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Assessing ecosystem services for informing land-use decisions: a problem-oriented approach

Johannes Förster [1,2,3], *Jan Barkmann* [4], *Roman Fricke* [5], *Stefan Hotes* [6], *Michael Kleyer* [7], *Susanne Kobbe* [8], *Daniel Kübler* [9], *Christian Rumbaur* [10], *Marianna Siegmund-Schultze* [11], *Ralf Seppelt* [1,3], *Josef Settele* [12,13], *Joachim H. Spangenberg* [12,14], *Vera Tekken* [15], *Tomáš Václavík* [1,16] and *Heidi Wittmer* [2]

ABSTRACT. Assessments of ecosystem services (ES), that aim at informing decisions on land management, are increasing in number around the globe. Despite selected success stories, evidence for ES information being used in decision making is weak, partly because ES assessments are found to fall short in targeting information needs by decision makers. To improve their applicability in practice, we compared existing concepts of ES assessments with focus on informing land use decisions and identified opportunities for enhancing the relevance of ES assessments for decision making. In a process of codesign, building on experience of four projects in Brazil, China, Madagascar, and Vietnam, we developed a step-wise approach for better targeting ES assessments toward information needs in land use decisions. Our problem-oriented approach aims at (1) structuring ES information according to land use problems identified by stakeholders, (2) targeting context-specific ES information needs by decision makers, and (3) assessing relevant management options. We demonstrate how our approach contributes to making ES assessments more policy relevant and enhances the application of ES assessments as a tool for decision support.

Key Words: *decision support; ecosystem services assessment; land use; problem-oriented;*

INTRODUCTION

Assessments of ecosystem services (ES) are increasing in number (Seppelt et al. 2011, Abson et al. 2014), but it is questioned whether they actually generate knowledge that is relevant for decision makers (Honey-Rosés and Pendleton 2013, Laurans et al. 2013, Martinez-Harms et al. 2015). The majority of ES assessments tend to generate knowledge on ecological functions and economic values (Abson et al. 2014) with little consideration of the information demand by decision makers for addressing a particular land-use problem (Honey-Rosés and Pendleton 2013). For example, only 8 out of 340 cases of ES valuation published in scientific literature actually report how information on the value of ES is used in local decision making (Laurans et al. 2013). ES assessments have not yet proven to effectively change land management and policies in public and private sectors (Abson et al. 2014, Ruckelshaus et al. 2015).

Nonetheless, ES assessments can be an attractive tool for supporting decisions on land use because they can highlight benefits and trade-offs between different land-use options, ideally by integrating biophysical and socioeconomic methods (Daily et al. 2009, Fisher et al. 2009, TEEB 2010, Ruckelshaus et al. 2015). Therefore, ES assessments are increasingly used in decision-oriented processes, including environmental impact assessments (EIA; e.g., Pischke and Cashmore 2006) and land-use planning for biodiversity conservation (Goldman et al. 2008) and catchment management (e.g., Ruckelshaus et al. 2015). The ES concept is also popular in national and international policy processes, including national ecosystem assessments, the Aichi Biodiversity Targets of the United Nations Convention on Biological Diversity (CBD), the Work Plan of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), and the Biodiversity Strategy of the European Union.

The term "ecosystem services" describes benefits that ecosystems —comprising species, genes, biotic and abiotic structures and processes—provide to human well-being (Millennium Ecosystem Assessment 2005, Fisher et al. 2009). Harnessing and managing ES often requires knowledge on the potential of ecosystems to provide ES and takes the investment of skills, labor, materials, and energy (Spangenberg et al. 2014*a*). The cultural and political context influences which ES are appropriated and how. Land use is then the result of this complex human-ecosystem interaction which is described as social-ecological system (SES; Ostrom 2007). Components or processes of ecosystems only become ES, if someone actively or passively benefits from them (Jax et al. 2013). Hence, the definition of ES involves subjective judgments of what is perceived as benefit, making ES a normative concept (Jax et al. 2013, Schröter et al. 2014). Using a broad interpretation,

