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Ecosystem services assessment tools for African Biosphere Reserves: a review and user-informed classification

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Abstract

While the concept of ecosystem services which links biodiversity to human wellbeing, is by now well-known, its translation into actual management decisions is still uneven. African Biosphere Reserves, which are to be living labs for sustainable development, embody the idea of synergies between people and nature. Gaining knowledge about the provision, the use and the trends of ecosystem services in these reserves is essential to ensure their global change-proof management. The diversity of rapidly evolving ecosystem services assessment tools requires a systematic and informed selection, in order to ensure that prospective tool users select the most adequate tool, aligned to their needs and context. Based on a Delphi survey of future tool users, and on a review of ecosystem services assessment tools, we propose guidance to users to select the most suited tool based on the context of African Biosphere Reserves, and on tool requirements regarding data input, necessary skills, outputs and types of ecosystem services addressed. The use of the a Delphi survey and the focus on African Biosphere Reserves are new elements that contribute to the theory and practice of ecosystem services assessment.

Keywords: ecosystem services, assessment tools, Biosphere Reserves, Africa, Delphi;

1 Introduction

Biodiversity is under threat at global and local level. Its continuous decline threatens human wellbeing directly and indirectly, as human systems and biodiversity-based natural systems are closely intertwined. The loss of biodiversity alters the functioning of ecosystems and decreases their ability to provide society with essential goods and services (Cardinale *et al.*, 2012; Costanza *et al.*, 2017). The diversity of services provided by ecosystems includes provisioning services such as freshwater and food, regulating services such as air and water purification and climate regulation, supporting services such as nutrient cycling, and cultural services reflecting the deeply embedded relations between human beings and nature (Mukherjee *et al.*, 2014; Chan *et al.*, 2016; IPBES, 2019). In this manuscript, we follow the four-categories classification of IPBES (2019), yet other classifications exist (van Oudenhoven *et al.*, 2018). While ecosystem services are by now well-known and well analysed (Costanza *et al.*, 2017) as the 2005 Millennium Ecosystem Assessment and the recent work of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) show, these services are under threat by ongoing unsustainable human development crossing the systemic boundaries representing the so-called 'safe operating space for humanity' (Steffen *et al.,* 2015). The recent emergence of the 'nature's contributions to people'-idea in the constantly evolving concept of ecosystem services, fosters a more inclusive definition in which indigenous knowledge is explicitly considered (Diaz *et al.*, 2018). The boom of ecosystem services research, applications and policies has led to high expectations among scientists, policy-makers and natural resources managers regarding possible quick wins that could start turning the tide of biodiversity loss, while simultaneously enhancing *e.g.* carbon sequestration and delivery of watershed functions. However, moving from scientific knowledge and societal awareness about ecosystem services to effective real-world decision-making and impact remains challenging. Notwithstanding some success stories, ecosystem services are currently still inadequately acknowledged in decision-making processes (Ruckelshaus *et al.*, 2015).

The wellbeing of people is directly dependent on ecosystem services (Suich *et al.*, 2015) and access to the benefits provided by a steady flow of the ecosystem services contributes to poverty alleviation (Fisher *et al.*, 2014). The challenge of biodiversity loss is particularly acute in developing countries, where economies and a large part of their population depends on goods and services provided by local ecosystems (IPBES, 2018). These countries, often rich with and highly dependent on natural resources, would benefit from the inclusion of ecosystem services in their policy-making processes. Although their economies and a large share of their population is directly dependent on goods and services provided by local ecosystems (IPBES, 2018), until now, these are often not managed sustainably. Africa in particular, has a high proportion of Least Developed Countries (UN CDP, 2018), contains multiple biodiversity hotspots (Myers *et al.*, 2000) and shows a particularly high direct dependency on ecosystem services (*e.g.* 62 percent of its rural population depends directly of ecosystem services for its survival (IPBES, 2018)). Moreover, the continent is expected to suffer an ever-increasing decline in biodiversity, in part due to a rapidly expanding population as the continent's population is expected to double by 2050, reaching 1.25 billion people (UN, 2019). The value of Africa's biodiversity for human well-being is still vastly under-researched (IPBES, 2018).

The linkages between the conservation of biodiversity which forms the basis of the generation of ecosystem services and human development, lies at the roots of UNESCO's Man and Biosphere (MAB) programme (Cuong *et al.*, 2017). The programme finds its spatial expression in a global network of Biosphere Reserves (or MAB Reserves). These reserves must meet a minimal set of criteria in order to be proposed by national authorities and subsequently be designated by UNESCO. The sites are widely recognized as being locations where the sustainable development idea, which gained new momentum following the adoption of the Sustainable Development Goals (SDGs), can be implemented (Pool-Stanvliet *et al.*, 2018). This network of sites also provides an opportunity to realize and fine-tune the 'ecosystems approach' to natural resource management, which fosters a strategy "*for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way*" (CBD, 2004).

Biosphere Reserves entail a mosaic of ecological (sub-)systems that typically provide a diverse set of ecosystem services and exhibit different degrees of vulnerability, and hence require a differential and adaptable management. They are typically divided into a protected core area, a buffer zone and a transition area (Pool-Stanvliet *et al.*, 2018). This zonation allows for differential use of ecosystem services and for a range of management regimes within each Biosphere Reserve. Managers hence need to identify the ecosystem services delivered by the Biosphere Reserve and need to ensure the long-term provision of these services. Together with the additional income generated by carefully designed Payments for Ecosystem Services (PES) schemes, Biosphere Reserves can continue to improve the livelihoods of the millions of people living in their transition zones and beyond (UNESCO, 2016).

A better knowledge and integration of ecosystem services is a key priority for African Biosphere Reserves, as these reserves are facing high anthropogenic pressures. Common causes are the rapid population growth, its strong dependence on natural resources for its livelihoods, weak institutions and competing stakeholder interests in challenging governance conditions (German Federal Agency of Nature Conservation, 2011). Insight in the state and flux of ecosystem services and their use, and in the risks that ecosystem services are facing, is key for sustainable management (Maron *et al.*, 2017). An assessment of the social and economic value of ecosystem services can provide important leverage to safeguard and manage Biosphere Reserves and their ecosystem services in a plural way, acknowledging the interests of a wide range of stakeholders. As an example of current threats to well-known and globally recognized biodiversity hotspots in Africa, the recent threats emanating from oil exploration in the Virunga National Park (Democratic Republic of the Congo) and the adjacent Queen Elizabeth Biosphere Reserve (Uganda) should be kept in mind. The economic value of the ecosystem services provided by the intact, un-exploited Virunga National Park, as compiled by WWF & Dalberg (2013) fed the international pressure which ultimately convinced the Congolese government to opt for long-term conservation benefits instead of short-term oil profits.

To ensure that ecosystem services contribute to improved decision-making, the assessment of these services -and their contributions to human wellbeing needs to become systematic, quantifiable, robust and credible (Bagstad *et al.*, 2013). Solid methods to assess and map ecosystem services exist, but remain insufficiently known, used and communicated (Maes *et al.,* 2013; Martinez-Harms *et al.*, 2016; Ruckelshaus *et al.*, 2015). Many decision-support tools have been developed in recent years, yet their applicability and user-friendliness are often context-, site- and user-specific. Moreover, their application is often limited due to high demands of data, skills, time and resources. In order to structure and understand the diversity of these tools, some authors performed reviews attempting to classify these methods and analyse their trade-offs. Bagstad *et al.* (2013) evaluated ecosystem services assessment tools based on their suitability to be mainstreamed in environmental decision-making processes in the most resource-efficient way. Pandeya *et al.* (2016) reviewed tools that contribute to better policy making and are locally applicable in data-scarce areas. Grêt-Regamey *et al.* (2017) reviewed tools that have been operationalized into decision-support for a range of sectors such as water, soil, forest, agriculture and transport; while IUCN (2018) reviewed tools to model and value ecosystem services in among others World Heritage Sites and Key Biodiversity Areas. Despite these valuable efforts, a review of widely applicable, rapid and affordable tools to assess multiple ecosystem services in the specific context of African Biosphere Reserves, building on the expectations of the prospective users of such tools, was still lacking. In this study, we identify the expectations of prospective tool users, review existing rapid ecosystem services assessment tools based on an integration of these user-generated criteria and criteria from the literature, and subsequently provide users with guidance on ecosystem services assessment tool selection.

In order to ensure that managers of African Biosphere Reserves and other stakeholders gain rapid and reliable access to the ecosystem services assessment tools that are best suited to their demands, their capacities and the available data and resources, this study aims to:

- Provide insight into the evolving landscape of ecosystem services assessment tools and their applicability in the context of African Biosphere Reserves;
- Identify the perspective of prospective users of ecosystem services assessment tools (*e.g.* Biosphere Reserve managers) on management challenges and preferences regarding tool format and objectives;
- Evaluate the characteristics of ecosystem services assessment tools to facilitate an informed selection process when choosing which tool to apply;
- Critically reflect on the design and the use of current and future ecosystem services assessment tools in African Biosphere Reserves.

2 Methodology

2.1 Selecting ecosystem services assessment tools for African Biosphere Reserves: a stepwise approach

The diversity of ecosystem services assessment tools (see *e.g.* Bagstad *et al.*, 2013; Grêt-Regamey *et al.*, 2017; IUCN, 2018) can make it difficult for prospective tool users to see the wood for the trees. We opted for a three-step approach to identify the tools that may be suitable for African Biosphere Reserves.

