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Review of decision support tools to operationalize the ecosystem services concept

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ABSTRACT

The ecosystem services concept provides a valuable framework for analyzing and acting on the linkages between people and their environment. By making the values of nature explicit, it allows discussions about trade-offs between services and thus a prioritization of management options. The integration of the ecosystem services concept into decision making remains however challenging. Based on a thorough literature review of 68 tools for integrating ecosystem services into decision making, we analyze the current state, gaps and trends in the operationalization of the ecosystem services concept. We evaluate how well various policy sectors are covered with the tools and highlight gaps where more development is needed. While for some policy sectors such as agriculture or forestry several tools have been developed to support the integration of nature's benefits into concrete decisions, tools are missing where the link between policies and ecosystem services is less evident for example regarding cultural services related to land use policies as well as services supported by soils. Furthermore, the successful implementation of tools requires a good understanding of decision-making processes to bridge gaps in the science-policy interface. Based on the analysis of the application of tools in case studies, we evaluate the establishment of tools over time in different policy sectors and the frequency of their application.

1. Introduction

Current land-use changes clearly diminish the capacity of ecosystems to sustain their productivity in the long run, from the local to the global scales (Foley et al., 2005). Securing the sustainable provision of the services they provide presents a major challenge to decision makers (Cardinale et al., 2012): competing interests for natural resources need to be balanced, yet the impact of land-use practices are often difficult to predict (Carpenter et al., 2009). But while land-change science has made considerable advances in understanding land-use change and thus in understanding human-environment systems, the generated knowledge is often not suitable for decision making (Turner et al., 2007). Particularly, the uncertainties related to global change call for more value judgement in decision making (Polasky et al., 2011), involving personal, subjective attitudes. Open dialogues about critical trade-offs as well as mutual learning processes between scientists, decision makers and stakeholders involved (Owens et al., 2004) have been suggested to support the integration of value judgement in decision-making processes. Participatory processes have been shown to enhance the quality of decisions by allowing the evaluation of multiple and often competing decision criteria, but such processes need to be well designed (Reed, 2008). Based on their experience from ecosystem services (ES) assessments, Rosenthal et al. (2014) emphasized the importance of iterative stakeholder engagement to enable a more informed dialogue.

The ES concept is seen as an opportunity to guide sustainable resource management as it makes the services of nature explicit and thus allows the analysis of trade-offs and impacts of different management options. The ES concept integrates ecological, economic and social aspects by focusing on the values of nature for humans, thus providing a suitable framework to tackle complex problems related to sustainable resource use humanity is facing today. Recently, efforts have increasingly been made to operationalize the ES concept, for example under the EU Biodiversity Strategy (European Commission, 2011) and the MESEU project which supports its implementation, under several EU FP7 research programs such as OpenNESS, OPERAs, or GreenSurge as well as EU H2020 projects such as ESMERALDA, but also worldwide, for example with the guidance for U.S. Federal agencies to integrate ES into decision making (Donovan et al., 2015). According to the glossary developed by the OpenNESS project, operationalization is defined as "the process by which concepts are made usable by decision makers" (Potschin et al., 2014). Blueprints

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have been proposed to make ES assessments more consistent (e.g., Seppelt et al., 2012, Crossman et al., 2013), while acknowledging for the diversity needed to address different aspects of human-environment systems. Despite the vast increase in ES studies in recent years, it has been shown that the outputs of these assessments, especially the maps, are not yet suitable for decision making for five reasons (Martínez-Harms and Balvanera, 2012; Schägner et al., 2013): First, today's, ES assessments are often conducted with simplistic approaches that are strongly relying on available land-use/ land-cover data. This approach allows the identification of general trends, yet the poor fit between land-use based proxies and ES limits the application for the analysis of spatially explicit ES assessment (Eigenbrod et al., 2010) and the formulation of site-specific policy recommendations (Schägner et al., 2013). Second, precision and accuracy of ES assessments and related uncertainties are rarely addressed (Seppelt et al., 2011), yet crucial for decision makers. Third, the consideration of the demand side and/or the monetary valuation of ES presents a major challenge (Wolff et al., 2015) requiring the integration of different disciplines, which is still lacking in most studies (Schägner et al., 2013). Martín-López et al. (2014) show substantial differences in the outcome of a study if different value dimensions are considered, from biophysical to socio-cultural to economic. Fourth, research is focusing on key ES and yet information on many other services is scarce but essential for sound decision making (e.g., Martínez-Harms and Balvanera, 2012). Finally, ES assessments insufficiently account for political and organizational aspects of decision making (Laurans and Mermet, 2014). They often span across several administrative structures, i.e., address different policy aspects, which are often covered by different governmental ministerial or departmental units such as spatial planning and forestry (Primmer and Furman, 2012). Such institutional challenges, including limited capacities of relevant policy units or dispersed authorities, complicate the operationalization of the ES concept (Scarlett and Boyd, 2015). There are recommendations for a better implementation of ES into decision making spanning from the further development of policy instruments and financial mechanisms to a better understanding of the decision-making process and a better representation of methods and results to a more interdisciplinary research (Daily et al., 2009; de Jonge et al., 2012; Laurans et al., 2013; Ruckelshaus et al., 2015). Adelle et al. (2012) stress the role of policy appraisal to inform decision makers rather than providing the "best" solution. Owens et al. (2004) illustrate critical points in policy appraisal such as the discussion if objective, value-free knowledge exists or the misleading, oversimplified assumption of decision makers as a uniform entity rather than individuals representing different interest groups. They discuss the potential of tools such as multi-criteria decision analysis to handle subjectivity.

Efforts are made in model development to better support environmental decision making. Jakeman et al. (2011) identified "the need to diagnose elements that lead to successful process, training for professional and technical competencies, and increased access to stable platforms and interchangeable models and modelling tools" as key challenges of integrated modelling for environmental decision support. These models can be embedded in decisions support systems (DSS) that "enhances a person or group's ability to make decisions" (Power et al., 2015). While progress has been made in the development of DSS, the selection of appropriate ES tools for a specific decision process further complicates the implementation of such tools, as there is no clear guidance available. Guidance for the selection of tools for sustainability assessments has been discussed in the literature and partly also covers ES tools, see for example de Ridder et al. (2007), Ness et al. (2007) or Gasparatos and Scolobig (2012). While these studies are comprehensive, providing a clear classification scheme, they seem to be too broad to provide guidance for ES assessments. The ValuES project (http://aboutvalues.net/) offers an online navigation through a decision tree for the selection of ES tools illustrated with case studies. It is easily understandable also for people who are not familiar with the ES concept or assessment methods, thus offering a good starting point. Recently, the Restoration Ecosystem Services Tool Selector (RESTS) framework has been published guiding the user through a set of 13 ES assessment tools suitable for forest restoration. While the current version is using a spreadsheet, a web-based version is in progress (Christin et al., 2016). Bagstad et al. (2013) evaluated 17 ES tools according to their suitability to support decision making by applying them in a case study. This analysis provides valuable information about time requirements, availability, scalability and generalizability of the tools. However, comprehensive information about the use and robustness of ES tools in different policy sectors is missing but crucial to better guide the selection of tools and their implementation into decision making. This paper presents a thorough literature analysis of scientific articles integrating ES into decision support tools. Our results show the establishment of ES tools over time in different policy sectors and the frequency of their application. We extract from the articles various information, such as the types of ecosystems and services the tools address as well as the scales they are applied at. The analyses provide guidance for the selection of tools in different policy context. We discuss the further development of tools and policy appraisal needed to support the operationalization of the ES concept.

