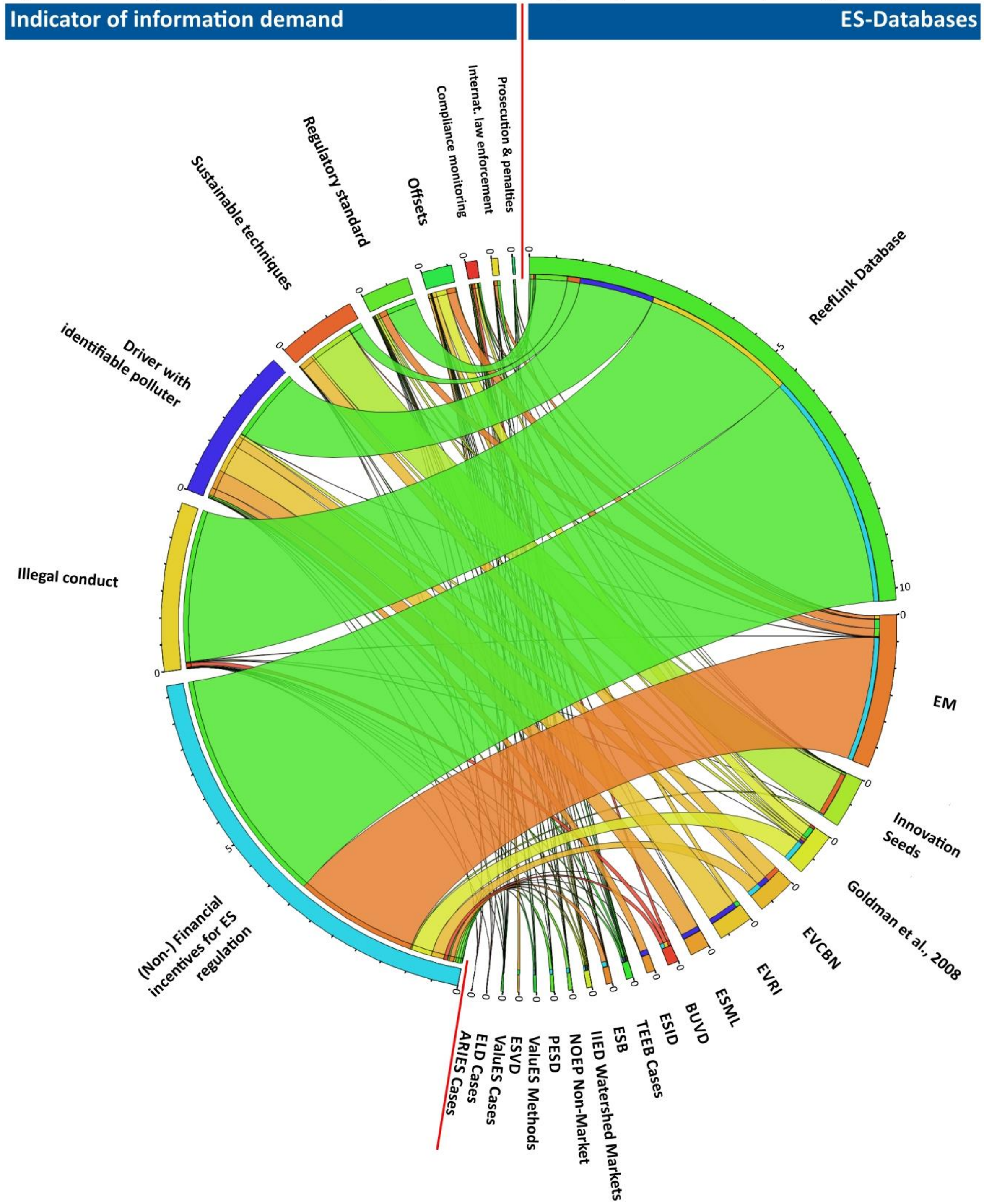
(Fig continues...)