Step 1: Selection of ecosystem services assessment tools based on a review of existing tools, on the scientific literature and on the specific context of African Biosphere Reserves. This selection was based on the *'initial selection criteria'*.

Step 2: Identification of '*user-generated characteristics'* to perform a detailed assessment of ecosystem services assessment tools;

Step 3: Classification of selected tools.

2.2 Step 1: Selection of a range of ecosystem services assessment tools

An initial screening of ecosystem services assessment tools, frameworks, guidelines and methods (from now on referred as 'tools') was carried out based on the review of the literature in specialized scientific journals (including: *Ecosystem Services, Ecological Economics, Ecological Indicators, Ecological Modelling,* and the *Journal of Environmental Management*) and in the scientific search engines *Web of Science* and *Google Scholar* for the following keywords: ecosystem services assessment, ecosystem services tool, ecosystem services toolkit, ecosystem services framework, ecosystem services guideline(s) and ecosystem services assessment method. Additional tools were identified from specialized databases built by the *Ecosystem Knowledge Network* (https://ecosystemsknowledge.net/), the *Ecosystem Services Partnership* (https://www.es-partnership.org/) and the *ValuES* method navigator (http://www.aboutvalues.net/method_navigator/). Key sources for this step include: Bagstad *et al.* (2013), Grêt-Regamey *et al.* (2017), Oosterbroek *et al.* (2016), Pandeya *et al.* (2016), Peh *et al.* (2013). Only tools that fulfilled the following set of '***initial selection criteria'*** were selected for Step 2:

- Generalizable (*i.e.* applicable across a variety of social-ecological settings, while allowing to take into account different local specificities), to account for the diversity of African Biosphere Reserves;
- Applicable at the landscape scale (*i.e.* going beyond application on small patches only, allowing to include large zones with different management regimes and/or intensity), as African Biosphere Reserves typically encompass zones (core area, buffer zone, transition area) with different management rules;
- Applicable independently (*i.e.* without *a priori* requiring external expertise); as there is typically a lack of availability of ecosystem services expertise in African Biosphere Reserves;
- Affordable (*i.e.* without requiring a priori financial investment); as African Biosphere Reserves typically lack sustainable funding;
- Able to assess multiple ecosystem services (*i.e.* not focusing on only one category of ecosystem services (*e.g.* not only carbon sequestration, or only water)), as African Biosphere Reserves encompass a wide range of ecosystem services;

- Rapid (*i.e.* requiring less than a year to apply the tool), as African Biosphere Reserve staff are often burdened by excessive workload and as management decisions often need to be made on relatively short time scales.

The initial selection criteria were based on the objectives of the study (identifying rapid and accessible tools within the context of African Biosphere Reserves). The specificities of the African Biosphere Reserves-context were based on a document of the German Federal Agency of Nature Conservation (2011). The initial selection criteria were then complemented with a range of tool characteristics that reflect the preferences of potential tool users. These characteristics were compiled by way of a Delphi exercise (see Section 2.3).

2.3 Step 2: Identification of user preferences regarding ecosystem services assessment tools

Despite the increasing awareness of including stakeholder preferences into decision-making, until now, reviews focusing on ecosystem services assessment tools have typically failed to systematically acknowledge the perspective of prospective tool users. In order to gather the perspectives and expectations of the prospective users of ecosystem services assessment tools in African Biosphere Reserves, we used the Delphi technique. The Delphi technique is a structured, anonymous and iterative survey, and typically aims to addressing complex issues that require inputs from different disciplines and backgrounds (Mukherjee *et al.*, 2015). The Delphi participants remain mutually anonymous (no participant knows what any other participant is responding), which contributes to address a range of social pressures that can negatively affect group-based approaches (biases such as groupthink, halo effects, egocentrism, and dominance are reduced – as there is no face-to-face interaction among participants) (Mukherjee *et al.*, 2015). During the successive rounds of the iterative Delphi survey, participants tend to move towards consensus on some issues, as they are progressively exposed to the opinions of their peers (Mukherjee *et al.*, 2015). In our study, we set the level of consensus at >50%, meaning that a tool's characteristic is accepted (deemed relevant for an ecosystem services assessment tool) if at least 50% of the respondents selected the characteristic after round 2 (which is in line with Von der Gracht (2012) and Mukherjee *et al.*, (2015)).

For this study, all Delphi participants were members of the African Network of Biosphere Reserves (AfriMAB), who are all involved with the strategic and/or day-to-day management of African Biosphere Reserves. All attendants of the 5th General Assembly of AfriMAB, held in Ibadan, Nigeria, in September 2017, were given the opportunity to participate in the Delphi survey. We conducted a two-round Delphi survey, that could be answered online using Google Forms, or completed on paper forms. Each Delphi round consisted of two main sections: *i.* the management challenges faced by African Biosphere Reserve managers; *ii.* the desired characteristics of ecosystem services assessment tools (reflecting users' expectations of these tools). The two rounds of the online survey were completed individually and anonymously by the respondents in September 2017. Twenty-four respondents participated in the first Delphi round, and twenty-two participants took part in the second round, which is in line with the average number of respondents in Delphi studies as reported by Mukherjee *et al.* (2015) and Hugé *et al.* (2018). The profile of the respondents is described in the Results section.

2.4 Step 3: Classification of selected tools

In step 3, ecosystem services assessment tools are classified based on the required inputs, the outputs, the skills required to apply the tool and the ecosystem services that are considered by the tool. This classification is visualized by Venn-diagrams (Figures 2-5), and all selected tools are briefly described in Table 4.

3. Results

3.1 Results of Step 1: from a longlist to a shortlist of ecosystem services assessment tools

Appendix 1 provides an overview of the 51 ecosystem services assessment tools that were selected during the initial screening, using the initial selection criteria (Step 1). This longlist of tools was then reduced to 17 tools, following the steps outlined in Sections 2.1 and 2.2, using the user-generated selection criteria. These 17 selected tools (the 'shortlist') are evaluated and classified in Section 3.3 below.

3.2 Results of Step 2: user expectations regarding ecosystem services assessment tools

3.2.1 Profile of the Delphi respondents

We present the profiles of the respondents of the second round (n = 22), as these respondents completed the full Delphi process (in line with Mukherjee *et al.*, 2014). Figure 1 gives the profile of the actual Delphi respondents and the profile of all the participants to the 2017 AfriMAB General Assembly (which hence represents the population from which the Delphi respondents originate).

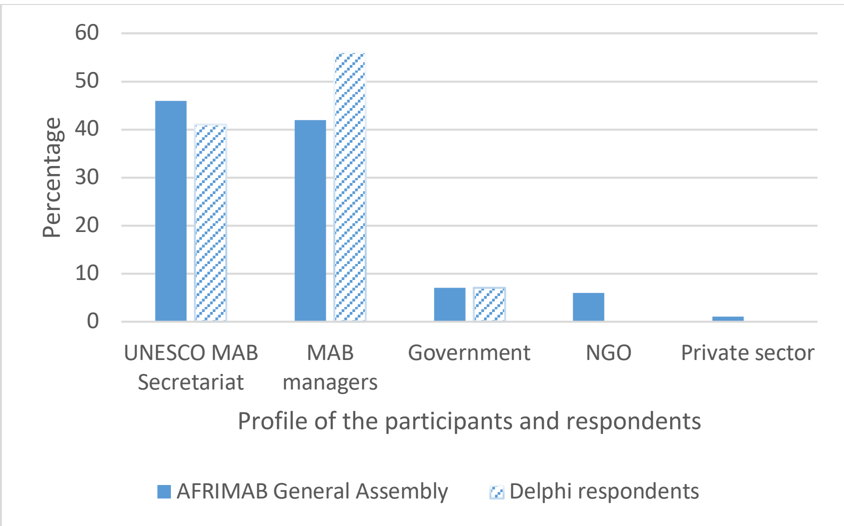

Figure 1: Profile of the Delphi respondents and the participants to the 2017 AfriMAB General Assembly (in %)

3.2.2 Main management challenges faced in African Biosphere Reserves

Table 1 presents the main management challenges according to the Delphi respondents

Table 1: Main management challenges in African Biosphere Reserves according to the respondents. Only challenges scoring over >50% consensus are mentioned with the percentage indicating the share of respondents that selected this challenge. The trends in scores between round 1 and round 2 are indicated.

	Consensus level	Score variance	Trends in scores between rounds (↑ indicates increase, ↓ indicates decrease)
Inadequate financial resources	90%	15%	↑
Pressure from human activities	70%	20%	↓
Limited capacity (*e.g.* human resources)	55%	15%	↑
Unavailability of data to support management	55%	20%	↑

3.2.3 Desired characteristics of ideal-typical ecosystem services assessment tools

Table 2 outlines the desired characteristics of an ideal-typical ecosystem services assessment tool, according to the Delphi respondents. Criteria to evaluate ecosystem services assessment tools can be drawn from this set of user-generated desirable characteristics. These criteria are synthesized in Section 3.3.