2. Methods

To describe the current state of the operationalization of the ES concept for decision making, we conducted a broad literature review of scientifically published studies. We followed the recommendations for systematic reviews of the PRISMA statement originally suggested for reviewing medical studies but also applicable to other disciplines (see Liberati et al., 2009). The search for the relevant articles was conducted in two main phases by two reviewers to enhance reliability as illustrated in Fig. 1. An initial screening of articles was done by reviewer 1 in July 2015 by searching the academic search engines Google Scholar, Web of Science and Science Direct for the keywords "decision support tool ecosystem services", "decision support tool ecology", "decision support platform ecosystem services" and "decision support model ecosystem services". The search resulted in an initial selection of 84 articles, from which we further selected only articles describing a tool which a) is used for assessing several ES and/or biodiversity to allow trade-off analysis, b) use tools that are operational, i.e., provide some type of user interface and c) are written in English. We hereby refer to a rather broad definition of a tool in the sense of a tool to quantify and value ES. As we only consider tools with a user interface, we excluded studies only describing conceptual models, general methodological approaches or frameworks.

To capture trends in the use of the tools, we also considered tools that were very recently developed and not yet published, as well as tools that do not explicitly mention the term "ecosystem services," but which were nevertheless considered to address the theme (e.g., clearly describing ES, such as water purification or erosion control). As a result, 26 tools from the 84 articles were included in the final review by reviewer 2 according to the three selection criteria. 11 of the articles were review articles from which the original sources for the tools described were also checked. This resulted in 17 additional tools included in the review. Because the initial search did not capture a wide sample of tools, a second article search was conducted in December 2015 by reviewer 2 in Web of Science by using the keywords "ecosystem services" AND "tool". From this search, 18 tools were added to the final review. Aiming to provide a full picture of available ES tools and their application, we included tools developed under the EU OPERA's project which are in the process of publication. While the database search covered two tools of the OPERA's project (mDSS, TESSA), six additional OPERA's tools considered suitable for this review (BackES, ToSIA, Streamline canvas tool, Scenario toolbox, Our Ecosystem webmapping tool and CBA-typology) were also included as well as one from the MESEU project (QUICKScan). Three of them have

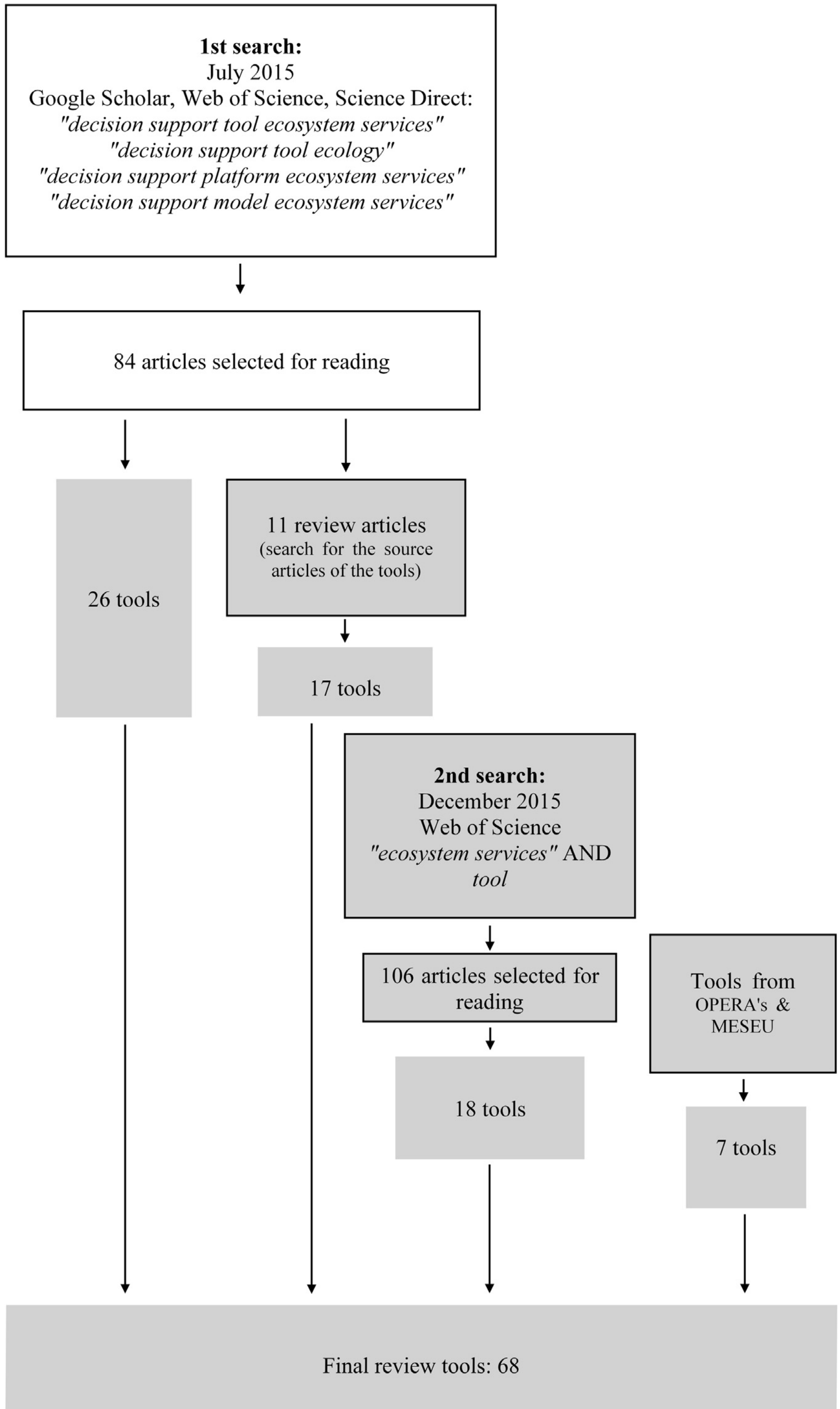

Fig. 1. Flow diagram of the search strategy, white boxes refer to reviewer 1 and grey boxes to reviewer 2.

not been scientifically published (CBA-typology, Scenario toolbox, Streamline canvas tool), one has been published, but the publication only addresses one ES (Our Ecosystem webmapping tool) and one was published in 2016 and therefore not found during the database search (BackES). One tool has been published, but was not found during the database searches (ToSIA). In total, 68 tools were finally included in the review.