C) Reform environmentally harmful subsidies



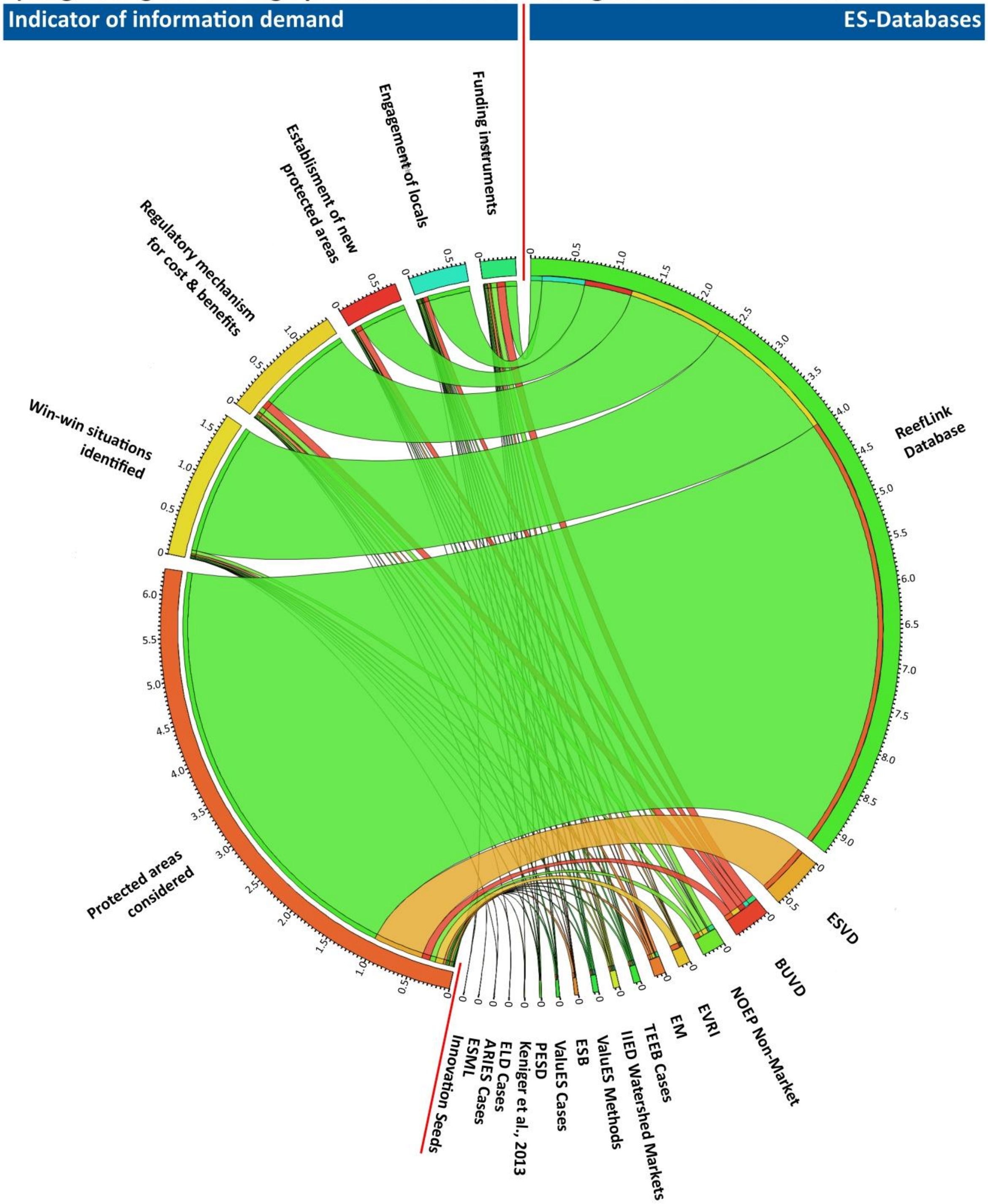
(Fig continues...)

D) Addressing environmental degradation through regulation and pricing



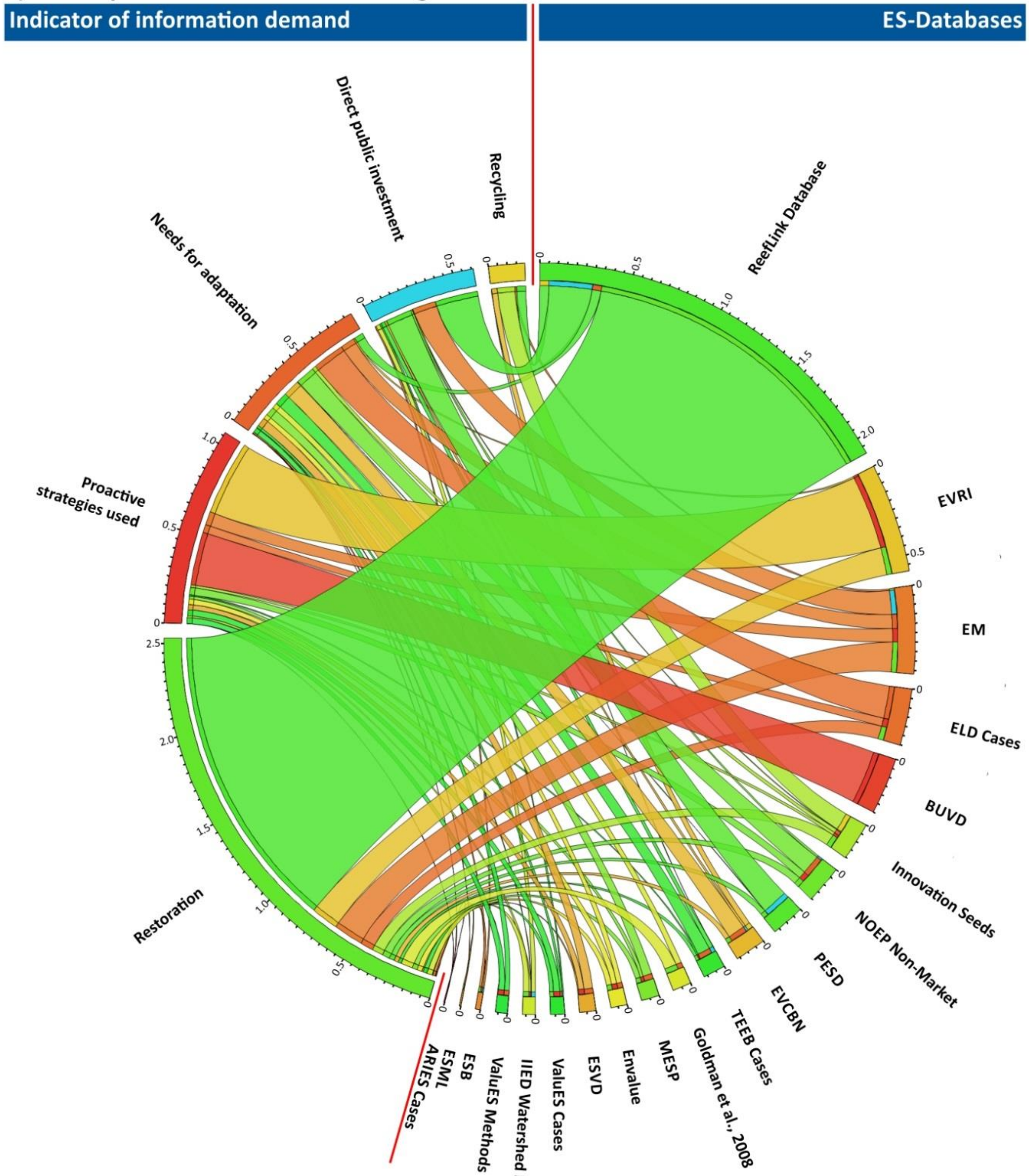
(Fig continues...)