Table 2: Results of the Delphi (after 2 rounds) regarding the desired characteristics of ecosystem services assessment tools. Only characteristics with scores showing >50% consensus are presented. (*ES stands for ecosystem services*)

Tool characteristics		Consensus level	Score variance	Trend in scores between rounds (↑ indicates increase, = indicates stable trend, ↓ indicates decrease)
Inputs	Maps	78%	15%	↓
	Quantitative input	83%	5%	=
	Qualitative input	61%	5%	↓
Skills required	Low expertise requirements to be applied	55%	20%	↑
	Hiring someone to apply ES assessment tools	84%		↑
	Fieldwork technically demanding	56%	20%	↑

	Fieldwork expensive	67%	10%	↑
Outputs	Quantitative output	53%	15%	↑
	Economic valuation	58%	5%	↑
	Provide results that are easy to communicate	55%	5%	↑
Ecosystem services addressed	Ability to assess multiple types of ES	60%	10%	↓
Purpose	Environmental awareness raising & education	70%	10%	↓
	Scoping & description of provided ES	65%	10%	↑
	Supporting ES monitoring & evaluation	65%	25%	↑
	Identifying livelihood, development & investment opportunities	55%	25%	↓

3.2.4 Fine-tuning the user-generated tool characteristics

In order to fine-tune the desired characteristics expressed by the –future- tool users in Table 2, we propose sub-categories for the user-generated characteristics, and we add an estimate of the time required to apply the tool. The characteristics and their sub-categories are based on the Delphi (see Table 2) and complemented by sub-categories from the existing literature (incl. Peh *et al.,* 2013; Grêt-Regamey *et al.,* 2017; Pagella & Sinclair, 2014; Turner *et al.*, 2016; Villa *et al.*, 2014).

Table 3: Synthesis table outlining characteristics of ecosystem services assessment tools, based on the fine-tuning of user-generated preferences

Tool characteristics	Categories (multiple possibilities per tool)
Inputs	• Spatial data (maps, GIS data) • Stakeholder-based input • Data from field sampling (own site-specific data) – primary sources • Available data – secondary sources
Skills required	• GIS software & skills • Skills in field ecology • Skills in stakeholder's involvement/ participatory processes
Outputs	• Spatial data • Qualitative outputs • Quantitative outputs • Economic valuation
Ecosystem services addressed	• Provisioning

	• Regulating • Cultural • Supporting
Purpose	• Modelling land use and/or climate change • Modelling / mapping ecosystem services flows & benefits • Comparison of scenarios / options • Identification of actions & strategies • Impact assessment • Visualizing ecosystem services • Economic valuation / cost effectiveness study • Communication & capacity-building

3.3 Results of Step 3: Classification of the selected ecosystem services assessment tools

Table 4 describes all ecosystem services assessment tools that meet the initial selection criteria outlined in Step 1 (Section 2.2), and describes these tools using the user-generated key tool characteristics outlined in Table 3 (Section 3.2).

Table 4: Description of ecosystem services assessment tools. (⏱ indicates that applying the tool typically takes days-weeks, ⏱⏱weeks-months and ⏱⏱⏱months-year; 'available data' refers to secondary data, which do not need to be collected specifically for the tool's application).

Tool	Input	Skills	Output	Ecosystem services	Purpose	Sources
A Geographic Information Systems-based LUC change model (GEOMOD) ⏱⏱	Spatial data; Available data	GIS	Spatial data; Quantitative data;	A-Supporting: biodiversity, water purification, soil formation; B- Regulating: climate and water regulation, erosion control, moderation of extreme events; C-Provisioning: food & fibre, raw materials; D-Cultural: recreation, cultural diversity.	Modelling land use and/or climate change;	Estoque & Murayama, 2012
ARIES Artificial Intelligence for Ecosystem Services ⏱/ ⏱⏱	Spatial data; Available data	GIS	Spatial data; Quantitative data; Qualitative data: Economic valuation	A-Supporting: water supply; B-Regulating: carbon sequestration and storage, flood regulation, nutrient regulation, sediment regulation; C-Provisioning: subsistence fisheries; D-Cultural: open space proximity, aesthetic viewsheds, recreation	Modelling / mapping ecosystem services flows & benefits; Comparison of scenarios / options;	Bagstad *et al*., 2013; Villa *et al*., 2014
CLIMSAVE Integrated Assessment (IA) Platform ⏱⏱	Available data		Spatial data; Quantitative data; Qualitative data	A-Supporting: /; B-Regulating: climate regulation, flood regulation, water flow regulation, pollination; C-Provisioning: food, fresh water, raw materials; D-Cultural: /	Impact assessment; Identification of actions & strategies; Economic valuation / cost effectiveness study;	Harrison *et al.* 2015
Co$ting Nature ⏱	Available data	GIS, Field ecology	Spatial data; Quantitative data; Qualitative data	A-Supporting: biodiversity, total carbon; B-Regulating: water quantity and quality, hazard mitigation; D-Cultural: recreation	Modelling / mapping ecosystem services flows & benefits; Identification of actions & strategies; Impact assessment;	Co$ting Nature, 2018

Tool	Input	Skills	Output	Ecosystem services	Purpose	Sources
Ecosystem Services Review ⏱⏱⏱	Stakeholder-based input; Available data	Stakeholder involvement	Qualitative data	All	Identification of actions & strategies; Economic valuation / cost effectiveness study;	Hanson *et al.* 2012.
Ecosystem Services Review for Impact Assessment ⏱⏱	Stakeholder-based input	Stakeholder involvement; Field ecology	Qualitative data	All	Impact assessment; Comparison of scenarios / options; Identification of actions & strategies;	Landsberg *et al.* 2014; Landsberg *et al.* 2011
ESP-VT Ecosystem Services Partnership Visualization Tool ⏱	/ (visualization tool)	GIS	Spatial data; Quantitative data; Economic valuation	All	Visualizing ES	Drakou *et al.* 2015
Green Infrastructure Valuation Toolkit ⏱⏱	Spatial data; Stakeholder-based input; Field sampling; Available data		Quantitative data; Quantitative data; Economic valuation	A-Supporting: biodiversity, land management; B-Regulating: climate change adaptation and mitigation, water and flow management; C-Provisioning: investment, labour productivity	Comparison of project options; Modelling land use and/or climate change; Economic valuation / cost effectiveness study;	Natural Economy Northwest *et al.* 2010
Interdisciplinary Decision Support Dashboard (IDSD) ⏱⏱	Spatial data, Stakeholder-based input; Available data; Field sampling		Spatial data; Quantitative data; Qualitative data	A-Supporting: landscape structure and composition, soil nutrient balance, soil organic matter, carbon stocks, climate; B-Regulating: water availability; C-provisioning: fuel wood availability, variability in livelihood	Modelling / mapping ecosystem services flows & benefits; Comparison of scenarios / options;	Fegraus *et al.* 2012.

Tool	Input	Skills	Output	Ecosystem services	Purpose	Sources
InVEST Integrated Valuation of Ecosystem Services and Tradeoffs ⏱⏱⏱	Spatial data; Stakeholder-based input; Available data	GIS, Stakeholder involvement	Spatial data; Quantitative data; Economic valuation	A-Supporting: habitat quality, water purification; B-Regulating: crop pollination, climate regulation, coastal protection, marine water quality, habitat risk assessment; C-Provisioning: timber production, energy production, aquaculture production; D-Cultural: scenic quality, nature-based recreation and tourism	Modelling / mapping ecosystem services flows & benefits; Comparing scenarios; Impact assessment; Economic valuation / cost effectiveness study	Tallis, 2013
i-Tree Eco. Tools for assessing and managing forests & community trees ⏱⏱	Available data; Field sampling	GIS, Field ecology	Quantitative data; Spatial data	All	Comparison of scenarios / options; Communication & capacity-building; Identification of actions & strategies	USDA, 2015
MARXAN and MARXAN with zones ⏱⏱⏱	Spatial data; Field sampling; Available data; Stakeholder-based input	GIS, Field ecology	Spatial data; Quantitative data; Qualitative data	Any ES that can be modelled spatially	Economic valuation / cost effectiveness study; Comparison of scenarios / options; Modelling / mapping ecosystem services flows & benefits;	Ball *et al.,* 2009.