During the review, we realized that many tools described in the articles have been further developed. If a more recent publication was found providing different or additional information about the tool, the most recent article was used as an additional or replacing source. Not all articles provided the necessary information needed to categorize the tool in further analyses; in those cases, more than one article or a web-source was used to retrieve additional information. As a result, the actual amount of scientific articles (73) used for the review is higher than the amount of tools (68). A full list of articles and web-sources is provided in Appendix A. Because of the difficulties in getting an overview of the stage of development of the tools and their application frequency, an additional search for each tool was conducted in Web of Science. The keyword(s) used for the search were either the tool name, or in the absence of a clear name for the tool, different combinations of author name(s) and keywords. From the search results, the year of the first and last publication and the total amount of publications for each tool was recorded yet these additional articles were not analyzed in more detail. Thus, the application frequency describes the number of times a tool was mentioned in scientific publications including literature reviews and studies referring to the tool as an example. For further analyses, we collected information provided in the reviewed studies based on the following categories:

Policy sector for which the tool was designed. The policy categories followed the OPERA's WP 4.1 report (Kettunen et al., 2014), which analyzed the policy needs for the operationalization of the ES concept and developed categories to systematically assign ES to sectoral policies. Policy categories included air, water, soil, forest, agriculture and rural development, marine and coastal (including fisheries), regional development, climate, bioenergy and transport. To better meet the needs of this review, the category "regional development" was replaced by "spatial planning" and the category "conservation and protected areas" was added as a new category as well as the category "multiple," which includes tools that could not clearly be assigned to one specific sector. For the rest of the tools, we assigned each tool to one policy sector best describing its area of use. It should be noted however, that only one fifth of the studies actually describe the tool being applied within a certain policy context or being suitable for a certain policy assessment. Therefore, the categorisation of tools into policy sectors is rather based on *potential* than *actual* links between tools and policies.

Types of ES the tool can handle (either described for the case study or described for the tool in general). ES were categorized according to the MEA reporting categories provisioning, regulating, cultural and supporting services, along with their sub-groups (e.g., climate regulation, erosion regulation) (Millennium Ecosystem Assessment, 2005). This information was accompanied by two sub topics, including *the consideration of biodiversity* (yes/no), and *the explicit mentioning of the ES concept* (yes/no).

Type of ecosystems addressed in the case studies and *country, where the case study was conducted.* The categories (Millennium Ecosystem Assessment, 2005) include marine, coastal, inland water, forest, dryland, island, mountain, polar, cultivated and urban. The additional category "multiple" describes studies covering more than one ecosystem.

The following information addressing the functionalities of the tools was also collected and included *the possible scale of application of the tool (*local, regional, national, global or multiple, if the tool was described as suitable for multiple scales), *general input data type for the tool* (qualitative, quantitative or both), *detailed input data type for the tool* (statistics, spatial information, expert knowledge or field survey data, multiple types for one tool are possible), *stakeholder involvement as users* (yes/no), *allowing addressing uncertainty* for example by a sensitivity *analysis* (yes/no), *time requirements for using the tool* (low/medium/high), *spatially explicit outputs* (yes/no), *detailed output type* (biophysical measures or valuations, such as monetary values or preference scores/weights assigned by stakeholders or experts), *generalizability* (yes/no), and finally the *level of development* (prototype, under development or operational). Time requirements were considered high if context specific adjustments, expert training and/or additional data such as surveys were required and low if the tool was based on readily available input data.

3. Results

In this section, we summarize the information collected for the selected tools to better understand their application potential in terms of geographical location, ecosystem types and scales, their data needs, and their use for policy support.

3.1. Geographical application and ecosystem types

Most ES-based tools were applied in developed countries (Fig. 2), particularly in the United States of America and the United Kingdom. The large number of tools applied in the U.S. and the U.K. might also reflect the fact that we reviewed only publications in English. In contrast, in developing countries a narrower selection of tools, often not developed locally (TESSA and InVEST are the most common) were used in case studies. In general, most tools were applied in multiple ecosystems (42%), which were bound by administrative boundaries or functional spaces such as a watershed consisting of e.g., urban areas, forests, and cultivated areas. From the more specific case study applications, most were applied in forests or cultivated land. Applications focusing only on island, marine, mountain and dryland areas were rare, and none of the studies was conducted in polar ecosystems.

3.2. ES and spatial scales

Fig. 3 gives an overview of the ES categories that can be assessed with the tools in relation to the scales at which the tool can be applied. For this figure, only studies that explicitly mention ES were considered. In general, the reviewed ES tools allow integration of particularly regulating and provisioning services into local and regional decision-making processes, whereas cultural and supporting services at the national and global scales have not often been addressed. Some tools, including InVEST, ESP-VT, the Interdisciplinary Decision Support Dashboard and the Scenario toolbox were described as suitable for all scales. Roughly 70% of the ES tools addressed biodiversity, usually in terms of habitat potential/provision/connectivity, species diversity and/or rare species. While most tools addressed multiple service groups, 13% of the ES tools focused on only one ES category, usually regulating services. Most common regulating services that can be addressed by the tools include climate regulation (carbon sequestration) followed by erosion regulation and moderation of extreme events (such as wildfire, flooding, avalanches etc.); as for provisioning services, they especially focus on integrating raw materials (usually timber) and food into decision making, while recreation is the most commonly addressed cultural ES. Tools that did not explicitly mention ES were mostly applied at the local scale addressing regulating and provisioning services.

3.3. Description of the tools and types of data

The reviewed tools cover a broad range, from simple instruments such as interactive pdf's to complex computer models. The tools were not assigned to pre-defined categories based on tool types or methods used (e.g., as in de Ridder et al. (2007) or Ness et al. (2007)) due to the large overlaps in such categories, but some general groups among the tools could be recognised: the majority of the tools included in the review can be described as tools with a focus on scenarios allowing for a better understanding of the impacts of different management practices on ES, such as thinning (forestry tools) or land-use change (spatial planning tools). These tools often integrate multi criteria decision analysis (MCDA) approaches, such as Sim4Tree, HEUREKA, LANDIS or MONSU supporting the assessment of different outcomes in terms of ES trade-offs. Some tools focus on providing information, for example in the form of web-platforms for querying ES maps and presenting ES case studies (EnviroAtlas, ESP-VT, ESLab, GecoServ, Interdisciplinary Decision Support Dashboard and Our Ecosystem webmapping tool), while other tools have an emphasis on the economic aspects (Ecological-economic simulation model, CBA-typology, Benefit Transfer Toolkit and Marxan). A few tools can also be described as "model suites" (ARIES, InVEST, MIMES and Wetland Ecosystem