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



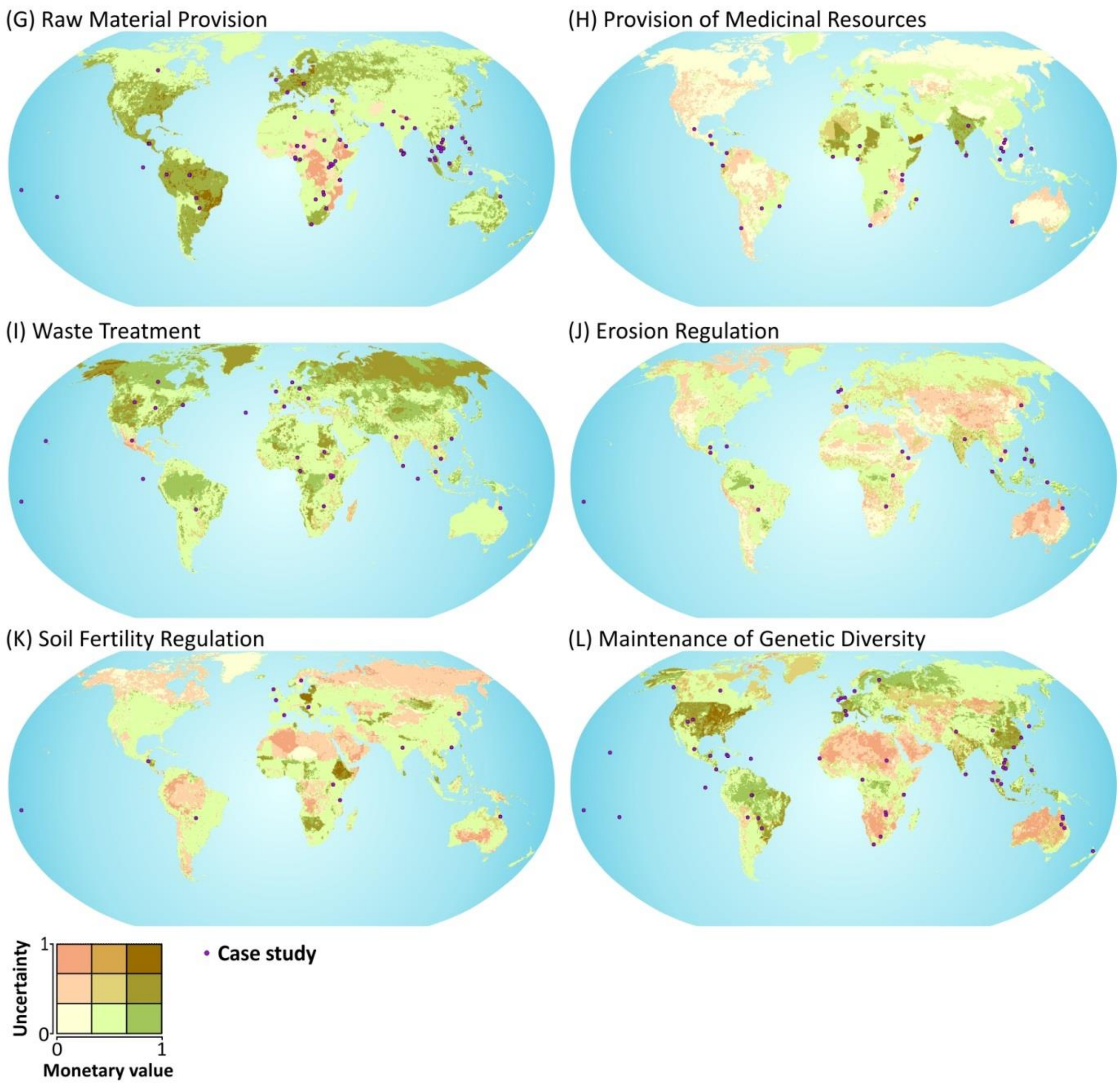
(Fig continues...)

F) Direct public investment in ecological infrastructure and restoration



S2.1 Fig. Quantitative matches between information supply provided by databases and information demand of policy instruments for safeguarding ES, part 2. The chord diagrams connect information supply from 29 databases (right half) with indicators of information demand (left half) for six policy instruments (A-F). The diagrams visually link matches between database entries and indicators of information demand (colored arc connections) by quantifying the relative contributions (percentage values in outer monochrome arcs) of database entries to indicators of information demand. For (A) two chord diagrams are shown. (A.1) illustrates matches for different aspects of the policy instrument ‘Extending accounting systems through nature-based indicators’, while (A.2) focus specifically on the interdisciplinary and multidimensional character of databases’ entries in accordance with the integrative framework defined by Daily et al. [12].