Tool	Input	Skills	Output	Ecosystem services	Purpose	Sources
PA-BAT The Protected Areas Benefits Assessment Tool ⏱ → ⏱⏱	Stakeholder-based input	Stakeholder involvement	Qualitative data; Economic valuation	All	Modelling / mapping ecosystem services flows & benefits; Economic valuation / cost effectiveness study	Dudley & Stolton, 2009
Simulation of Terrestrial Environments (SITE) ⏱ → ⏱⏱	Spatial data; Stakeholder-based input; Field sampling; Available data	Stakeholder involvement	Spatial data; Quantitative data; Qualitative data	Potentially all	Comparison of scenarios / options; Impact assessment	Helmholtz Centre for Environmental Research-UF, 2018
Social values for ecosystem services (SolVES) ⏱⏱	Spatial data; Stakeholder-based input	GIS; Stakeholder involvement	Spatial data; Quantitative data; Qualitative data	A-Supporting: habitats for species, biodiversity; B-Regulating: /; C-Provisioning: /; D-Cultural: aesthetic inspiration for culture, spiritual experience and identity, tourism, recreation.	Modelling / mapping ecosystem services flows & benefits; Economic valuation / cost effectiveness study; Communication & capacity-building	Sherrouse & Semmens 2015
Soil Water and Assessment Tool (SWAT) ⏱⏱ → ⏱⏱⏱	Spatial data; Available data; Field sampling	GIS	Spatial data; Quantitative data; Qualitative data	A-Supporting: …; B-Regulating: water quality, soil erosion, carbon stock, flood regulation, etc.; C-Provisioning: water yield, crop yield, vegetation biomass, etc.; D-Cultural:/	Modelling land use and/or climate change; Impact assessment;	Duku *et al.* 2015.
Toolkit for Ecosystem Service Site-based Assessment (TESSA) ⏱ → ⏱⏱	Stakeholder-based input; Available data; Field sampling	Stakeholder involvement	Quantitative data; Qualitative data; Economic valuation	A-Supporting: /; B-Regulating: climate regulation, flood protection, water quality improvement; C-Provisioning: harvested wild and cultivated goods, water provision; D-Cultural: nature-based recreation	Comparison of scenarios / options; Economic valuation / cost effectiveness study	Peh *et al.* 2013

3.4 Visual representation of the ecosystem services assessment tools

While Table 4 provides a detailed schematic description of every ecosystem services assessment tool, Figure 2-5 provide a visualization of the inputs, outputs, required skills and addressed ecosystem services for each tool (the 'components' of each lens are in line with Table 3). The full names of the tools can be found in Table 4. This visual representation allows prospective tool users to quickly select which tool suits their needs and capacities best. Moreover, it allows to select tools based on different perspectives (*e.g.* based on available input data, on desired outputs *etc.*). As can be seen in the Figures, some tools require a combination of data types, and multiple skills, while other tools can be applied with a more limited range of skills and/or data. Future tool users can select the most adequate tool according to their expectations, data availabilities and available capacity. The tools are placed in their respective Venn-diagrams based on the descriptions and reports of applications of the tools. Figures 2-5 are simplified representations of some key characteristics of the tools (*e.g.* some quantitative output tools can allow for –some- economic valuation too), and/or tools can of course be combined.

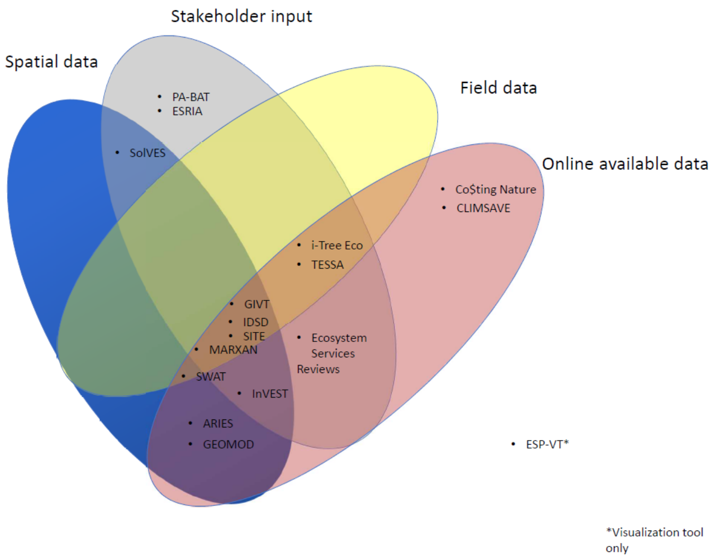

Figure 2: Overview of ecosystem services assessment tools based on required input data ***(online available data refers to secondary data, which have already been collected prior to the application of the tool)***

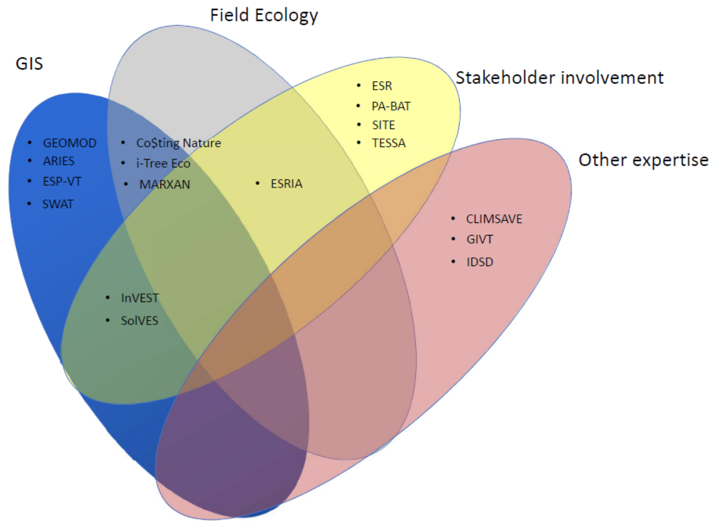

Figure 3: Overview of ecosystem services assessment tools based on required skills

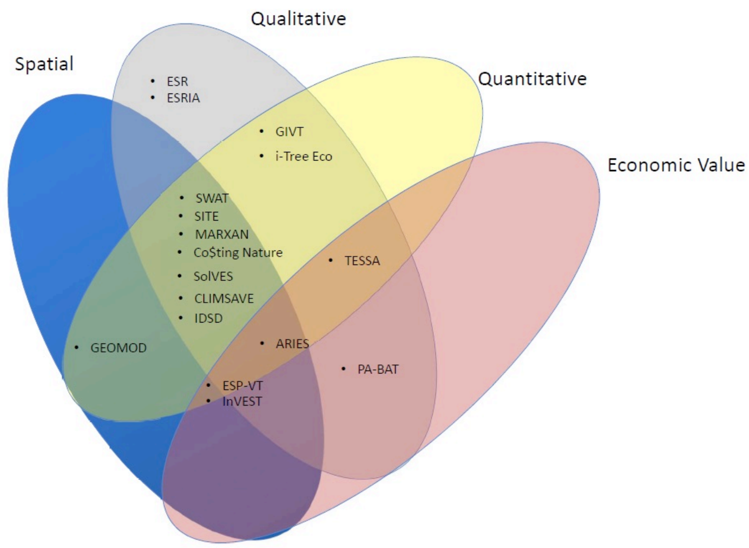

Figure 4: Overview of ecosystem services assessment tools based on generated output data

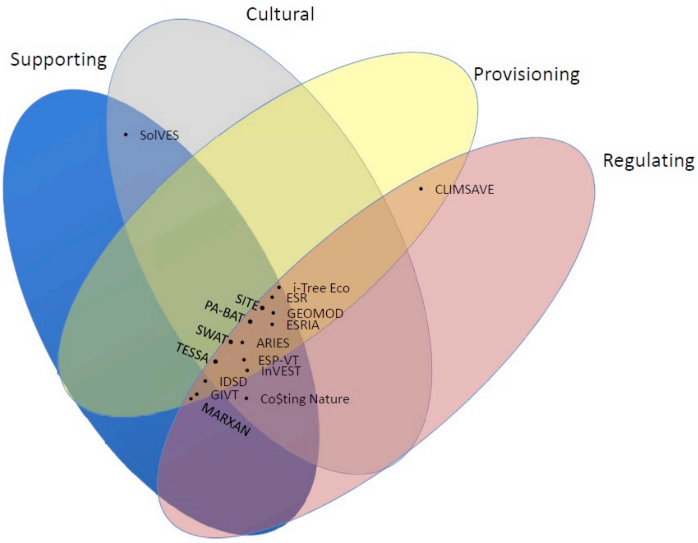

Figure 5: Overview of ecosystem services assessment tools based on ecosystem services addressed

4. Discussion

4.1 The methodological challenge of selecting suitable ecosystem services assessment tools

The potential impact one can have on decision-making by adopting and translating the concept of ecosystem services has triggered high expectations among scientists and managers since the concept was popularized in 2005. This has led to the development of a wide range of tools that have as stated aims the translation, visualization and 'easy' communication of the inherently complex processes that drive the provision, use and management of ecosystem services. Faced with real-world constraints such as limited time, limited financial resources and limited capacity, scientists, reserve managers and decision-makers constantly need to make trade-offs regarding which tool to use to assess and map ecosystem services. While other authors have proposed categorizations and criteria to select the most appropriate ecosystem services assessment tools (*e.g.* Bagstad *et al.*, 2013; Pandeya *et al.,* 2016, Grêt-Regamey *et al.*, 2017; IUCN, 2018), the tool evaluation approach and the choice architecture we propose in this current study is based on the systematic identification of user preferences, for which we used the Delphi method. However, while useful to elicit knowledge and preferences, the Delphi method cannot be used as the only source of information to develop criteria for tool selection. The participants' backgrounds introduce some subjectivity, as all were AfriMAB meeting attendants and hence have a stated interest and a deep knowledge of the challenges of managing Biosphere Reserves. Furthermore, in Delphi, the anonymity of respondents may introduce a lack of accountability; and a Delphi should ideally be combined with quantitative data collection to assess the representativeness of some opinions. The Delphi method allows to collect both the individual and the collective intelligence of the participants, and is suited in situations where there is a lack of established facts and when a consensus needs to be found on complex issues. The number of participants (n=22) that completed the two Delphi rounds is within the range of other Delphi studies (between 8 and 46 participants (Mukherjee *et al.*, 2015)). To obtain a more comprehensive picture of the different stakeholders' expectations regarding ecosystem services assessment tools, ideally a larger number of potential users should be contacted. It is also striking that no AfriMAB attendants from the NGO or private sector replied to the survey – however this could be explained by their very low numbers at the meeting. In order to harness the power of live group discussions while simultaneously ensuring that tool quality criteria can be prioritized, a series of Nominal Group Technique-applications and follow-up Delphis could be useful in the future. Furthermore, given the diversity of direct and indirect beneficiaries of ecosystem services provided by African Biosphere Reserves, the pool of indirect tool users (or at least of people whose lives can be impacted by the uptake of the findings of the proposed tools) should be widened, and they should ideally be included in tool selection processes.