[1]UFZ - Helmholtz Centre for Environmental Research, Department Computational Landscape Ecology, Leipzig, Germany, [2]UFZ - Helmholtz Centre for Environmental Research, Department Environmental Politics, Leipzig, Germany, [3]Institute of Geoscience & Geography, Martin-Luther-University Halle-Wittenberg, Halle (Saale), Germany, [4]Environmental and Resource Economics, Department of Agricultural Economics and Rural Development, Georg-August-Universität Göttingen, Göttingen, Germany, [5]Faculty of Biology, Department of Animal Ecology, Philipps University of Marburg, Marburg, Germany, [6]Department of Ecology, Animal Ecology, Philipps-Universität Marburg, Marburg, Germany, [7]Landscape Ecology Group, Institute of Biology and Environmental Sciences, University of Oldenburg, Oldenburg, Germany, [8]Department of Animal Ecology and Conservation, University of Hamburg, Biocentre Grindel, Hamburg, Germany, [9]Institute for World Forestry, University of Hamburg, Hamburg, Germany, [10]Hydrology and River Basin Management, Technische Universität München, München, Germany, [11]Environmental Assessment and Planning Research Group, Technische Universität Berlin, Berlin, Germany, [12]UFZ - Helmholtz Centre for Environmental Research, Department of Community Ecology, Animal Ecology and Social-Ecological Research, Halle, Germany, [13]iDiv - German Centre for Integrative Biodiversity Research, 04103 Leipzig, Germany, [14]Sustainable Europe Research Institute SERI Germany, Cologne, Germany, [15]Institute for Geography and Geology, Department of Sustainability Science and Applied Geography, Ernst Moritz Arndt University of Greifswald, Greifswald, Germany, [16]Department of Ecology and Environmental Sciences, Palacký University Olomouc, Olomouc, Czech Republic

in which ES benefits are based on multiple values, the ES concept can be valuable for decision support: it allows assessing human dependence on ecosystems through inter- and transdisciplinary research, integrating perspectives and values of different stakeholder groups, and guiding decisions on resource use (Reyers et al. 2010, Jax et al. 2013, Abson and Hanspach 2014, Schröter et al. 2014). A narrow interpretation, in which ES benefits are only based on monetary values, evokes criticism of the ES concept for being anthropocentric, fostering a utilitarian and economic perspective, with the risk of promoting commodification and exploitation of nature (Turnhout et al. 2013, Schröter et al. 2014). Because of this normative character, there is no standard interpretation and application of the ES concept, but it is clear that it requires transparency about its context, purpose, and definitions (Jax et al. 2013).

Since 1997 the number of scientific publications addressing ES has increased 27-fold, particularly in the natural-science literature (Abson et al. 2014). Biophysical characteristics of ES (e.g., Egoh et al. 2009), their cultural and social significance (e.g., Chan et al. 2012*a, b*), and economic value (e.g., Christie et al. 2012) are assessed and integrated into models (e.g., Nelson et al. 2009) and maps (e.g., Crossman et al. 2013) that describe interdependencies and trade-offs between land-use options. However, interdisciplinary ES assessments remain the exception with only 8.5% of ES studies being truly interdisciplinary (Abson et al. 2014).

Integrating a social-ecological system (SES) perspective into ES assessments, with land use being viewed as a system of interlinked natural and socio-political processes, offers a way of making such assessments more relevant to decision making (Spangenberg et al. 2014*a*). An SES perspective within ES assessments allows (i) the analysis of how human demand constitutes potential services (Spangenberg et al. 2014*b*), (ii) the identification of dependencies of ES users on ecosystems, and (iii) an understanding of trade-offs among management options (Cowling et al. 2008, Seppelt et al. 2011, Carpenter et al. 2012).

Guidance exists on integrating an SES perspective into ES assessments (e.g., Reyers et al. 2013), accounting for cultural and social values (Chan et al. 2012*a, b*), using ES information in landscape planning and management (de Groot et al. 2010), and mainstreaming ES into policies and practice (Cowling et al. 2008, Daily et al. 2009). However, the attempt to account for all social-ecological factors can make ES assessments a complex and resource-intense endeavor (e.g., Cowling et al. 2008, Chan et al. 2012*a*). Experience from practice shows that complex assessments are not necessarily more helpful for decision support (Ruckelshaus et al. 2015). Decision makers do not necessarily need an exhaustive understanding of the social-ecological system, but they need sufficient arguments to make a choice between land-use options. Therefore, designing problem-oriented ES assessments, which focus on the information demand by decision makers, can help make ES assessments more decision relevant (Honey-Rosés and Pendleton 2013).