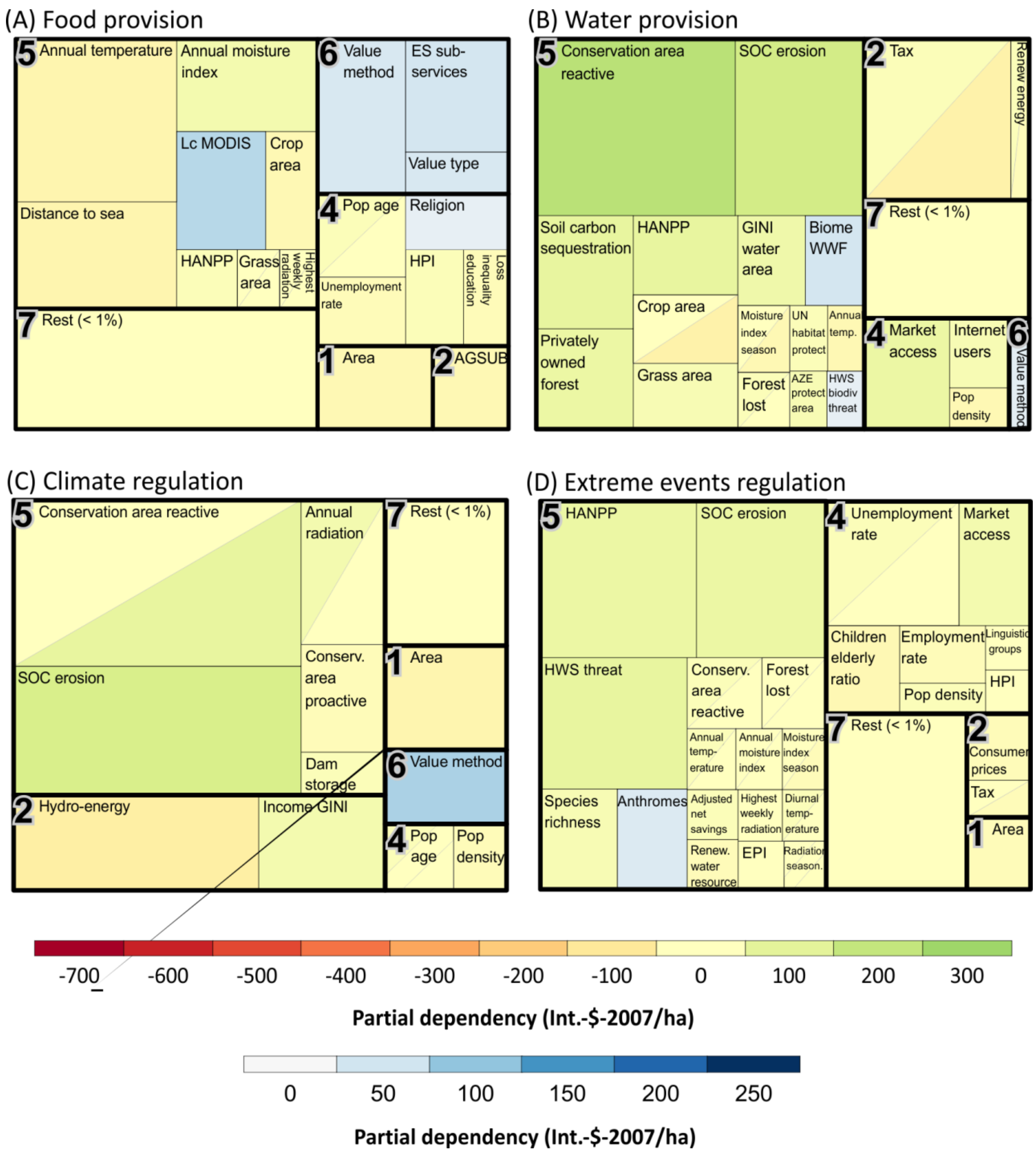
Supplementary Material Chapter 3



S3.1 Fig. Global spatial distribution of monetary estimates and uncertainties, part 2. This map is the completion of the Fig 3.4 and shows the remaining six ES that were not presented in detail in Chapter 3. The bivariate maps illustrate the extrapolated relative monetary values (yellow to green) and uncertainties (yellow to red) of the meta-analytic value transfer functions for the ES: (G) raw material provision, (H) provision of medicinal resources, (I) waste treatment, (J) erosion regulation, (K) soil fertility regulation, and (L) maintenance of genetic diversity.

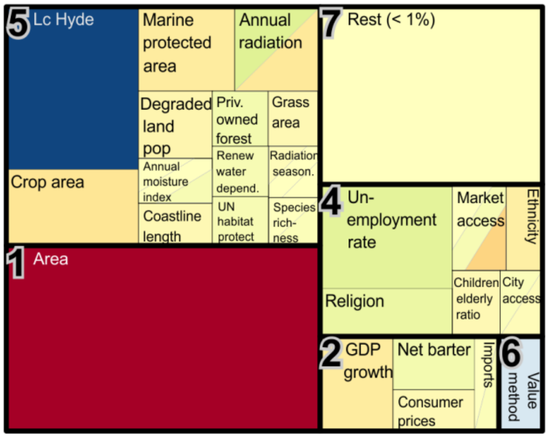
S3.1 Table (see CD). Case studies included for value transfer functions. The table gives an overview of the references from valuation studies included for the benefit transfer models.

S3.2 Table (see CD). Covariates included for value transfer functions. The table shows covariates either from valuation databases [85; 55] or from other global datasets. Information is listed for the names of covariates, the thematic groups they belong to (1) scale, 2) economy, 3) policy/governance, 4) society, 5) ecology, 6) valuation methods), spatial and temporal scale of covariates as well as their sources. Only those covariates are mentioned that showed a statistical influence in one of the value transfer functions.

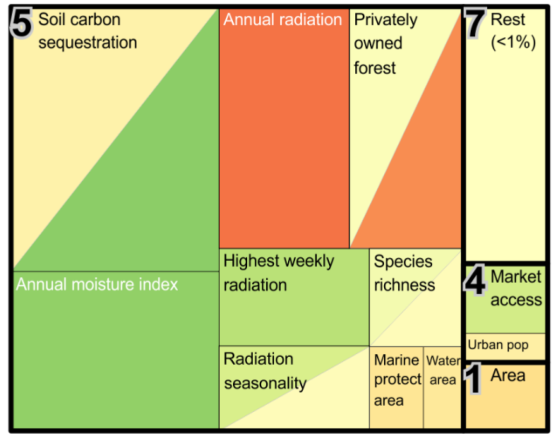


(Fig continues...)