When evaluating a range of tools (n=17), one is unavoidably confronted by the challenges of presenting dense information in a user-friendly yet systematic way. While tables outlining the characteristics of tools are a common presentation format (*e.g.* in Bagstad *et al.*, 2013, Pandeya *et al.*, 2016; IUCN, 2018), arrows depicting successive (ever more in-depth) steps in the process of ecosystem services assessment (as in Bagstad *et al.*, 2013) are also used. Every tool classification system also emphasizes different aspects of the tools, depending on the scope of the analysis and the preferences of the authors: Pandeya *et al.* (2016) classify tools based on their valuation approaches; Grêt-Regamey *et al.* (2017) classify tools based on their spatial scales, while IUCN classifies tools (among others) based on the underlying reasons to measure ecosystem services (*e.g.* private sector engagement, funding and investment, knowledge generation).

In this study we have avoided the use of a decision-tree to guide users to the most suited tool (contrary to *e.g.* IUCN (2018)), and instead provide four 'lenses' to select a tool in our visualization (Figures 2-5), allowing prospective tool users to base their selection on the required input data, the expected output, the required skills and/or the types of ecosystem services addressed by the tool. In Table 4, the overall purpose of each tool is added, as are the time requirements. In doing so we chose not to pre-empt the selection process of the users.

Inevitably, making choices regarding which criteria are deemed most relevant and useful to select a tool involves a reduction of all possible criteria that are found in the literature. The user expectations guided the selection of criteria, while existing literature provided fine-tuning.

The lack of coordination between tool developers and practitioners is an enduring problem, already identified by Bagstad *et al.* (2013), which is however hard to avoid due to the innovative, open-source character of many tools. A pragmatic approach to ecosystem services assessment tools ideally requires a search for synergies between external and local learning objectives and hence may require the combination of different (part of) tools (Van Noordwijk *et al.*, 2013). For example, combining field data with existing environmental datasets improves the quality of ecosystem services maps (Martinez-Harms *et al.*, 2016). For example, the TESSA-tool's preliminary scoping appraisal could be used to get a general overview of ecosystem services state and trends, by convening a number of participatory workshops. The TESSA-workshops typically yield a list of priority ecosystem services. The dynamics of these priority ecosystem services could then be modelled using, e.g. the InVEST tool, while PA-BAT could be applied to estimate their economic value. ESP-VT could be applied to visualize the ecosystem services findings, which would facilitate communication to a wider public. A flexible yet informed, cherry-picking approach to tools application can be justified by data requirements, data availabilities and by the urgency to present decision-makers with ecosystem services information in a timely manner.

4.2 The African Biosphere Reserve context

While ecosystem services assessment tools can in theory be used everywhere, many tools come with restrictions that cannot easily be ignored. The challenges of African Biosphere Reserves, as identified by the Delphi respondents (see Section 3.2.2) highlight lack of human and data resources. While these user-identified management challenges do not provide completely new information (e.g. compared to German Agency for Nature Conservation (2011)), the consensus levels indicate the priorities of the respondents. As suggested by Kratzer & Ammering (2019), Biosphere Reserves may provide the institutional framework for rural social innovations – which could address some of the identified management challenges. Some ecosystem services assessment tools require input of existing datasets which may be incomplete, reflecting the geographic bias in ecological research and the comparative neglect of Africa (DiMarco *et al*., 2017), and/or reflecting the lack of centralized and accessible data repositories, despite the ongoing efforts of among others, the Clearing House Mechanism (CHM) of the Convention of Biological Diversity. Some tools may require skills that are not widely distributed in the rural areas of Africa, where most of the African Biosphere Reserves are located. Especially ground truthing, the economic valuation of biodiversity and the application of modern technologies in biodiversity monitoring are lacking in the global South (Vanhove *et al*., 2017). Some tools were initially developed with a non-African context in mind (such as CLIMSAVE with its European focus or the i-Tree-Eco set of tools, which have a USA-focus). This does not necessarily mean these tools are not applicable in an African context, however data availability may be an obstacle. The IDSD-tool on the other hand, has been developed with a Tanzanian context in mind (Fegraus *et al*., 2012).

Next to the specific data and capacity challenges, the direct dependence of many stakeholders on ecosystem services provided by Biosphere Reserves highlights the need to explicitly acknowledge the perceptions of ecosystem services' providers and beneficiaries (Pandeya *et al.,* 2016), and to measure and monitor stakeholders' expectations and perceptions about ecosystem services use and trends. This is especially relevant in a context of increasing human pressure in and around African Biosphere Reserves as identified by the Delphi respondents. A tool like SOLVES focuses specifically on stakeholder perceptions of non-monetary values ascribed to particular ecosystem services, the so-called social values of ecosystems. In total seven of the seventeen tools do require stakeholder engagement skills (see Figure 3) and hence take into account stakeholders' perceptions. The RESPA-tool (which lies outside the scope of this review) assesses stakeholders' familiarity with ecosystem services and their relative importance to them (Rey-Valette *et al*., 2017). While locals, often have context-specific knowledge of ecosystem services that is easily missed by modelling tools, their input and hence often long-term (informal) managers of ecosystem services is also essential to develop collaborative, socially robust solutions with large buy-in. This is an essential element of inclusive conservation, which encompasses different motivations for conservation, ranging from the intrinsic to the instrumental (Tallis & Lubchenco, 2014; Chan *et al*., 2016). Given the exemplary function of African Biosphere Reserves as 'living labs' where inclusive sustainable development can be realized, any ecosystem services assessment tool that is used within this context should ideally be able to encompass the diversity of views on nature and its management. This de-polarizing approach to conservation and natural resource management is of utmost importance in the African context, where governance challenges remain pervasive, and where the threat of the militarisation of conservation is real (Duffy *et al*., 2019).

4.3 From applying tools to influencing decision-making

Applying carefully selected ecosystem services assessment tools based on a user's set of expectations is a first step, yet the ultimate objective is to have an impact on actual decisions, *e.g.* decisions related to the management of a Biosphere Reserve. Bridging the gap between science and policy by linking nature and human wellbeing is the stated aim of the ecosystem services concept (see *e.g.* Mace, 2014). This requires tool outputs that are easily communicated to decision-makers, and a capacity of decision-makers to take up and engage with these outputs. Decision-makers typically prefer a variety of ecosystem services metrics (Ruckelshaus *et al*., 2015), which may require the use of tools producing multiple outputs, or the combination of complementary tools (see also

Section 4.1). In order to be useful to decision-makers, tools must be customizable (Martinez-Lopez *et al.*, 2019) and must foster innovation. Experimentation (*e.g.* using modules originating from different tools) needs to be encouraged, hence the importance of freely available tools and supporting datasets. Training is required both at the data production side (scientists, managers, consultants applying the tools) and at the data uptake and translation side (decision-makers, managers). Transparent communication about the motivations underlying methodological choices is essential. Communicating uncertainty is key in order to ensure the credibility of rapid ecosystem services assessment tools and in order to allow for informed and flexible management trade-offs by decision-makers. However, Grêt-Regamey *et al.* (2017) state that almost half the tools their team reviewed do not quantify these uncertainties. The lack of maintenance and long-term availability of some tools and their online support is a risk, and a consequence of the often time-limited project-based funding of such tools. Uptake and institutionalization of these tools, for example by networks such as AfriMAB could contribute to solve this issue.

While most tools reviewed in this study have been extensively applied in the field, not all have been applied in Biosphere Reserves, and not all applications have been subject to scientific scrutiny. The INVEST tool applications have been reviewed by Ruckelshaus *et al.* (2015) and have had impact at different decision-making levels. The TESSA tool application for the Shivapuri-Nagarjun National Park in Nepal yielded estimates of avoided monetary loss thanks to conservation (Peh *et al.,* 2016). In order to evaluate the range of impacts ecosystem services assessment tools can have on decision-making on the short- and the long-term, a more comprehensive model of tool effectiveness needs to be kept in mind, focusing on their substantial impact on well-defined decisions, as well as on their less directly measurable normative impact (*e.g.* tools fostering social learning and changing mind-sets) (Hugé *et al.,* 2015). This requires tools that are suitable to incorporate stakeholders' perspectives on ecosystem services use, trends and management. Such tools ideally include accessible and graphic data collection methods (rich pictures, participatory mapping), and can also include serious games (Merlet *et al.*, 2018). An increased awareness of the diversity of existing tools and guidance for prospective tool users will increase the number of applications of such tools and will consequently increase our understanding of their impact.