To address this challenge, we compared existing frameworks for assessing ES in social-ecological systems. We identified prevailing gaps in these approaches and, based on the experience from four case studies in Brazil, China, Madagascar, and Vietnam, we codesigned and tested a problem-oriented ES assessment approach that prioritizes information demand by decision makers. We discuss how our approach contributes toward making ES assessments a more relevant tool for decision making. The case studies are part of the Sustainable Land Management (SLM) Program, funded by the German Federal Ministry for Education and Research (BMBF), with the objective of fostering transformations toward more sustainable land stewardship (Eppink et al. 2012).

BUILDING ON FIELD EXPERIENCE

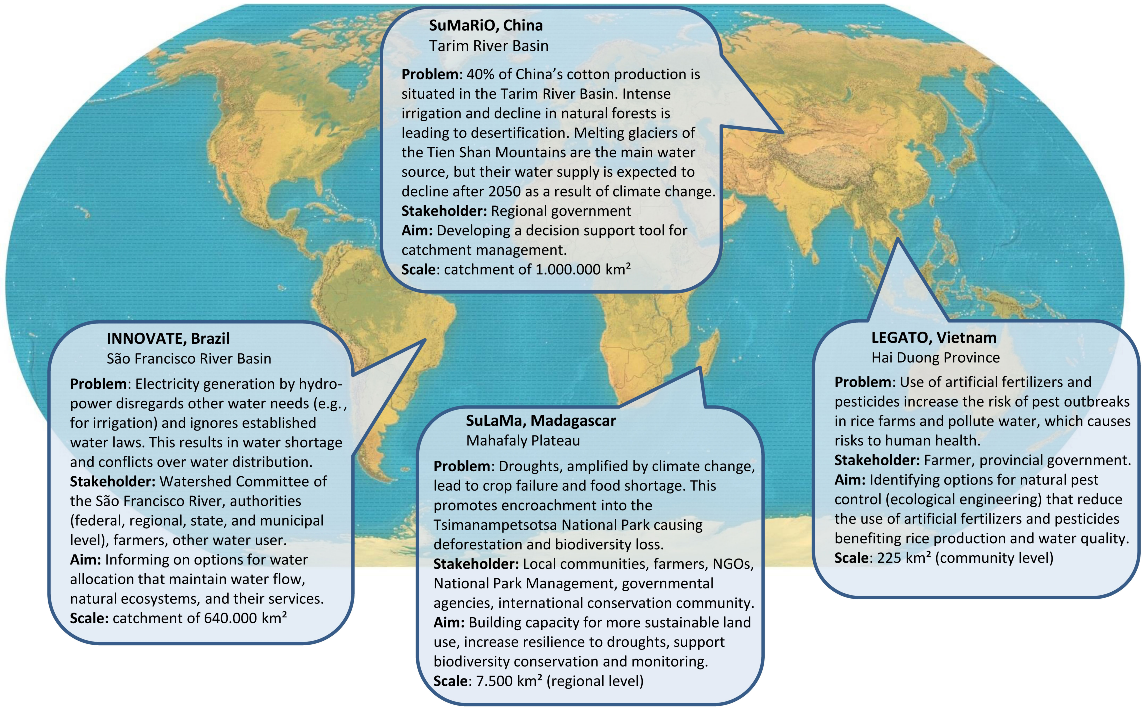
Building on the experience of four place-based projects (Fig. 1) and comparing existing frameworks for ES assessments (Fig. 2), we collaboratively identified aspects that are critical for a problem-oriented ES assessment, using workshops and expert consultations. The four case studies use ES assessments to guide decisions on land use problems related to agriculture, water use, and ecosystem conservation at local to regional scales.