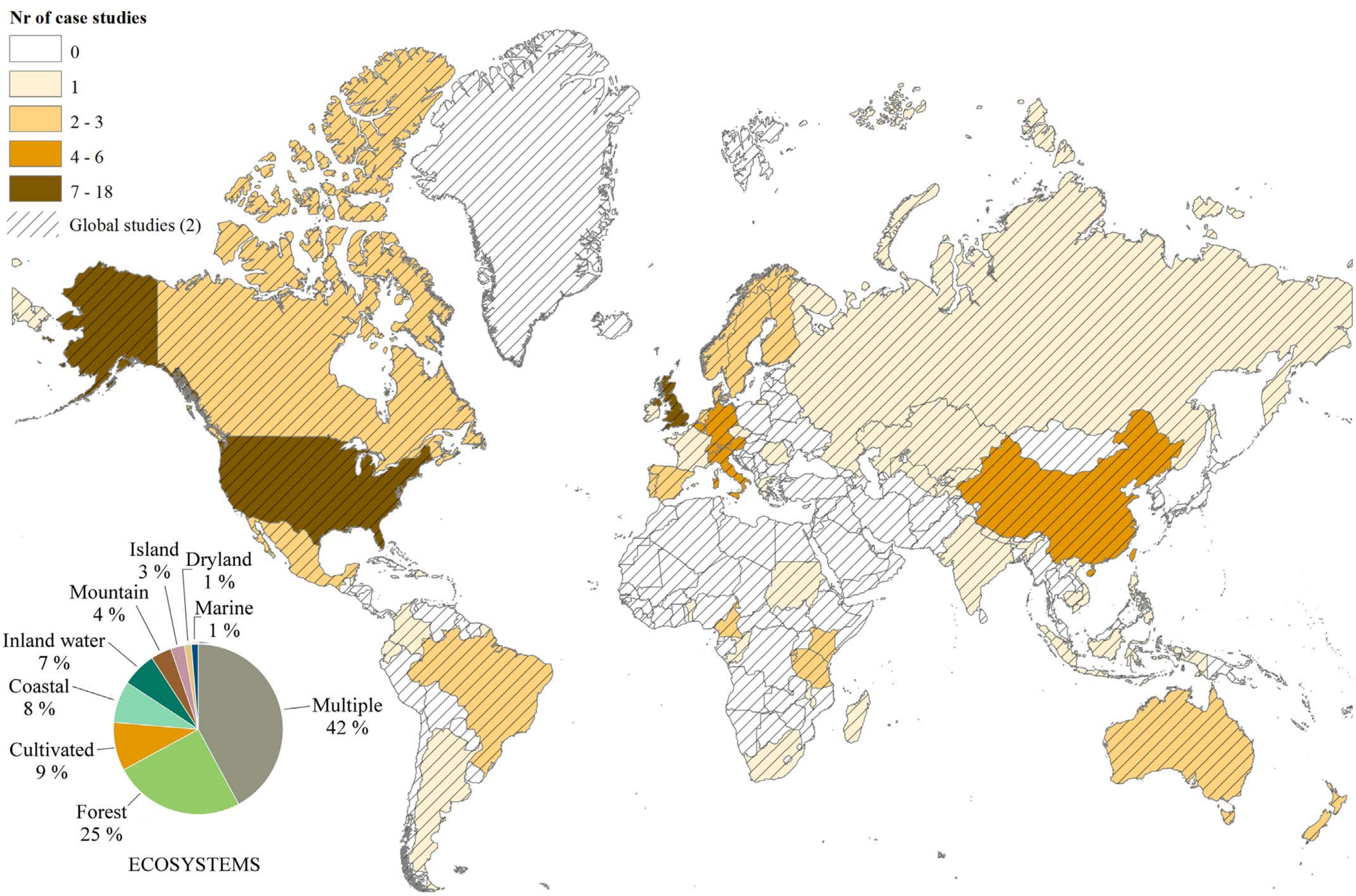

Fig. 2. Global distribution of case study locations by country and type of ecosystem, in which the tools were applied. The categorisation for the number of case studies is based on natural breaks.

Services Model Prototype) which provide multiple approaches to be chosen based on the problem description.

Reviewed tools were mainly targeted to provide spatially explicit ES information (76%). While the required input data are usually quantitative or a combination of qualitative and quantitative, outputs are mainly provided as spatial information or the tool facilitates the connection to GIS software. Nearly 70% of the tools allow the use of different types of scenarios, such as climate, economic, land-use or management scenarios. Input data types included mostly a combination of several types of data, most often spatial information and statistics. Outputs are generally in biophysical units (~60% biophysical

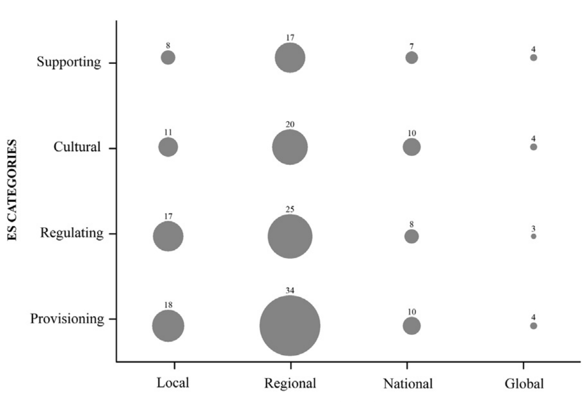

Fig. 3. Spatial scales at which the tool could be applied in relation to ES categories. Only tools specifically addressing ES were considered.

or both), while one third of the tools focus on valuation, either in terms of money, or giving preference values or weights that are based on either expert or stakeholder evaluation. Uncertainty was addressed by less than half of the tools, usually in the form of a sensitivity analysis.

We also looked at information about the potential generalizability of the tools and their time requirement. Based on the description of the tool generalizability in the reviewed studies, or if the tool had been applied in many case study locations, approximately half of the tools could be described as generic. When it comes to the level of development, approximately one quarter of the tools were described in the reviewed papers as “prototype,” “proof of concept,” “pilot” or “under development”. This might however also be due to the outdated source references. Some studies mentioned different versions of the tool, sometimes also describing the history of the tool. 21 of the reviewed tools were either described as prototypes or under development, thus the majority of the selected tools were considered operational. The tools that were described as prototypes or under development were mainly addressing multiple policy sectors (ESLab, ESP-VT, Our Ecosystem) and spatial planning (SAORES, Letsmap do Brazil, Ecosystem Portfolio Model, Pimp your Landscape) at regional to local or multiple scale. Time requirements were difficult to categorize, as this is strongly dependent on data availability, the desired data accuracy and generalizability, details are provided in Appendix A.

3.4. Policy application

Tools that were clearly used for a certain policy or discussed in the context of a policy include MIMES, FVS, MedAction PSS, MULINO mDSS, Evoland modelling platform 3.5, CLIMSAVE, SAORES, Polyscape, EVALUWET, CITYgreen, ToSIA, ESTIMAP, EnviroAtlas, the web-based visualization platform and QuickScan. The policies addressed include in descending ranking order spatial planning (Evoland, SAORES, Polyscape, CITYgreen, ESTIMAP, web-based visualization platform), multiple policy sectors (MIMES, EnviroAtlas, QuickScan), water (MULINO mDSS, EVALUWET), forest (FVS, ToSIA), soil (MedAction PSS) and climate (CLIMSAVE). These tools are usually described as operational, except for CLIMSAVE and the web-based visualization platform, which are considered prototypes as well as SAORES and EVALUWET, which are under development. Roughly half of these tools could be applied in a generic manner and six of them address uncertainty, while none was applied in developing countries. Few of these tools are applied at the local scale (FVS, EVALUWET) and regional scale (MedAction PSS, Evoland modelling platform 3.5, SAORES, CITYgreen), most tools can be applied at multiple scales. Stakeholders are intended users of all these tools except MIMES and for ESTIMAP, no information was found.

Most of the tools included in the review have been published after the turn of the century (Fig. 4), which is also described by Gómez-Baggethun et al. (2010), as a period when the ES concept started gaining ground in the political agenda. The term "ecosystem services" was explicitly mentioned in 69% of the reviewed studies. These tools are frequently applied in studies related to multiple policy sectors, spatial planning, agricultural policies and conservation. Particularly tools covering forest policies addressed ES but did not mention the term explicitly. The policy sectors best supported by ES-based tools include forestry and spatial planning, based on the high number of tools assigned to both sectors, their high publication frequency and the spread of publications over a long period of time. Earliest publications were found in forestry as well as agriculture, which encompass also two of the most frequently published tools, the Forest Vegetation Simulator (FVS) (275 publications) and CropSyst (210 publications). Marxan was frequently used for conservation planning with 226 publications. The long timespan and high amount of publications among forestry and agriculture tools is unsurprising, considering that these sectors have already well-established policies and regulations considering ES such as food, timber harvest or hazard protection. However, most of the reviewed studies of forestry tools did not mention ES explicitly, whereas nearly all reviewed studies in other sectors such as spatial planning or the category "multiple" explicitly mentioned ES.