5. Conclusion

The diverse and dynamic landscape of ecosystem services assessment tools reflects the diversity of representations of the relationship between people and nature. Ecosystem services assessment tools typically start from a range of assumptions about what is important, what is measurable and what is urgent to address – and these assumptions differ between the teams developing the tools. This situation creates a rich landscape of tools in which potential tool users may find it difficult to navigate. The difficult trade-off between simple and complex approaches to ecosystem services assessment should not lead to inaction, as the diversity of tools and their respective strengths and coverage offer opportunities for users with different expectations to find the most suitable tool, while also providing inspiration for users aiming at developing new tools.

In this study, we presented a classification of ecosystem services assessment tools that are adapted to the context of African Biosphere Reserves, based on a combination of literature review and an iterative user survey. We proposed two 'tools to select tools': a Table and a series of visualizations which highlight the main components of a range of ecosystem services assessment tools (input data, output data, skills required, ecosystem services addressed covered, time constraints and purpose). There is no one-size-fits-all approach to ecosystem services assessment tools, and the resource-constrained context of African Biosphere Reserves creates extra challenges that will influence the tool selection process. Tools are not applied in a governance vacuum. Hence the impact of the application of such tools should not only be measured based on their technical quality, but also on their short- and long-term impact on actual decision-making – *i.e.* on the management of Biosphere Reserves. A range of tools that are discussed in this paper has been and/or is currently being applied within the frame of the EVAMAB project (http://www.biodiv.be/evamab), funded by the Belgian Scientific Policy (BELSPO) in collaboration with UNESCO. Given the strategic importance of African Biosphere Reserves as key sources of ecosystem services for a directly nature-dependent human population, and given the exemplarity of Biosphere Reserves as living labs for sustainable development, the sound selection and application of ecosystem services assessment tools takes on a particular urgency.

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Appendix 1

Longlist of ecosystem services assessment tools (compiled following the initial selection criteria in Section 2.2), from which the shortlist of tools suitable for African Biosphere Reserves was compiled (using the user-generated selection criteria in Section 2.3). The selected tools, which are further discussed in Section 3.3, are indicated with a * in the Table below.

#	Name	Source	Selected (indicated with *)
1	**Simulation of Terrestrial Environments (SITE)**	Helmholtz Centre for Environmental Research-UF, Leipzig. http://www.ufz.de/index.php?en=37508	*
2	**Green Infrastructure Valuation Toolkit**	Natural Economy Northwest, CABE, Natural England, Yorkshire Forward, The Northern Way, Design for London, Defra, Tees Valley Unlimited, Pleasington Consulting Ltd, and Genecon LLP. 2010. Building natural value for sustainable economic development: Green Infrastructure Valuation Toolkit. Version 1.4 (updated in 2016). http://bit.ly/givaluationtoolkit	*
3	**i-Tree Eco. Tools for assessing and managing forests & community trees**	USDA. 2015. i-TreeEco. Retrieved in August 2015. Available at http://www.itreetools.org/ eco/.	*
4	**ESP-VT Ecosystem Services Partnership Visualization Tool**	Drakou, E.G., Crossman, N.D., Willemen, L., Burkkhard, B., Palomo, I., Maes, J., Peedell, S. 2015. A visualization and data-sharing tool for ecosystem service maps: Lessons learnt, challenges and the way forward. Ecosystem Services 13 (2015) 134-140. Coordinated and hosted by the Joint Research Centre of the European Commission (JRC-EC).	*
5	**MARXAN and MARXAN with zones**	Ball, I.R., H.P. Possingham, and M. Watts. 2009. Marxan and relatives: Software for spatial conservation prioritisation. Chapter 14: Pages 185-195 in spatial conservation prioritisation: Quantitative methods and computational tools. Eds Moilanen, A., K.A. Wilson, and H.P. Possingham. Oxford University Press, Oxford, UK. Watts, M.E. 2016. marxan.io: A web app for systematic conservation planning. Revision 46.	*

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6	**PA-BAT The Protected Areas Benefits Assessment Tool**	Dudley, N. & Stolton, S. 2009: The Protected Areas Benefits Assessment Tool. A methodology, WWF – World Wide Fund for Nature, Gland. Revision done in 2012	*
7	Scoping ES for Impact Assessment (WRI)	Landsberg, F., Treweek, J., Stickler, M.M., Henninger, N. & Venn, O. 2014. Weaving ecosystem services into impact assessment. A step-by-step method. World Resources Institute. Landsberg, F., S. Ozment, M. Stickler, N. Henninger, J. Treweek, O. Venn, and G. Mock. 2011. Ecosystem Services Review for Impact Assessment: Introduction and Guide to Scoping. WRI Working Paper. World Resources Institute, Washington DC.	
8	EcoServ-GIS	Winn, J.P., Bellamy, C. C., and Fisher, T. 2015. EcoServ GIS User Guide: EcoServ-GIS Version 3.3 (Great Britain): A toolkit for mapping ecosystem services. User Guide. The Wildlife Trusts. Bellamy, C. C., Winn, J.P., and Fisher, T. 2014. "EcoServ-GIS Version 2 (England only): A Wildlife Trust toolkit for mapping multiple ecosystem services. User Guide (Document Version 2.1, April 2014)", Durham Wildlife Trust.	
9	EnviroAtlas	Pickard, B.R., Daniel, J., Mehaffey, M., Jackson, L.E. & Neale, A. 2015. EnviroAtlas: A new geospatial tool to foster ecosystem services science and resource management. Ecosystem Services 14 (2015) 45-55. Developed by the United States Environmental Protection Agency (US EPA)	.
10	A soil-plant-atmosphere system dynamic model (DAISY)	Abrahamse, P. & Hansen, S. 2000. Daisy: an open soil-crop-atmosphere system model. Environmental modelling & software 15: 313-330.B9. Ghaley, B.B. & Porter, J.R. 2014. Ecosystem function and service quantification and valuation in a conventional winter wheat production system with DAISY model in Denmark. Ecosystem Services, 10, 79–83. http://daisy.ku.dk/download/	
11	Coastal Resilience Mapping Portal	The Nature Conservancy. http://coastalresilience.org/natural-solutions/	

#	Name	Source	Selected (indicated with *)
12	Guide to Corporate Ecosystem Valuation (CEV). A framework for improving corporate decision-making.	The World Business Council for Sustainable Development http://www.wbcsd.org/Clusters/Ecosystems-Landscape-Management/Resources/Guide-to-Corporate-Ecosystem-Valuation	.
13	GUMBO Global Unified Metamodel of the Biosphere	Boumans et al. 2000. Modelling the dynamics of the integrated earth system and the value of global ecosystem services using the GUMBO model. Ecological Economics 2000. Article in Press. http://www.uvm.edu/giee/?Page=research.html&SM=researchsubmenu.html	
14	EwE Ecopath with Ecosim	University of British Columbia's Fishery Centre. http://ecopath.org/	
15	DOPA Digital Observatory for Protected Areas	http://dopa.jrc.ec.europa.eu/en/documentation	
16	Biocarbon tracker	https://ecometrica.com/article/biocarbon-tracker	
17	Capturing Coral Reef ES (CCRES)	World Bank. http://ccres.net/	
18	Sim4Tree Decision Support System (DSS)	Dalemans, F., Jacxsens, P., Van Orshoven, J., Kint, V., Moonen, P. & Muys, B. 2015. Assisting sustainable forest management and forest policy planning with the Sim4Tree Decision Support System. Forests, 6, 859–878.	
19	Buffers Decision Support System (DSS). Not more information available: prototype.	Deeks, L.K., Duzant, J.H., Owens, P.N. & Wood, G.A. 2012. A decision support framework for effective design and placement of vegetated buffer strips within agricultural field systems. Advances in Agronomy, 114, 225–248.	
20	**Soil Water and Assessment Tool (SWAT)**	Duku, C., Rathjens, H., Zwart, S.J. & Hein, L. 2015. Towards ecosystem accounting: a comprehensive approach to modelling multiple hydrological ecosystem services. Hydrology and Earth System Sciences, 19, 4377–4396.	*
21	**A Geographic Information Systems-**	Estoque, R.C. & Murayama, Y. 2012. Examining the potential impact of land use/cover changes on the ecosystem services of Baguio city, the Philippines: A scenario-based analysis. Applied Geography, 35, 316–326.	*

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	based LUC change model (GEOMOD)		
22	**Interdisciplinary Decision Support Dashboard**	Fegraus, E.H., Zaslavsky, I., Whitenack, T., Dempewolf, J., Ahumada, J.A., Lin, K. & Andelman, S.J. 2012. Interdisciplinary Decision Support Dashboard: A New Framework for a Tanzanian Agricultural and Ecosystem Service Monitoring System Pilot. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 5(6), 1700–1708.	*
23	Online Wetland Ecosystem Services Model Prototype	Feng, M., Liu, S., Euliss, N.H., Young, C. & Mushet, D.M. 2011. Prototyping an online wetland ecosystem services model using open model sharing standards. Environmental Modelling & Software, 26, 458–468.	
24	Pimp Your Landscape (PYL)	Fürst, C., Volk, .M, Pietzsch, K. & Makeschin, F. 2010. Pimp Your Landscape: A Tool for Qualitative Evaluation of the Effects of Regional Planning Measures on Ecosystem Services. Environmental Management, 46, 953–968.	
25	**CLIMSAVE Integrated Assessment (IA) Platform.**	Harrison, P.A., Holman, I.P. & Berry, P.M. 2015. Assessing cross-sectorial climate change impacts, vulnerability and adaptation: an introduction to the CLIMSAVE project. Climatic Change, 128, 153–167.	*
26	A Virtual Laboratory for Ecosystem Services (ESLab)	Holmberg, M., Akujärvi, A., Anttila, S., Arvola, L., Bergström, I., Böttcher, K., Feng, X., et.al. 2015. ESLab application to a boreal watershed in southern Finland: preparing for a virtual research environment of ecosystem services. Landscape Ecology, 30, 561–577.	
27	Spatial assessment and optimization tool for regional ecosystem services (SAORES)	Hu, H., Fu, B., Lü, Y. & Zheng, Z. 2015. SAORES: a spatially explicit assessment and optimization tool for regional ecosystem services. Landscape Ecology, 30, 547–560.	
28	CITYgreen	Jantz, C.A. & Manuel, J.J. 2013. Estimating impacts of population growth and land use policy on ecosystem services: A community-level case study in Virginia, USA. Ecosystem Services, 5, e110-e123.	