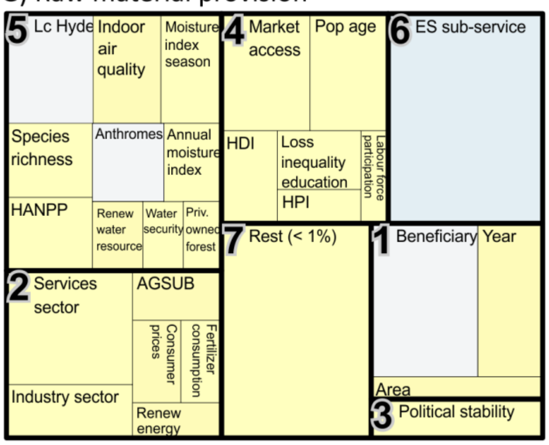
(E) Recreation Service



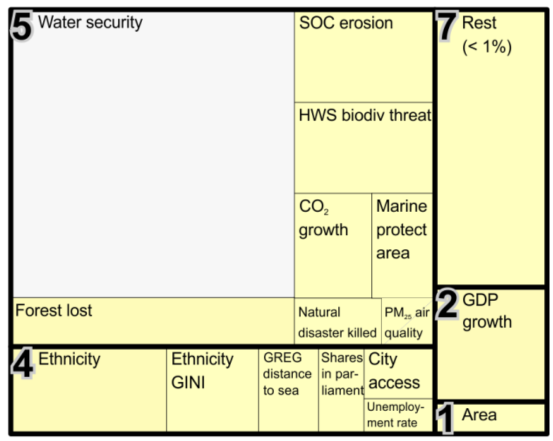
(F) Habitat service

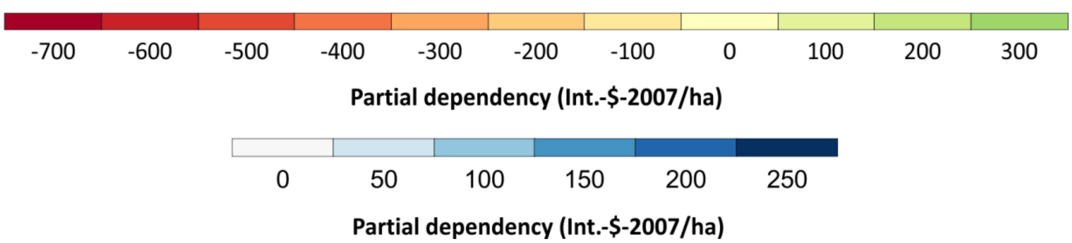


(G) Raw material provision

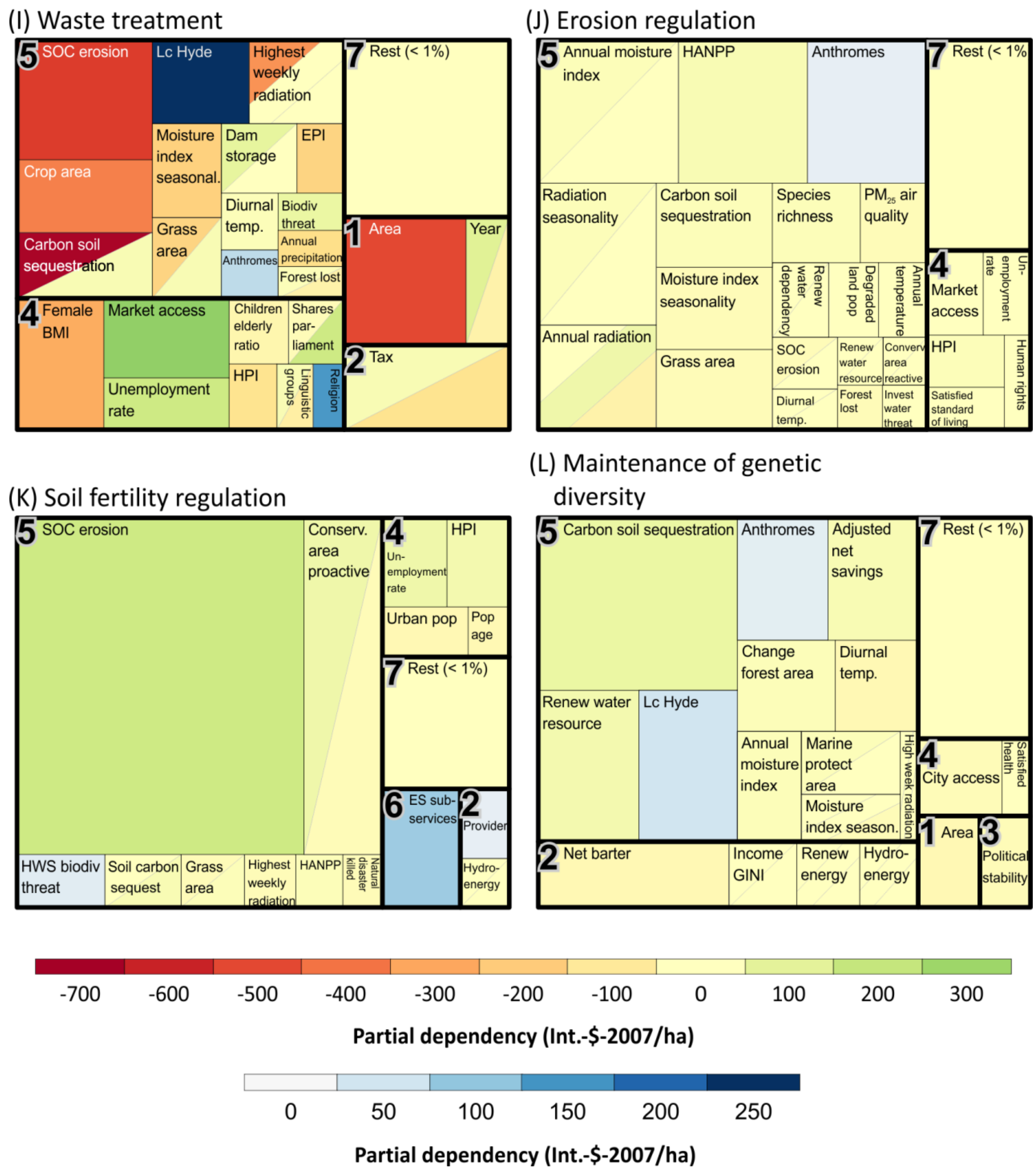


(H) Provision of medicinal resources





(Fig continues...)