Many of the more recent tools, which have been described in only one publication focus on spatial planning or cover various policy sectors and are therefore assigned to the category "multiple". Also tools assigned to one specific policy sector often take into account issues related to other policy sectors: for example, only one tool was assigned to the policy sector climate, yet many tools address carbon sequestration as an ES. Similarly, the sector soil has only one tool, but soil related issues, such as erosion regulation was frequently addressed by other tools. This indicates that in an increasingly complicated decision-making environment, there is a demand and increasingly a supply for integrated tools suitable for addressing multiple sectors. Very few tools were assigned to the marine sector and coastal areas; in addition, all of them were published only once and were not recent. No tools were assigned to policy sectors transport, air or bioenergy. Marxan was used in one study to assess biofuel crop production (Stoms et al., 2012), but based on other studies still considered as mainly a tool for conservation. Air quality was addressed as an ES by five tools, of which three are assigned to category "multiple" (ESTIMAP, EnviroAtlas, QUICKScan) and two focus on urban forests/trees (CITYgreen, UFORE), but there was no tool focusing solely on air.

4. Discussion

This review shows that there is a variety of ES tools available, which are fully developed and are widely applicable. The results illustrate current state, trends and gaps in the operationalization of the ES concept. Although the analysis is restricted to scientifically published studies, the results show which policy sectors, services and ecosystems can currently be addressed by available tools. Our evaluation provides valuable guidance in the selection of ES tools related to different policy context thus supporting the efforts to put ES into practice. However, other aspects to be considered when selecting tools include the accessibility of the software, the costs and the required level of expertise.

Results show that ES are well implemented in tools designed to support decision making at local and regional scales. Malinga et al. (2015) evaluated in their recent review the spatial scale of ES assessments and found similarly that most studies address intermediate scales, which are most important for land management. The reviewed ES tools were first applied in the early 1990s in forest and agricultural policy followed by spatial planning and water sectors. This indicates that ES are well established in policy sectors that have a long tradition in the management of natural resources and the services they provide such as forest, agriculture and water, but also the common consideration of these resources in spatial planning. Yet, studies related to forest policies rarely explicitly mentioned ES, which suggests that although ES are thematically addressed, the concept as such is not well incorporated. This also shows that it is challenging to try to find a broad collection of ES tools addressing different policy sectors, since many of them cannot be found by using ES as keywords. This is in contrast to studies related to spatial planning or multiple policies, where ES are explicitly addressed. Over half of the reviewed studies addressed also biodiversity. However, there is an ongoing debate about whether traditional conservation strategies focusing on biodiversity also benefit ES provision, see Adams (2014) for example. Win-win situations where conservation measures benefit both biodiversity and ES hotspots are difficult to identify and require a major interdisciplinary research effort (Naidoo et al., 2008).

There is an increase in both frequency and variety of the reviewed ES tools after 2003, which is in line with the MEA and the following increase in scientific publications reported for example by Chaudhary et al. (2015). Recently developed tools, i.e., after 2010 mostly address multiple policy sectors and either focus on the delivery of ES information for example on web-platforms, or provide a selection of ES assessment methods such as InVEST. Also in spatial planning, new tools have been introduced while in other policy sectors existing tools were further developed and applied. To address current challenges in guiding human-environment systems towards a sustainable use of resources, a more cross-sectoral view is required that considers the different policies. Our results indicate that the recently developed ES tools aim at providing information for multiple policy sectors and supporting the implementation of ES tools in spatial planning.

Most tools can address regulating services, mainly climate regulation, erosion regulation and moderation of extreme events together with provisioning services, usually raw materials and food. As for cultural services, recreation was most frequently considered. This indicates that the operationalization of the ES concept so far is focusing on a relatively narrow selection of services. This is in line with findings of other ES review studies (Martínez-Harms and Balvanera, 2012; Schägner et al., 2013; Malinga et al., 2015). Yet, there is an ongoing debate about the selection of key ES to be considered, as evaluating all services is not possible, but a bias in the selection of ES towards easily determined or popular services should be avoided (e.g., Maes et al., 2012; Martínez-Harms and Balvanera, 2012; Primmer and Furman, 2012).

The majority of the reviewed tools evaluate ES in biophysical units but the tools that were clearly used for a specific policy usually provided results both in biophysical and monetary units. Schägner et al. (2013) describe in their review that mostly monodisciplinary approaches are used to determine ES either focusing on the spatial biophysical or the socioeconomic aspects, yet interdisciplinary work is needed to further develop ES assessments (Steffen, 2009). The monetary valuation of ES