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29	An Ecosystem Portfolio Model (EPM)	Labiosa, W.B., Forney, W.M., Esnard, A.-M., Mitsova-Boneva, D. Bernknopf, R., Hearn, P., Hogan, D. et.al. 2013. An integrated multi-criteria scenario evaluation web tool for participatory land-use planning in urbanized areas: The Ecosystem Portfolio Model. Environmental Modelling & Software, 41, 210–222.	
30	Probabilistic Map Algebra Tool (PMAT)	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. Environmental Modelling & Software, 71, 30–38.	
31	The Tool for Sustainability Impact Assessment (ToSIA)	Lindner, M., Werhahn-Mees, W., Suominen, T., Vötter, D., Zudin, S., Pekkanen, M., Päivinen, R. et.al. 2012. Conducting sustainability impact assessments of forestry-wood chains: examples of ToSIA applications. European Journal of Forest Research, 131, 21–34.	
32	Letsmap do Brasil	Lorz, C., Neumann, C., Bakker, F., Pietzsch, K., Weiss, H. & Makeschin, F. 2013. A web-based planning support tool for sediment management in a meso-scale river basin in Western Central Brazil. Journal of Environmental Management, 127, S15-S23.	
33	The ecosystem services module (ESTIMAP) of the European Land Use based Integrated Sustainability Assessment platform (LUISA)	Maes, J., Barbosa, A., Baranzelli, C., Zulian, G., Batista e Silva, F., Vandecasteele, I., Hiederer, R. et.al. 2015. More green infrastructure is required to maintain ecosystem services under current trends in land-use change in Europe. Landscape Ecology, 30, 517–534.	
34	A Spatial Decision Support System (SDSS) for landscape evaluation	Pechanec, V., Brus, J., Kilianová H. & Machar, I. 2015. Decision support tool for the evaluation of landscapes. Ecological Informatics, 30, 305–308.	

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35	Gulf of Mexico Ecosystem Service Valuation Database (GecoServ)	Plantier-Santos, C., Carollo, C. & Yoskowitz, D.W. 2012. Gulf of Mexico Ecosystem Service Valuation Database (GecoServ): Gathering ecosystem services valuation studies to promote their inclusion in the decision-making process. Marine Policy, 36, 214–217.	
36	VDDT© (Vegetation Dynamics Development Tool)/ TELSA© (Tool for Exploratory Landscape Analysis) software suite (+ Data Basin online collaboration tool)	Price, J., Silbernagel, J., Miller, N., Swaty, R., White, M. & Nixon, K. 2012. Eliciting expert knowledge to inform landscape modelling of conservation scenarios. Ecological Modelling, 229, 76–87.	
37	Forest landscape model (LANDIS 4.0)	Shang, Z., He, H.S., Xi, W., Shifley, S.R. & Palik, B.J. 2012. Integrating LANDIS model and a multi-criteria decision-making approach to evaluate cumulative effects of forest management in the Missouri Ozarks, USA. Ecological Modelling, 229, 50–63.	
38	Cropping system model (CropSyst)	Stöckle, C.O., Kemanian, A.R., Nelson, R.L., Adam, J.C., Sommer, R. & Carlson, B. 2014. CropSyst model evolution: From field to regional to global scales and from research to decision support systems. Environmental Modelling and Software, 62, 361–369.	
39	Water Supply Stress Index (WaSSI) model	Sun, S., Sun, G., Caldwell, P., Mcnulty, S.G., 2015. Drought impacts on ecosystem functions of the U.S. National Forests and Grasslands: Part I evaluation of a water and carbon balance model. Forest Ecology and Management, 353, 260–268.	
40	SOILCONSWEB-GCI platform http://www.landconsultingweb.eu/EN_index.html	Terribile, F., Agrillo, A., Bonfante, A., Buscemi, G., Colandrea, M., D'antonio, A., De Mascellis, R. et.al. 2015. A Web-based spatial decision supporting system for land management and soil conservation. Solid Earth, 6, 903–928.	

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41	Ecosystem services assessment tool for agroforestry (ESAT-A)	Tsonkova, P., Quinkenstein, A., Böhm, C., Freese, D. & Schaller, E. 2014. Ecosystem services assessment tool for agroforestry (ESAT-A): An approach to assess selected ecosystem services provided by alley cropping systems. Ecological Indicators, 45, 285–299.	
42	Interactive model-based spatial information and support system (LandCaRe DSS)	Wenkel, K.-O., Berg, M., Mirschel, W., Wieland, R., Nendel, C. & Köstner, B. 2013. LandCaRe DSS - An interactive decision support system for climate change impact assessment and the analysis of potential agricultural land use adaptation strategies. Journal of Environmental Management, 127, S168-S183.	.
43	A web-based visualization platform	Wissen Hayek, U., Teich, M., Klein, T.M. & Grêt-Regamey, A. 2016. Bringing ecosystem services indicators into spatial planning practice: Lessons from collaborative development of a web-based visualization platform. Ecological Indicators, 61, 90–99.	
44	Decision-support system for heterogeneous multi-criteria multi-expert decision-making (MCMEDSS)	Zagonari, F. & Rossi, C. 2013. A heterogeneous multi-criteria multi-expert decision-support system for scoring combinations of flood mitigation and recovery options. Environmental Modelling & Software, 49, 152–165.	
45	**TESSA**	Peh, K.S.-H., Balmford, A., Bradbury, R.B., Brown, C., Butchart, S.H.M., Hughes, F.M.R., Stattersfield, A., Thomas, D.H.L., Walpole, M., Bayliss, J., Gowing, D., Jones, J.P.G., Lewis, S.L., Mulligan, M., Pandeya, B., Stratford, C., Thompson, J.R., Turner, K., Vira, B., Willcock, S., Birch, J.C., 2013. TESSA: A toolkit for rapid assessment of ecosystem services at sites of biodiversity conservation importance. Ecosystem Services 5: 51–57	*
46	**SolVES (Social Values for Ecosystem Services)**	Sherrouse, B.C. & Semmens, D.J. 2015. Social values for ecosystem services, version 3.0 (SolVES 3.0)—Documentation and user manual: U.S. Geological Survey (USGS) Open-File Report 2015–1008.	*

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48	**Costing Nature**	Co$ting Nature, 2018 http://www.policysupport.org/costingnature. Last accessed March 1st, 2019.	*
49	**INVEST (Integrated Valuation of Ecosystem Services and Tradeoffs)**	Tallis H.T. 2013. InVEST tip User's Guide: Integrated Valuation of Environmental Services and Trade-offs. A modeling suite developed by the Natural Capital Project. www.naturalcapitalproject.org. Last accessed March 1st, 2019.	*
50	**Ecosystem Services Review**	Hanson, C., J. Ranganathan, C. Iceland, & Finisdore, J. 2012. *The Corporate Ecosystem Services Review: Guidelines for Identifying Business Risks and Opportunities Arising from Ecosystem Change*. Version 2.0. Washington, DC: World Resources Institute.	*
51	**Ecosystem Services Review for Impact Assessment**	Landsberg, F., S. Ozment, M. Stickler, N. Henninger, J. Treweek, O. Venn, and G. Mock 2011. *Ecosystem Services Review for Impact Assessment: Introduction and Guide to Scoping*. WRI Working Paper. World Resources Institute, Washington DC, USA & Landsberg, F., Treweek, J., Stickler, M.M., Henninger, N. & Venn, O. 2014. Weaving ecosystem services into impact assessment. A step-by-step method. World Resources Institute, Washington DC, USA.	*

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52	Our Ecosystem	Ingwall King, L. & Ivory, S. 2015. Report on Information tools for ES/NC data capture, storage, presentation and use/Trialling new and enhanced data capture, indicator-based and information tools within Exemplars. Report for the EU FP7 OPERAs project. Grant Agreement No 308393. http://www.operas-project.eu/sites/default/files/resources/ms4.15-updated-report-testing-information-tools-esnc.doc	
53	QuickSCAN	Verweij, P., Winograd, M., Perez-Soba, M., Knapen, R. & Van Randen, Y. 2012. QUICKScan: a pragmatic approach to decision support. In: R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.), International Environmental Modelling and Software Society (iEMSs) 2012 International Congress on Environmental Modelling and Software Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany. http://www.iemss.org/society/index.php/iemss-2012-proceedings.	
54	MIMES	Boumans, R., Roman, J., Altman, I. & Kaufman, L. 2015. The Multiscale Integrated Model of Ecosystem Services (MIMES): Simulating the interactions of coupled human and natural systems. Ecosystem Services 12: 30–41	
55	4S Tool	Kirilenko, A., Chivoiu, B., Crick, J., Ross-Davis, A., Schaaf, K., Shao, G., Singhania, V. & Swihart, R. 2007. An Internet-based decision support tool for non-industrial private forest landowners. Environmental Modelling & Software 22: 1498–1508	