S3.2 Fig. Effects of most influential variables for twelve ES value transfer functions. The treemaps (A) to (L) illustrate the relative influence (importance) of covariates in BRT models (value transfer functions) to explain the variance of monetary values. Each rectangle represents a covariate. Rectangle groups numbered from 1 to 7 (delimited by bold black lines) reflect groups of covariates, namely: 1) scale, 2) economy, 3) policy, 4) society, 5) ecology, 6) valuation methods, 7) rest <1% (not clearly assignable). The sizes of rectangles show the importance of covariates in a BRT model (in percentage). Rectangle colours illustrate the strength of relationship between monetary values and covariates. Greenish colours symbolize positive correlation and reddish negative, expressed in International-$-2007 per hectare. Multiple colours can occur for nonlinear effects of variables. Bluish colours represent categorical variables and show the maximum range between the levels. Only covariates with an importance greater than 1% were visualized.

S3.1 Box. Extended description for model fitting and uncertainties.

For the development of value transfer functions the following assumptions have been made [66]:

(1) the existence of meta valuation functions from which values can be inferred;
(2) that differences between sites can be captured through a monetary vector [218];
(3) values are supposed to vary in a systematic way captured by a price deflator index [351];
(4) primary valuation studies provide 'correct' estimates of marginal values; and
(5) meta-analytic publication selection errors can be neglected.

I created meta-analytic value transfer functions for each ES based on boosted regression trees (BRT). Therefore, I utilized the 'Generalized Boosted Regression Models' library [239; 240] from the programming language R [241]. I normalized the response variable by using a log transformation and fitted the BRT models to a Gaussian response type. The relative influence (importance) of covariates in the BRT models were calculated based on the number of times a variable is selected for splitting, weighted by the squared improvement of the model as a result of each split, and averaged over all trees [352]. Then I verified the robustness and stability of the value transfer functions by changing BRT model parameters. Model settings were derived from recommendations of most up-to-date literature. I tested different model settings by optimizing BRT learning rate (lr), tree complexity (tc), minimal number of observations in terminal nodes (mintn) and number of trees (nt).

The lr controls the rate model complexity is increased. Smaller lr are generally preferable to faster ones, because they shrink the contribution of each tree more, and help the model to reliably estimate the response [330]. I used values from 0.0005, 0.0001, 0.00005, 0.00001. The size – number of nodes respectively splits – of a tree controls whether interactions are fitted. With more complex trees fewer trees being required for minimum error, but the contribution of these interaction effects can be difficult to detect. Furthermore, the mintn affect the complexity of a tree, conditional on the number of observations in the trees terminal nodes [353]. For small samples there is no advantage for using large trees (high tc) [330]. Due to the small sample size for each ES in my analysis, I used a tc of 1 (decision 'stump' of two terminal nodes) that fit simple additive effects and tested a mintn of 3, 5 and 8 respectively [353]. These tuning parameter then affecting the nt required for a reliable value transfer. For the identification of an optimal nt I used a three-fold cross-validation, in accordance to [354]. With the determination of an optimal nt over-fitting models to training data can be reduced and their generality enhanced, consequently, the model performance improved when values are transferred to unsampled areas. The final parameters selected for the BRT models were shown in Fig S.3.3. Based on the optimized model parametrization for 12 ES types (839 monetary values) out of 22 (1,033 monetary values) statistical significant value transfer functions could be computed and most influential covariates estimated (Fig 3.3 and S3.2 Fig). Data was not sufficient for generating value transfer functions, if there were less than 11 studies or less than 25 data points. All covariates with more than 1% relative influence on BRT models were considered.