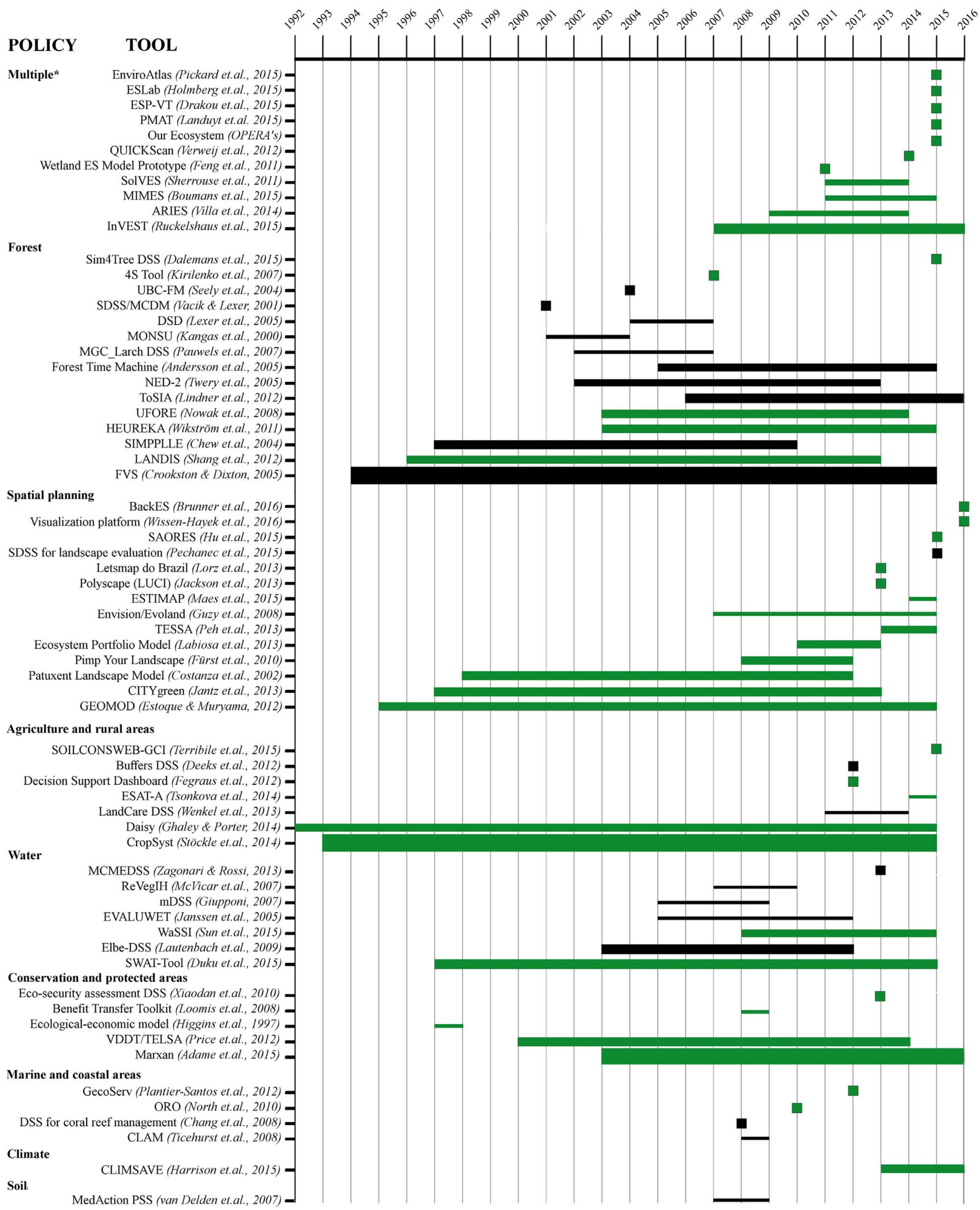

Fig. 4. Number of publications per tool since the first year of its emergence in the scientific literature. The bar length indicates the time between the first and the last publication and the bar width indicates the total amount of publications. Tools marked in green explicitly mention ES. The square symbols indicate tools for which only one publication was found. *Category "Multiple" includes tools that could not be clearly assigned to one main policy sector.

however, has been controversially discussed both regarding the issue of putting value on nature (e.g., McCauley, 2006) as well as for the methodological aspects (see Farley (2012)). Results of the reviewed tools are mostly represented in a spatially explicit manner, which allows the localization of hotspots of ES provision, the analysis of synergies and trade-offs between ES or the spatial comparison of supply and demand thus revealing areas under pressure (see Maes et al., 2012). Conversely, the use of ES maps has been critically discussed by Hauck et al. (2013) regarding issues of credibility and legitimacy and should thus be applied carefully. Information about the uncertainty of the results is crucial for decision making and is provided by less than half of the reviewed tools. The lack of information about the quality of model outputs has also been identified as a problem in the review of Seppelt et al. (2011). However, the consideration of uncertainty in ES assessments (Grêt-Regamey et al., 2013) could be supported by a recently published GIS plugin, which determines the uncertainty of Bayesian Belief Network-derived ES maps (Landuyt et al., 2015).

Despite the progress in the operationalization of the ES concept, our results reveal that ES tools for decision making were mostly applied in developed countries, considering both the amount of case studies and the variety of tools. Similar findings were described by Schägner et al. (2013). Tools should be adjusted to meet conditions of limited data availability and technical capacity in developing countries. The availability of ES information for decision support is in strong contrast to the needs of the rapidly growing population in developing countries which places high pressure on natural resources (Seto et al., 2012). However, there are initiatives such as the Natural Capital Project, that foster the integration of ES into decision making also in developing countries as illustrated by Ruckelshaus et al. (2015), who have applied the InVEST model in 20 different case studies around the world. Few tools are available that address ES at the global scale. This is unsurprising as there are only few global policy instruments such as the Convention on Biological Diversity (CBD). The establishment of IPBES (Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services) over the last years (see Chaudhary et al., 2015) might support the operationalization of the ES concept also in developing countries and at the global scale as it aims at reporting on trends in biodiversity and ES to inform decision making on regional to global scales worldwide (Larigauderie and Mooney, 2010).

New methods should also be developed to integrate cultural ES into decision support tools. While the reviewed tools mostly focus on recreation, other cultural services such as cultural heritage or spiritual significance are more difficult to assess as they strongly relay on personal perception (Daniel et al., 2012). To capture individual preferences particularly relevant for cultural ES, Participation GIS tools (PGIS) and public participation GIS (PPGIS) tools such as SolVES seem to be a promising approach (Brown and Fagerholm, 2015). Besides the methodological challenges, some ecosystems and services seem to be less "popular," i.e., less interesting and not considered a priority on the political agenda: for example, cultural services addressing both environmental and social aspects span across different organizational units, i.e., not matching a current policy sector, a problem described by Primmer and Furman (2012).

While the broad selection of tools included in this review together with the thorough analysis and categorisation of the retrieved information provides valuable results on the state of the operationalization of the ES concept, there are some limitations. First of all, the selection criteria aimed to narrow the search to provide relevant information on the operationalization of the ES concept while still capturing studies that address ES yet do not explicitly mention the term. While we thus replaced "ecosystem services" by "ecology" in the search there still is a variety of resource management tools from different disciplines that were not captured, such as the storm water management tool SWMM, the EPIC soil erosion and productivity model, the CLUE land use land cover change model or the LPJ dynamic vegetation model, to name a few. This reflects the fact that the ES concept is overreaching and combines knowledge from different disciplines. An exhaustive review of environmental decision support tools including resource management tools would have been highly resource intensive, yet provide little information specifically on the operationalization of ES for different policy sectors. Second, as our search for the number of publications per tool was based on the tool name and related keywords, we might be missing tools that changed the name in the course of their development. If possible, a change in the name was documented such as for the Evoland modelling platform, which is called Envision in newer versions. As we reviewed mostly one publication per tool in full detail and only searched for additional information if needed, we might be missing other applications of the tool for example in other places or at other scales. Third, because we only selected scientifically published studies, several currently available decision-support tools were not considered, such as Co$ting Nature, ESValue and EcoAIM, to name a few. Similarly, we did not include unpublished tools that are still under development except for the tools that were added from the OPERA's project. Considering the rapid growth of ES tools, it is likely that we missed a variety of tools that are under development but have not been scientifically published so far. Furthermore, policy making is usually not a key aspect of scientific publications in the field of ES thus including tools from other sources would complete the picture of the state of operationalization of the ES concept. Despite this restriction to academic literature our review includes widely-used tools that were developed in collaboration with NGOs such as InVest or MIMES as well as tools with a strong support from government agencies such as EnviroAtlas or ESP-VT. Finally, while some of the categories were clearly described in most articles such as the country or the type of ecosystem, the categorisation was often challenging as information was missing or not precise enough to allow a distinction between different categories.