In Madagascar, the SuLaMa project identifies options for enhancing the resilience of local communities to shortages in food and water supply caused by climate variability, and for mitigating encroachment into a protected area (Fig. 3). The LEGATO project in Vietnam analyzes rice farming practices that enhance natural pest control, increase yields, and reduce the use of pesticides causing water pollution (Settele et al. 2013; Fig. 4). In the São Francisco River watershed in Brazil, the INNOVATE project analyzes ES to support the Watershed Committee in addressing conflicts over water use for irrigation agriculture, electricity generation from hydropower, and domestic water use, while maintaining sufficient water flow for river ecosystems (Siegmund-Schultze et al. 2015; Fig. 5). In the Tarim River Basin in China, the SuMaRiO project informs the regional government on benefits and trade-offs involved in water use for cotton irrigation and the conservation of riparian forests, considering threats related to desertification and climate change (Rumbaur et al. 2015; Fig 6).

We compare our approach with eight existing frameworks (Fig. 2) that focus on assessing ES within social-ecological systems (SES) with the aim of providing decision support (Cowling et al. 2008, Carpenter et al. 2009, Daily et al. 2009, Ostrom 2009, Chan et al. 2012*a,* TEEB 2012, Reyers et al. 2013, Martinez-Harms et al. 2015).

Only three out of eight frameworks provide explicit guidance for focusing ES assessments on decision relevant problems. The TEEB approach (TEEB 2012) and Chan et al. (2012*a*) require (1) agreement on the problem, to (2) prioritize ES according to their relevance to the problem and stakeholders, and to (3) identify information needs by decision makers. However, the TEEB approach (2012) remains vague in how to assess ES from a SES perspective and Chan et al. (2012*a*) target mainly cultural values. Martinez-Harms et al. (2015) emphasize the importance of a stakeholder-driven problem identification and specification of objectives at the beginning of the assessment process, but they note that only 8% of case studies actually use stakeholder consultations in this process. Nevertheless, they provide little guidance on how to target problems and objectives relevant to decision makers. The other five approaches acknowledge the need to account for concerns of stakeholders, but the gaps under “Scoping phase A” (Steps 1-3 on the left side of Fig. 2) depict the lack of explicit guidance on tailoring ES assessments to decision needs.

Fig. 1. Case studies of the Sustainable Land Management Program (Eppink et al. 2012) for which the problem-oriented approach was developed and exemplified. Videos summarizing each case study can be accessed at the Program's website (URL: http://modul-a.nachhaltiges-landmanagement.de/de/mediathek-modul-a/videobeitraege/).



All approaches assume that developing an understanding of the social-ecological context and analyzing the flow of ES, their benefits, and trade-offs (Assessment phase B, Fig. 2) will generate information relevant to decision making (Implementation phase C, Fig. 2). This can be achieved, for example, through assessing the governance and resource system (Ostrom 2009), undertaking social and biophysical assessments (Cowling et al. 2008), analyzing the link between governance context and ES (Carpenter et al. 2009), and establishing social-ecological production functions (Reyers et al. 2013). However, trade-off analysis alone does not lead to changes in decision making (Daily et al. 2009). Focusing on the importance of ES information for decision making only after it has been generated involves the risk of missing decision relevant information. Furthermore, judging the relevance of information by scientific criteria can lead to advice that is lacking a policy perspective. It is recognized that, besides improving the science, a better integration of ES information in the development of policies and institutions is needed (Daily et al. 2009).

We propose closing these gaps by better tailoring ES assessments to problems at the very beginning of the assessment process and targeting specific information needs of decision makers. Building on the experience of the four case studies (Fig. 1), we developed a problem-oriented ES assessment approach to provide practical guidance for the assessment and synthesis of ES information with a focus on informing land-use decisions (Fig. 2). Our approach comprises a scoping phase (A), assessment phase (B), and implementation phase (C), and follows 5 steps: (Step 1) specify and agree with stakeholders on the problems to be addressed, (Step 2) identify ES beneficiaries and ES most relevant to decision making, (Step 3) define information needs of decision makers, (Step 4) assess ES flow within the SES context and impact of changes on ES benefits and trade-offs, and finally (Step 5) synthetize and integrate the generated information into processes of decision support. The approach is not intended to replace the existing frameworks, but to provide complementary guidance for designing and implementing ES assessments that are more relevant for decision making.