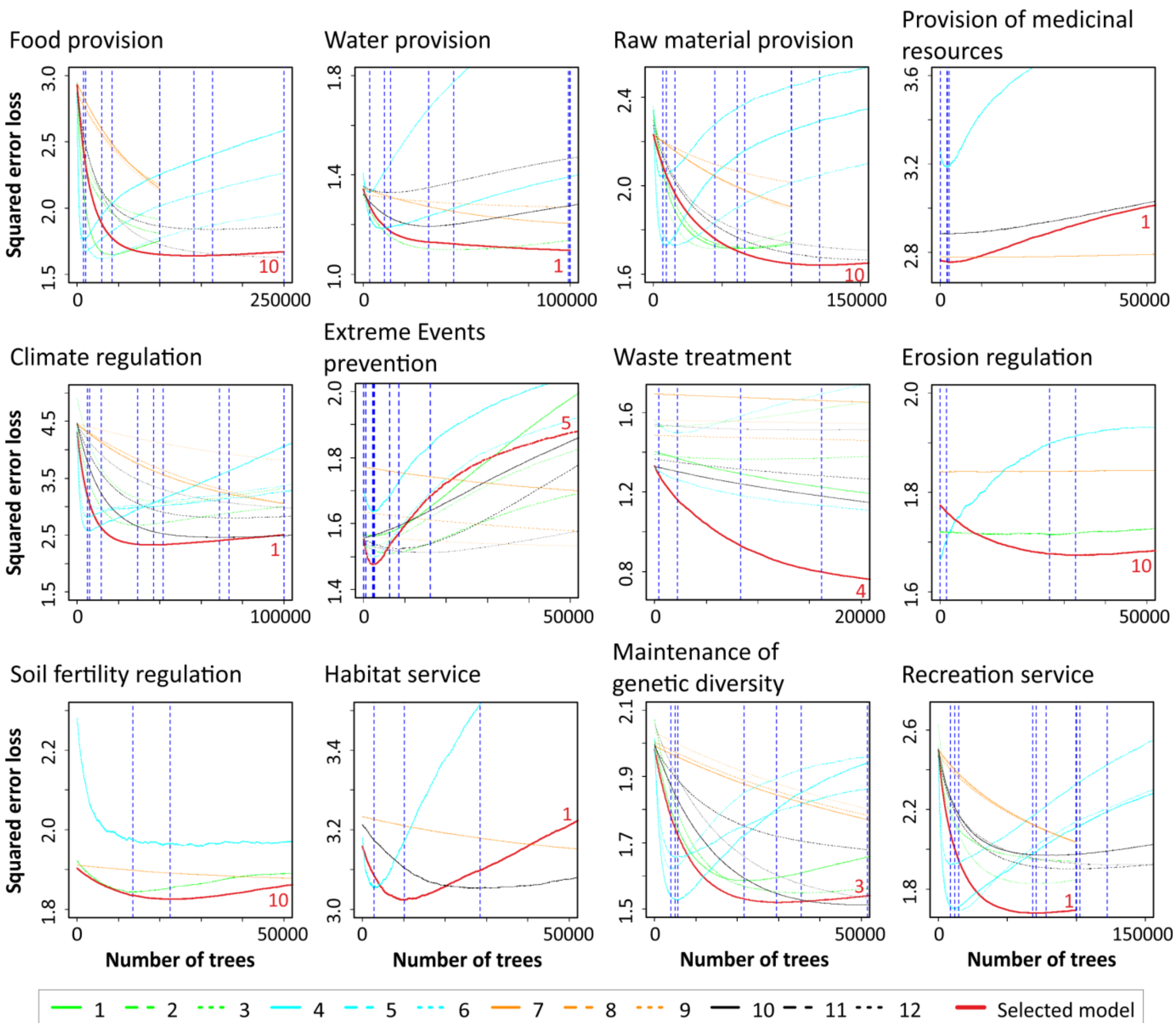
For the spatial extrapolation of values in unsampled areas I used the value transfer functions and applied them based on covariates of cells on a 30 arc min grid across the globe. Value transfer in geographic space was made by using scripts from 'Raster' library of R. Thus, I mapped for each ES type monetary values for the entire terrestrial earth surface (Fig 3.4 and S3.1 Fig).

To estimate the explanatory power of a value transfer function I computed the coefficient of determination R^2 for each value transfer function based on ten-fold cross-validation. Results were shown in Fig 3.3 (column 4).

Additionally, I examined each value transfer function for failure to generalize from training data in order

(Box continues…)

to estimate the confidence intervals around transferred values. Therefore, the bias that coincided with poor nt is shown by assuming nt-vectors from 100 to 100.000. For each ES separate BRT models were fitted and the 2.5- and 97.5-percentile values of the variance of monetary value for each grid cell calculated as an estimate of the confidence intervals. Value transfer in geographic space was made in the same way as I mentioned above for spatial extrapolation of values in unsampled areas. Thereafter, I mapped the range of percentiles for each grid cell and grouped it into three classes (low, middle, high).The grouping was conducted by equal-interval classification for each ES separately, i.e. division of percentile ranges into classes that contain an equal range of values. The final bivariate maps (Fig 3.4 and S3.1 Fig) were developed by mapping the overlay of low, middle and high uncertainty with extrapolated monetary values from the optimized models. Also, based on these classes the percentage area of terrestrial earth surface covered by low, middle and high uncertainty was calculated; see Fig 3.3 (column 4).



Legend number	lr [e-04]	nt [e+05]	mintn	Selected model
1	1	1	3	Water provision, Provision of medicinal resources, climate regulation, habitat & recreation service
2	1	1	5	
3	1	1	8	maintenance of genetic diversity
4	5	2.5	3	Waste treatment
5	5	2.5	5	Extreme events prevention
6	5	2.5	8	
7	0.1	1	3	
8	0.1	1	5	
9	0.1	1	8	
10	0.5	2.5	3	Food & raw material provision, erosion & soil fertility regulation
11	0.5	2.5	5	
12	0.5	2.5	8	

S3.3 Fig. Sensitivity analysis of BRT models. In order to optimize BRT models (value transfer functions) their parameter settings were tested (see S3.1 Box). The graphs show the model performance for twelve parameter configurations. In the table below, these configurations are specified. In addition to learning rate (lr), number of trees (nt) and minimal number of observations in the terminal nodes (mintn), there is also the selected model visualized. The selected model represents the optimized, final BRT model used for estimating relative influence of covariates on the variance of monetary valued ES and for extrapolating values in unsampled areas. Each selected model reduces the deviance of residuals in the model (squared error loss) the most and thus explains the variance of monetary values best.

Supplementary Material Chapter 4

S4.1 to S4.4 are part of the data CD enclosed at the back of the dissertation.

S4.1 Table. Legend for following tables S4.2 to S4.4.

S4.2 Table. Aims and sources of 29 databases considered for the analysis.

S4.3 Table. Number of evaluation criteria from ES databases that refer to topics relevant for the evaluation of effectiveness or efficiency.

S4.4 Table. Number of data entries from ES databases that refer to topics relevant for the evaluation of effectiveness or efficiency.

Content of CD

A CD is enclosed at the back of the dissertation. This CD contains data mentioned in the Chapters: ‘Supplemental Material Chapter 2 to 4’.

The following data is included:

- Supplementary Material Chapter 2
    - S2.1 Table. References of review on information demand.
    - S2.3 Table. Overview of policy instruments and indicators of information demand.
- Supplementary Material Chapter 3
    - S3.1 Table. Case studies included for value transfer functions.
    - S3.2 Table. Covariates included for value transfer functions.
- Supplementary Material Chapter 4
    - S4.1 Table. Legend for following tables S4.2 to S4.4.
    - S4.2 Table. Aims and sources of 29 databases considered for the analysis.
    - S4.3 Table. Number of evaluation criteria from ES databases that refer to topics relevant for the evaluation of effectiveness or efficiency.
    - S4.4 Table. Number of data entries from ES databases that refer to topics relevant for the evaluation of effectiveness or efficiency.