Only very few of the reviewed studies clearly addressed a certain policy, which is in line with findings from Schägner et al. (2013). To bridge this gap in the science-policy interface, ES assessments need to better address the requirements of decision makers (e.g., Primmer and Furman, 2012). Rosenthal et al. (2014) identified the '5 Ps' to affect the likelihood of success of the implementation of ES in decision-making: a) a clearly defined Policy question should be addressed, b) the timing of the assessment needs to match a Policy window to be effective, c) People are crucial for the success such as local leaders, d) Pertinent data should match the requirements of the assessment, and e) the science-policy Process should be iterative. While our review does not consider the impact of the selected tools on decision making, other studies found a tendency that simple and easy to use tools are preferred by decision makers, at least for everyday policy making (Nilsson et al., 2008, de Jonge et al., 2012). Although the success or impact of policy appraisal is difficult to evaluate, Adelle et al. (2012) found in their review that micro level recommendations such as more resources and training were easier to implement than more general, higher level recommendations. Owens et al. (2004) discuss the potential of policy appraisal to foster mutual, iterative learning processes. Besides the institutional and methodological challenges, the rapid progress in technological development could open new solutions for DSS and participatory approaches for example through mobile applications (Shim et al., 2002), interactive maps (Klein et al., 2015) or survey tools.

5. Conclusion

There is a variety of tools available to support the integration of ES into decision making. In this review, we focus on tools described in scientific publications thus omitting unpublished tools as well as tools described outside of academic literature. There are only few studies that clearly addressed a specific policy context. Despite this weak linkage, ES were most frequently addressed in policy sectors with a long tradition in the management of natural resources such as agriculture, water and forestry, but also conservation and spatial planning. Recently developed ES tools aim at providing information for multiple policy sectors, supporting the implementation of ES tools in spatial planning. The ES concept is not well operationalized in developing countries and at the global scale, but this shortcoming could be addressed by the recently established IPBES. While ES assessments have been well established for terrestrial ecosystems and a selection of services they provide, the implementation of the concept for cultural services is limited. To overcome this drawback, ES assessment approaches need to be further developed and some ecosystems and their services also need to be better implemented in policies.