APPLICATION

In the following the problem-oriented approach of the SLM Program is exemplified along the four case studies (Figs. 3 to 6). The approach is not a static, prescriptive blueprint for a linear assessment process. Each ES assessment is a unique undertaking, adapted to a specific decision within a social-ecological system and point in time, producing context specific outcomes. Hence, designing and implementing ES assessments, aiming at more sustainable land-management options, requires transdisciplinary expertise that accommodates different types of knowledge and allows for responding to context specific information needs (Görg et al. 2014). Ideally, ES assessments are embedded in a science-practice partnership that enables cogeneration of knowledge, which is both user-inspired and user-relevant (Ntshotsho et al. 2015).

The presented approach is flexible in that the sequence of steps can be altered and the thematic and methodological focus can be

Fig. 2. The problem-oriented approach for assessing ecosystem services (ES) of the Sustainable Land Management (SLM) Program (at top) compared with other approaches for assessing ES using a social-ecological systems (SES) perspective. Steps can be applied sequentially (arrows), interchangeably, and repetitively within iterative assessment procedures.

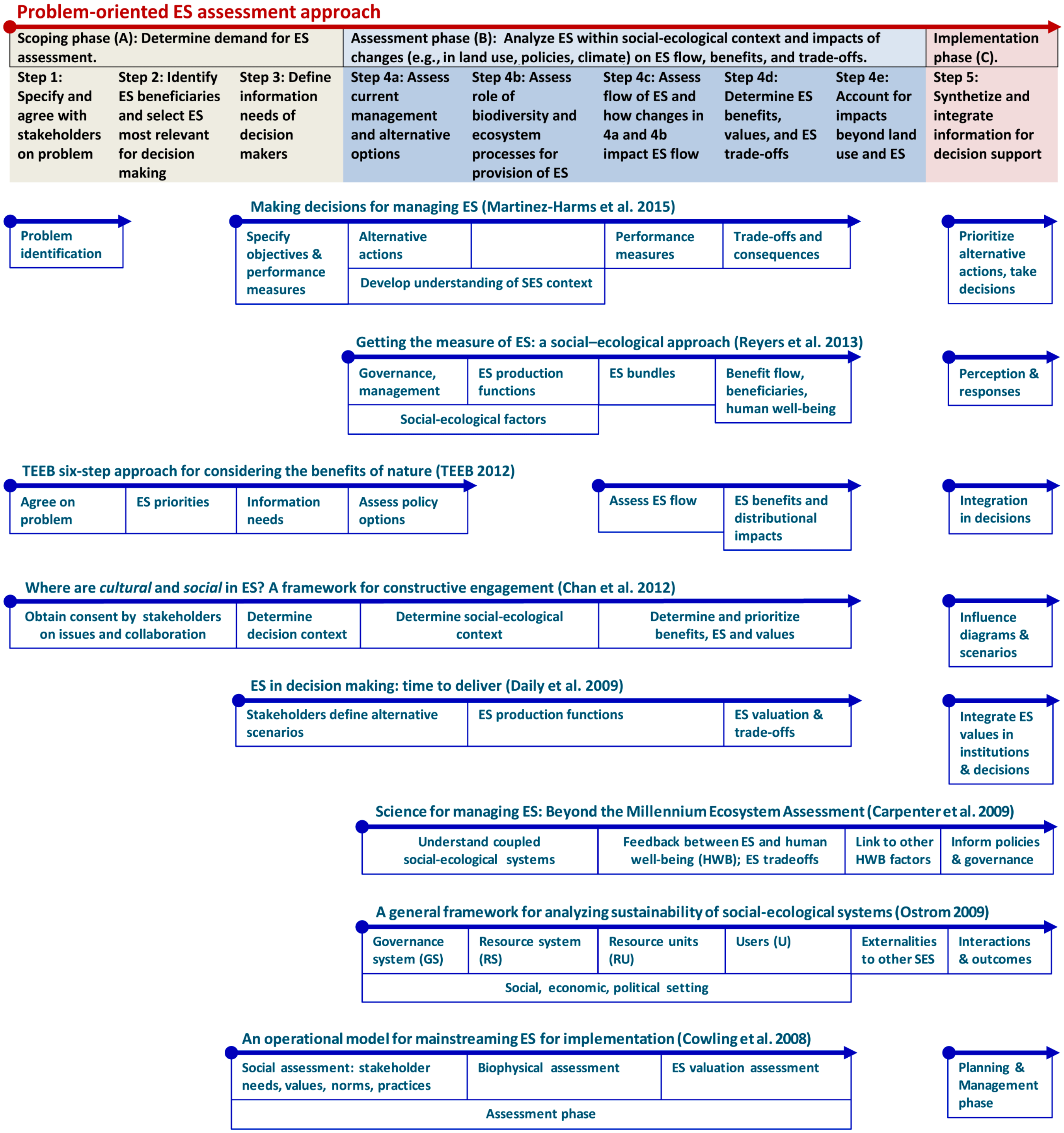


Fig. 3. Problem-oriented approach for assessing ecosystem services (ES): the case of the SuLaMa project on subsistence farming in Madagascar.

Scoping phase (A): Determine the demand for the ES assessment.			**Assessment phase (B): Analyze ES within social-ecological context and impacts of changes (e.g., in land use, policies, climate) on ES flow, benefits, and trade-offs.**					**Implementation phase (C).**
Step 1: Specify and agree with stakeholders on problem and relevant research question	**Step 2: Identify ES beneficiaries and select ES most relevant for decision making**	**Step 3: Define information needs of decision makers**	**Step 4a: Assess current management and alternative options**	**Step 4b: Assess role of biodiversity and ecosystem processes for provision of ES**	**Step 4c: Assess flow of ES and how changes in 4a and 4b impact ES flow**	**Step 4d: Determine ES benefits, values, and ES trade-offs**	**Step 4e: Account for impacts beyond land use and ES**	**Step 5: Synthetize and integrate information for decision support**
Communities suffer from food insecurity and few or no alternative income sources. **Managers of the Tsimanampetsotsa National Park (NPM)** identified deforestation and forest degradation mainly caused by farmers as causes for biodiversity loss. **Conflicts** between farmers and biodiversity conservation in National Park. **Drivers causing the problem include:** poverty, population growth, crop failure due to weather events including droughts, soil degradation, pests damaging crops, poor infrastructure (storage, market access).	**Farmers benefit from:** **Provision** of food from cultivated crops, livestock, wild alimentary plants, and wildlife, medicinal plants, fodder for livestock, fuelwood and timber from forests. **Regulation** of soil fertility, pest control, water availability. **Cultural values** including livestock as indicator for wealth and status, use of wild plants for ritual purposes. **National Park Management benefits from** maintaining habitat for biodiversity conservation.	Information is needed on **options for diversifying income strategies of farmers** and for building resilience to environmental shocks (droughts) and income loss. **How can the already existing coping strategies be enhanced?