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56	UBC-FM	Seely, B., Nelson, J., Wells, R., Peter, B., Meitner, M., Anderson, A., Harshaw, H., Sheppard, S., Bunnell, F.L., Kimmins, H. & Harrison, D. 2004. The application of a hierarchical, decision-support system to evaluate multi-objective forest management strategies: a case study in northeastern British Columbia, Canada. Forest Ecology and Management 199: 283–305	
57	DSD	Lexer, M.J., Vacik, H., Palmehetzhofer, D. & Oitzinger, G. 2005. A decision support tool to improve forestry extension services for small private landowners in southern Austria. Computers and Electronics in Agriculture 49: 81–102	
58	MONSU	Kangas, J., Store, R., Leskinen, P. & Mehtatalo, L. 2000. Improving the quality of landscape ecological forest planning by utilising advanced decision-support tools. Forest Ecology and Management 132: 157–171	
59	MGC_Larch_DSS	Pauwels, D., Lejeune, P. & Rondeux, J. 2007. A decision support system to simulate and compare silvicultural scenarios for pure even-aged larch stands. Annals of Forest Science 64: 345–353	
60	Forest Time Machine	Andersson, M., Dahlin, B. & Mossberg, M. 2005. The Forest Time Machine—a multi-purpose forest management decision-support system. Computers and Electronics in Agriculture 49: 114–128	

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61	Ned-2	Twery, M.J., Knopp, P.D., Thomasma, S.A., Rauscher, H.M., Nute, D.E., Potter, W.D., Maier, F. 2005. NED−2: A decision support system for integrated forest ecosystem management. Computers and Electronics in Agriculture 49: 24–43	
62	UFORE	Nowak, D.J., Crane, D.E., Stevens, J.C., Hoehn, R.E., Walton, J.T. & Bond, J. 2008. A Ground-Based Method of Assessing Urban Forest Structure and Ecosystem Services. Arboriculture & Urban Forestry 34: 347–358	
63	HEUREKA	Wikström, P., Edenius, L., Elfving, B., Eriksson, L.O., Lamas, T., Sonesson, J., Öhman, K. 2011. The HEUREKA forestry decision support system: An overview. Mathematical and Computational Forestry & Natural-Resource Sciences 3(2): 87–94	
64	SIMPPLLE	Chew, J.D., Stalling, C. & Moeller, K. 2004. Integrating knowledge for simulating vegetation change at landscape scales. Western Journal of Applied Forestry 19(2): 102–108	
65	FVS	Crookston, N.L. & Dixon, G.E. 2005. The forest vegetation simulator: A review of its structure, content, and applications. Computers and Electronics in Agriculture 49: 60–80	
66	BackES	Brunner, S.H., Huber, R. & Grêt-Regamey, A. 2016. A backcasting approach for matching regional ecosystem services supply and demand. Environmental Modelling & Software 75: 439–458	

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67	Visualization Platform	Wissen Hayek, U., Teich, M., Klein, T.M. & Grêt-Regamey, A. 2016. Bringing ecosystem services indicators into spatial planning practice: Lessons from collaborative development of a web-based visualization platform. Ecological Indicators 61: 90–99	
68	Polyscape (LUCI)	Jackson, B., Pagella, T., Sinclair, F., Orellana, B., Henshaw, A., Reynolds, B., McIntyre, N., Wheater, H. & Eycott, A. 2013. Polyscape: A GIS mapping framework providing efficient and spatially explicit landscape-scale valuation of multiple ecosystem services. Landscape and Urban Planning 112: 74–88	
69	Envision / EVOLAND	Guzy, M.R., Smith, C.L., Bolte, J.P., Hulse, D.W. & Gregory, S.V. 2008. Policy Research Using Agent-Based Modelling to Assess Future Impacts of Urban Expansion into Farmlands and Forests. Ecology and Society 13: 37	
70	Patuxent Landscape Model	Voinov, A., Costanza, R., Waigner, L., Boumans, R., Villa, F., Maxwell, T. & Voinov, H. 1999. Patuxent Landscape Model: Integrated Ecological Economic Modeling of a Watershed. Enviromental Modelling & Software 14: 473-491	
71	ReVegIH	McVicar, T.R., Ling Tao Li, Van Niel, T.G., Lu Zhang, Rui Li, Qin Ke Yang, Xiao Ping Zhang, Xing Min Mu, Zhong Ming Wen, Wen Zhao Liu, Yong An Zhao, Zhi Hong Liu & Peng Gao 2007. Developing a decision support tool for China's re-	

#	Name	Source	Selected (indicated with *)
		vegetation program: Simulating regional impacts of afforestation on average annual streamflow in the Loess Plateau. Forest Ecology & Management 251: 65-81	
72	mDSS	Mulino Decision Support System Tool. https://oppla.eu/product/2034	
73	EVALUWET	Janssen, R., Goossen, A., Verhoeven, M.L., Verhoeven, J., Omtzigt, A.Q.A & Maltby, E. 2005. Decision support for integrated wetland management. Environmental Modelling and Software 20: 215-229	
74	Elbe-DSS	Lautenbach, S., Berlekamp, J., Graf, N., Seppelt, R. & Matthies, M. 2009. Scenario Analysis and Management Options for Sustainable River Basin Management: Application of the Elbe DSS. Environmental Modelling and Software 24: 26-43	
75	Eco-Security Assessment DSS	Xiaodan, W., Xianghao, Z. & Pan, G. 2010. A GIS-based decision support system for regional eco-security assessment and its application on the Tibetan Plateau. Journal of Environmental Management 91: 1981-1990.	

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76	Benefit Transfer Toolkit	Loomis, J., Kroeger, T., Richardson, L. & Casey, F. 2008. Timm Kroeger, Leslie Richardson and Frank Casey1Benefit Transfer Toolkit for Fish, Wildlife, Wetlands, and Open Space. Western Economic Forum. https://core.ac.uk/download/pdf/6459622.pdf	
77	Ecological Economic Model	Higgins, S.I., Turpie, J.K., Costanza, R., Cowling, R.N., Le Maitre, D.C., Marais, C. & Midgley, G.F. 1997. An ecological-economic simulation model of mountain fynbos ecosystems: dynamics, valuation and management. Ecological Economics 22: 155-169	
78	ORO	North, E.W., King, D.M, XU, J., Hood, R.R., Newwell, R.I.E., Paynter, K., Kellogg, M.L, Liddel, M.K. & Boesch, F. 2010. Linking optimization and ecological models in a decision support tool for oyster restoration and management. Ecological Applications 20: 851-866	
79	DSS for coral reef management	Chang, Y.C., Hong, F.W. & Lee, M.T. 2008. A system dynamic based DSS for sustainable coral reef management in Kenting coastal zone, Taiwan. Ecological Modelling 211: 153-168	
80	CLAM	Ticehurst, J.L., Letcher, R.A. & Rissik, D. 2008. Integration modelling and decision support: A case study of the Coastal Lake Assessment and Management (CLAM) Tool. Mathematics & Computers in Simulation 78: 435-449	
81	MedAction PSS	Van Delden, H. 2007. Lessons learnt in the development, implementation and use of Integrated Spatial Decision Support Systems. 18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009. http://mssanz.org.au/modsim09	

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82	InFOREST	www.inforest.frec.vt.edu	
83	EcoAIM	Waage,S., Armstrong,K., Hwang,L., 2011.New Business Decision-Making Aids in An Era of Complexity, Scrutiny, and Uncertainty: Tools for Identifying, Assessing, and Valuing Ecosystem Services, BSR, SanFrancisco, California. Availablefrom: ⟨http://www.bsr.org/reports/BSR_ESTM_WG_Comp_ES_Tools_ Synthesis3.pdf⟩	
84	ESValue	Waage,S.,Armstrong,K.,Hwang,L.,2011. New Business Decision-Making Aids in An Era of Complexity, Scrutiny, and Uncertainty: Tools for Identifying, Asses- sing, and Valuing Ecosystem Services, BSR, SanFrancisco,California. Availablefrom: ⟨http://www.bsr.org/reports/BSR_ESTM_WG_Comp_ES_Tools_ Synthesis3.pdf⟩	
85	EcoMetrix	Parametrix, 2010. An Introduction to EcoMetrix: Measuring Change in Ecosystem Performance at the Site Scale. Parametrix, Portland, USA.	
86	NAIS	Troy,A.,Wilson,M.A.,2006.Mappingecosystemservices:practicalchallengesand opportunities inlinkingGISandvaluetransfer.EcologicalEconomics60, 435–449	

#	Name	Source	Selected (indicated with *)
87	Ecosystem Valuation Toolkit	http://www. esvaluation.org (Ecosystem Valuation Toolkit, 2012)	

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