Curriculum vitae

Personal details	
Name	Stefan Schmidt
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04/2013 – 04/2019	External PhD student (Geography), Martin Luther University Halle-Wittenberg, Faculty of Natural Sciences III Title of dissertation: Ecosystem service databases and their contribution to mainstream ecosystem service information
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01/2010 – 07/2010	Environmental Science (Post grado), Departamento de la Atmosfera y los Oceanos, University Buenos Aires, Argentina
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05/2011 – 07/2018	Helmholtz Centre for Environmental Research – UFZ, Leipzig, Germany Scientific staff in Department Computational Landscape Ecology
07/2007 – 10/2007	South African Weather Service, Cape Town, South Africa Meteorological assisstant in weather forecast office
07/2006 – 08/2007	Kunstraum GfK – Vivid Exhibitions, Hamburg, Germany Research assistant for communication design and scientific exhibitions

Leipzig, 15 April 2019

List of publications

Peer-reviewed journal articles

Schmidt S, Berghöfer A, Volk M, Seppelt R. (submitted). A review of global ecosystem service databases for evaluating effectiveness and efficiency of ecosystem service study outcomes. Regional Environmental Change.

Förster J, Schmidt S, Bartkowski B, Lienhoop N, Albert C, Wittmer H. 2019. Incorporating environmental costs of ecosystem service loss in political decision making: A synthesis of monetary values for Germany. Plos One 14 (2). doi: 10.1371/journal.pone.0211419

Lautenbach S, Mupepele AC, Dormann CF, Lee H, Schmidt S, Scholte SSK, Seppelt R, van Teeffelen AJA, Verhagen W, Volk M. 2019. Blind spots in ecosystem services research and implementation. Regional Environmental Change 1-22. doi: 10.1007/s10113-018-1457-9

Schmidt S, Seppelt R. 2018. Information content of global ecosystem service databases and their suitability for decision advice. Ecosystem Services 32 22-40. doi: 10.1016/j.ecoser.2018.05.007

Jacobs S, Dendoncker N, Martín-López B, Barton DN, Gomez-Baggethun E, Boeraeve F, McGrath FL, Vierikko K, Geneletti D, Sevecke Katharina J, Pipart N, Primmer E, Mederly P, Schmidt S, Aragão A, Baral H, Bark Rosalind H, Briceno T, Brogna D, Cabral P, De Vreese R, Liquete C, Mueller H, Peh KSH, Phelan A, Rincón Alexander R, Rogers SH, Turkelboom F, Van Reeth W, van Zanten BT, Wam HK, Washbourne C-L. 2016. A new valuation school: Integrating diverse values of nature in resource and land use decisions. Ecosystem Services 22, Part B 213-220. doi: 10.1016/j.ecoser.2016.11.007

Schmidt S, Manceur AM, Seppelt R. 2016. Uncertainty of Monetary Valued Ecosystem Services - Value Transfer Functions for Global Mapping. Plos One 11 (3): 22. doi: 10.1371/journal.pone.0148524

Seppelt R, Dormann CF, Eppink FV, Lautenbach S, Schmidt S. 2011. A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. Journal of Applied Ecology 48 (3): 630-636. doi: 10.1111/j.1365-2664.2010.01952.x

Reports

Förster J, Schmidt S, Bartkowski B, Wittmer H, Lienhoop N, Albert C. 2016. Datenbank über monetäre Werte von Ökosystemdienstleistungen und Biodiversität in Deutschland. Beitrag zur Methodenkonvention 3.0 des Umweltbundesamts (UBA). Version 1.0. Helmholtz-Zentrum für Umweltforschung UFZ, Leipzig.

Förster J, Schmidt S, Bartkowski B, Wittmer H, Lienhoop N, Albert C. 2016. Methodenkonvention 3.0 – Weiterentwicklung und Erweiterung der Methodenkonvention zur Schätzung von Umweltkosten, Sachverständigengutachten Arbeitspaket 2: Schätzung von Umweltkosten infolge Schädigung oder Zerstörung von Ökosystemen und Biodiversitätsverlust. Forschungskennzahl 3715 14 102 0, Helmholtz-Zentrum für Umweltforschung UFZ, Leipzig.

Berghöfer A, Manns F, Förster J, Schmidt S (eds.) 2014. ValuES Methods Database. Finding suitable methods for assessing ecosystem services. Version 1.0. Helmholtz-Zentrum für

Umweltforschung UFZ, Leipzig. Accessed June/2018. Available from: http://aboutvalues.net/method_database/

Schmidt S, Mupepele AC, Lee H, Paterson J, Seppelt R, Lautenbach S, Dormann CF, Volk M. 2014. Report on standardized metrics/indicators for monitoring the efficiency of ES/NC based measures. In: OPERAs - Operational Potential of Ecosystem Research Applications, European Union's Seventh Framework Programme 308393. Accessed June/2018. Available from: http://operas-project.eu/sites/default/files/resources/d2.2-report-standardized-metrics-and-indicators-monitoring-efficiency-es-nc-based-measuresfinale-2.pdf

Poster presentation

Schmidt S, Manceur AM, Seppelt R. 2015. Estimating uncertainties of monetary valued ecosystem services – a value transfer model for global spatial explicit mapping. 7th ESP International Conference 2015, Ecosystem Services for Nature, People and Prosperity. Stellenbosch, South Africa, November 2015

Declaration under oath

I declare under penalty of perjury that this thesis is my own work entirely and has been written without any help from other people. I used only the sources mentioned and included all the citations correctly both in word or content.

15. April 2019

Date

Signature of the applicant