** Information is needed on use of drought resistant crops, enhancing soil fertility and pest control, and livestock management, sustainable use of wild plants and wildlife. **National Park Management** requires better monitoring of biodiversity and habitat quality.	Current subsistence **farming practices already include diversified strategies** for crop and livestock production in order to reduce risks related to droughts and pests. Option 1: Explore local crop varieties that are more resistant **to droughts and pests** (e.g., bird resistant millet). Options 2: Test **alternative sources of fodder for livestock** during droughts in order to avoid encroachment in protected area. Option 3: Promote **home gardens** for planting vegetables for domestic consumption and sale on markets. Option 4: Assess role of **wild plants and wildlife for income** diversification.	Option 1: Analyze **resistance** of different crop varieties to **droughts and pests** and test options for enhancing **soil fertility**. Option 2: Analyze **productivity** of Samata, a plant potentially serving as alternative fodder for livestock. Option 3: Analyze **productivity of home gardens.** Option 4: Assess **wild plants and animals used by households.** Monitoring of National Park: analyze species abundance, deforestation, and forest degradation rates as **indicators for habitat quality**.	Option 1: **Local corn** is fast growing but little drought resistant. **Local manioc** is resistant against pests, but achieves lower prize on market as it is less tasty. Resistance of **millet** to birds needs further testing. Option 2: Suitability of **Samata as fodder** is tested (biomass and nutrient content). **Water** need for Samata could conflict with water need for food crops. Option 3: **Home gardens** have positive influence on food production for personal consumption and for sale on market. Option 4: **Wild plants and wildlife provide** food in periods of droughts. Medicinal plants are important for health care. **Trade-offs** to be assessed: Competition among farmers for water, land, and labor. Changes in spatial patterns of land use and impacts on encroachment into national park.	Option 1: **Farmers** benefit from crop diversification. It can improve food security, income, and increase resilience to droughts. However, best use of local varieties is still unclear. Option 2: **Fodder cultivation (Samata)** has potential to support livestock production. The potential scale of this practice is unclear yet. Option 3: **Home gardens** enhance food security and income for farmers and in particular women. Option 4: **Wild plants and animals** contribute to food security and health. The extent to which these options can reduce encroachment and deforestation in the national park is still being assessed.	**Cultural impacts:** change in livestock production can lead to **social changes,** as the number of livestock determines the social status. Changes in livestock distribution can impact **behavior** of cattle thieves. **Tourism sector** can increase in region with potential impacts on income generation and cultural values.	**Recommendations** to local organizations and decision makers include: **Diversification of crop and fodder production** (option 1 and 2) can be a viable option for enhancing resilience of local communities, since diversification is already part of traditional farming practices. However, the **effect on increasing income is unclear yet. Water remains to be a limiting factor.** Farmers and in particular women benefit from home gardens as a source of food and income. **Home gardens** (option 3) **should be promoted.** The effect of options 1-4 on reducing encroachment into the national park is still unclear.