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References

Adams, W.M., 2014. The value of valuing nature. Science 346, 549–551.
Adelle, C., Jordan, A., Turnpenny, J., 2012. Proceeding in parallel or drifting apart? A systematic review of policy appraisal research and practices. Environ. Plan. C: Gov. Policy 30, 401–415.
Bagstad, K.J., Semmens, D.J., Waage, S., Winthrop, R., 2013. A comparative assessment of decision-support tools for ecosystem services quantification and valuation. Ecosyst. Serv. 5, 27–39.
Brown, G., Fagerholm, N., 2015. Empirical PPGIS/PGIS mapping of ecosystem services: a review and evaluation. Ecosyst. Serv. 13, 119–133.
Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A., Mace, G.M., Tilman, D., Wardle, D.A., Kinzig, A.P., Daily, G.C., Loreau, M., Grace, J.B., Larigauderie, A., Srivastava, D.S., Naeem, S., 2012. Biodiversity loss and its impact on humanity. Nature 486, 59–67.
Carpenter, S.R., Mooney, H.A., Agard, J., Capistrano, D., Defries, R.S., Diaz, S., Dietz, T., Duraiappah, A.K., Oteng-Yeboah, A., Pereira, H.M., Perrings, C., Reid, W.V., Sarukhan, J., Scholes, R.J., Whyte, A., 2009. Science for managing ecosystem services: beyond the millennium ecosystem assessment. Proc. Natl. Acad. Sci. USA 106, 1305–1312.
Chaudhary, S., Mcgregor, A., Houston, D., Chettri, N., 2015. The evolution of ecosystem services: a time series and discourse-centered analysis. Environ. Sci. Policy 54, 25–34.
Christin, Z.L., Bagstad, K.J., Verdone, M.A., 2016. A decision framework for identifying models to estimate forest ecosystem services gains from restoration. For. Ecosyst. 3, 1–12.
Crossman, N.D., Burkhard, B., Nedkov, S., Willemen, L., Petz, K., Palomo, I., Drakou, E.G., Martín-Lopez, B., Mcphearson, T., Boyanova, K., Alkemade, R., Egoh, B., Dunbar, M.B., Maes, J., 2013. A blueprint for mapping and modelling ecosystem services. Ecosyst. Serv. 4, 4–14.
Daily, G.C., Polasky, S., Goldstein, J., Kareiva, P.M., Mooney, H.A., Pejchar, L., Ricketts, T.H., Salzman, J., Shallenberger, R., 2009. Ecosystem services in decision making: time to deliver. Front. Ecol. Environ. 7, 21–28.
Daniel, T.C., Muhar, A., Arnberger, A., Aznar, O., Boyd, J.W., Chan, K.M.A., Costanza, R., Elmqvist, T., Flint, C.G., Gobster, P.H., Grêt-Regamey, A., Lave, R., Muhar, S., Penker, M., Ribe, R.G., Schauppenlehner, T., Sikor, T., Soloviy, I., Spierenburg, M., Taczanowska, K., Tam, J., Von Der Dunk, A., 2012. Contributions of cultural services to the ecosystem services agenda. Proc. Natl. Acad. Sci. 109, 8812–8819.
de Jonge, V.N., Pinto, R., Turner, R.K., 2012. Integrating ecological, economic and social aspects to generate useful management information under the EU Directives' 'ecosystem approach'. Ocean Coast. Manag. 68, 169–188.
de Ridder, W., Turnpenny, J., Nilsson, M., Von Raggamby, A., 2007. A framework for tool selection and use in integrated assessment for sustainable development. J. Environ. Assess. Policy Manag. 09, 423–441.
Donovan, S., Goldfuss, C., Holdren, J., 2015. Memorandum for Executive Departments and Agencies: Incorporating ecosystem services into Federal decision making. Available from: ⟨https://www.whitehouse.gov/sites/default/files/omb/memoranda/2016/m-16-01.pdf⟩
Eigenbrod, F., Armsworth, P.R., Anderson, B.J., Heinemeyer, A., Gillings, S., Roy, D.B., Thomas, C.D., Gaston, K.J., 2010. The impact of proxy-based methods on mapping the distribution of ecosystem services. J. Appl. Ecol. 47, 377–385.
European Commission, 2011. Our life insurance, our natural capital: an EU biodiversity strategy to 2020. COM (2011) 244. Brussels.
Farley, J., 2012. Ecosystem services: the economics debate. Ecosyst. Serv. (1), 40–49.
Foley, J.A., Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land useScience 309, 570–574.
Gasparatos, A., Scolobig, A., 2012. Choosing the most appropriate sustainability assessment tool. Ecol. Econ. 80, 1–7.
Gómez-Baggethun, E., de Groot, R., Lomas, P.L., Montes, C., 2010. The history of ecosystem services in economic theory and practice: from early notions to markets and payment schemes. Ecol. Econ. 69, 1209–1218.
Grêt-Regamey, A., Brunner, S.H., Altwegg, J., Bebi, P., 2013. Facing uncertainty in ecosystem services-based resource management. J. Environ. Manag. 127 (Supplement), S145–S154.
Hauck, J., Görg, C., Varjopuro, R., Ratamäki, O., Maes, J., Wittmer, H., Jax, K., 2013. "Maps have an air of authority": potential benefits and challenges of ecosystem service maps at different levels of decision making. Ecosyst. Serv. 4, 25–32.
Jakeman, A.J., Sawah, S., Guillaume, J.H.A., Pierce, S.A., 2011. Making Progress in Integrated Modelling and Environmental Decision Support. In:Hřebíček, J., Schimak, G. & Denzer, R. (eds.). Proceedings of the Environmental Software Systems. Frameworks of eEnvironment: 9th IFIP WG 5.11 International Symposium, ISESS 2011, Brno, Czech Republic. Springer Berlin Heidelberg, Berlin, Heidelberg, June 27–29, 2011.
Kettunen, M., Then Brink, P., Underwood, E., Salomaa, A., 2014. Policy needs and opportunities for operationalising the concept of ecosystem services. Report for the EU FP7 OPERAs project, D4.1. Grant Agreement No 308393. Available at ⟨http://www.operas-project.eu/sites/default/files/resources/policy-needs-and-opportunities.pdf⟩.
Klein, T.M., Celio, E., Grêt-Regamey, A., 2015. Ecosystem services visualization and communication: a demand analysis approach for designing information and conceptualizing decision support systems. Ecosyst. Serv. 13, 173–183.
Landuyt, D., Van Der Biest, K., Broekx, S., Staes, J., Meire, P., Goethals, P.L.M., 2015. A GIS plug-in for Bayesian belief networks: towards a transparent software framework to assess and visualise uncertainties in ecosystem service mapping. Environ. Model. Softw. 71, 30–38.
Larigauderie, A., Mooney, H.A., 2010. The Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services: moving a step closer to an IPCC-like mechanism for biodiversity. Curr. Opin. Environ. Sustain. 2, 9–14.
Laurans, Y., Mermet, L., 2014. Ecosystem services economic valuation, decision-support system or advocacy? Ecosyst. Serv. 7, 98–105.
Laurans, Y., Rankovic, A., Billé, R., Pirard, R., Mermet, L., 2013. Use of ecosystem services economic valuation for decision making: questioning a literature blindspot. J. Environ. Manag. 119, 208–219.
Liberati, A., Altman, D.G., Tetzlaff, J., Mulrow, C., Gotsche, P.C., Ioannidis, J.P.A., Clarke, M., Devereaux, P.J., Kleijnen, J., Moher, D., 2009. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. Ann. Intern. Med. 151, (W-65-W-94).
Maes, J., Egoh, B., Willemen, L., Liquete, C., Vihervaara, P., Schägner, J.P., Grizzetti, B., Drakou, E.G., Notte, A.L., Zulian, G., Bouraoui, F., Luisa Paracchini, M., Braat, L., Bidoglio, G., 2012. Mapping ecosystem services for policy support and decision making in the European Union. Ecosyst. Serv. (1), 31–39.
Malinga, R., Gordon, L.J., Jewitt, G., Lindborg, R., 2015. Mapping ecosystem services across scales and continents – a review. Ecosyst. Serv. 13, 57–63.
Martín-López, B., Gómez-Baggethun, E., García-Llorente, M., Montes, C., 2014. Trade-offs across value-domains in ecosystem services assessment. Ecol. Indic. 37 (Part A), 220–228.
Martínez-Harms, M.J., Balvanera, P., 2012. Methods for mapping ecosystem service supply: a review. Int. J. Biodivers. Sci., Ecosyst. Serv. Manag. 8, 17–25.
Mccauley, D.J., 2006. Selling out on nature. Nature 443, 27–28.
Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being. Island Press, Washington, DC.
Naidoo, R., Balmford, A., Costanza, R., Fisher, B., Green, R.E., Lehner, B., Malcolm, T.R., Ricketts, T.H., 2008. Global mapping of ecosystem services and conservation priorities. Proc. Natl. Acad. Sci. 105, 9495–9500.
Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecol. Econ. 60, 498–508.
Nilsson, M., Jordan, A., Turnpenny, J., Hertin, J., Nykvist, B., Russel, D., 2008. The use and non-use of policy appraisal tools in public policy making: an analysis of three European countries and the European Union. Policy Sci. 41, 335–355.
Owens, S., Rayner, T., Bina, O., 2004. New agendas for appraisal: reflections on theory, practice, and research. Environ. Plan. A 36, 1943–1959.
Polasky, S., Carpenter, S.R., Folke, C., Keeler, B., 2011. Decision-making under great uncertainty: environmental management in an era of global change. Trends Ecol. Evol. 26, 398–404.
Potschin, M., Haines-Young, R., Heink, U., 2014. OpenNESS Glossary (V2. 0). Grant Agreement No 308428. Available from: ⟨http://www.openness-project.eu/library/reference-book⟩.
Power, D.J., Sharda, R., Burstein, F., 2015. Decision Support Systems (Wiley Encyclopedia of Management). John Wiley & Sons, Ltd.
Primmer, E., Furman, E., 2012. Operationalising ecosystem service approaches for governance: do measuring, mapping and valuing integrate sector-specific knowledge systems? Ecosyst. Serv. (1), 85–92.
Reed, M.S., 2008. Stakeholder participation for environmental management: a literature review. Biol. Conserv. 141, 2417–2431.
Rosenthal, A., Verutes, G., Mckenzie, E., Arkema, K.K., Bhagabati, N., Bremer, L.L., Olwero, N., Vogl, A.L., 2014. Process matters: a framework for conducting decision-relevant assessments of ecosystem services. Int. J. Biodivers. Sci., Ecosyst. Serv. Manag., 1–15.
Ruckelshaus, M., Mckenzie, E., Tallis, H., Guerry, A., Daily, G., Kareiva, P., Polasky, S., Ricketts, T., Bhagabati, N., Wood, S.A., Bernhardt, J., 2015. Notes from the field: lessons learned from using ecosystem service approaches to inform real-world decisions. Ecol. Econ. 115, 11–21.
Scarlett, L., Boyd, J., 2015. Ecosystem services and resource management: institutional issues, challenges, and opportunities in the public sector. Ecol. Econ. 115, 3–10.
Schägner, J.P., Brander, L., Maes, J., Hartje, V., 2013. Mapping ecosystem services' values: current practice and future prospects. Ecosyst. Serv. 4, 33–46.
Seppelt, R., Dormann, C.F., Eppink, F.V., Lautenbach, S., Schmidt, S., 2011. A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. J. Appl. Ecol. 48, 630–636.
Seppelt, R., Fath, B., Burkhard, B., Fisher, J.L., Grêt-Regamey, A., Lautenbach, S., Pert, P., Hotes, S., Spangenberg, J., Verburg, P.H., Van Oudenhoven, A.P.E., 2012. Form follows function? Proposing a blueprint for ecosystem service assessments based on reviews and case studies. Ecol. Indic. 21, 145–154.
Seto, K.C., Güneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc. Natl. Acad. Sci. 109, 16083–16088.

Shim, J.P., Warkentin, M., Courtney, J.F., Power, D.J., Sharda, R., Carlsson, C., 2002. Past, present, and future of decision support technology. Decis. Support Syst. 33, 111–126.

Steffen, W., 2009. Interdisciplinary research for managing ecosystem services. Proc. Natl. Acad. Sci. 106, 1301–1302.

Stoms, D.M., Davis, F.W., Jenner, M.W., Nogeire, T.M., Kaffka, S.R., 2012. Modeling wildlife and other trade-offs with biofuel crop production. Gcb Bioenergy 4, 330–341.

Turner, B.L., Lambin, E.F., Reenberg, A., 2007. The emergence of land change science for global environmental change and sustainability. Proc. Natl. Acad. Sci. 104, 20666–20671.

Wolff, S., Schulp, C.J.E., Verburg, P.H., 2015. Mapping ecosystem services demand: a review of current research and future perspectives. Ecol. Indic. 55, 159–171.