adapted to stakeholder needs. Applied in an iterative process, information generated in one step can inform previous and consecutive steps in feedback loops. The normative character of the ES concept helps to take into account different cultural and socioeconomic contexts and decision-making processes (Schröter et al. 2014) and to integrate multiple types of knowledge, e.g., combining traditional and scientific information. Integrative tools, which combine methods of natural and social science and synthesize qualitative and quantitative information, e.g., multicriteria analysis, tools for spatial analysis, and social-ecological models, are increasingly applied for ES assessments (e.g., Bagstad et al. 2013).

Scoping phase (A)

Step 1: Specify and agree with stakeholders on problem

Land-use related problems, drivers, and impacts are identified in step 1 through consultations of experts and stakeholders, review of literature, and available data (Table 1). Because stakeholders are not a homogenous group, e.g., politicians and farmers are both decision makers, consensus on often multilayered problems cannot be taken for granted. For example, in the case of competition for scarce resources, ES information can empower one party over others, leading to inequalities and potential conflicts. Thus, analyzing the distribution of benefits and disbenefits and the impacts on power relations is an important starting point for determining the focus and scales of the assessment.

For example, stakeholder interviews and constellation analysis (e.g., Bruns et al. 2011) helped INNOVATE in Brazil and SuMaRiO in China to identify large-scale water allocation issues at a catchment scale (area of 640.000 km^2 and 1 million km^2 respectively; step 1 in Figs. 5 and 6). In these catchments, water use involves trade-offs between irrigation, hydropower production, and maintaining minimum ecological flow for sustaining natural ecosystems that provide habitat for biodiversity and mitigate desertification (e.g., Siew et al. 2014). In contrast, the projects SuLaMa in Madagascar and LEGATO in Vietnam target farmers who make decisions on crop and livestock production ranging from a few hectares up to regional scales within mosaic landscapes (areas of 7500 km^2 and 225 km^2). SuLaMa and LEGATO aim at enhancing resilience of agricultural production against droughts and pest outbreaks to increase food security and household income, while ensuring biodiversity conservation (step 1 in Figs. 3 and 4).

To ensure a focus on "real-life" problems, LEGATO followed an approach of codesign and coproduction. Using stakeholder dialogues, relevant partners including local decision makers, farmers, researchers, and research institutions were consulted to identify research needs and elucidate synergies in capacities, knowledge, and skills. This process also ensured political acceptance and support of the project by all partners, taking into account institutional settings, involving different levels of local and regional governance, and respecting power structures.

Table 1. Examples of questions, actions, and indicators for determining the demand for the ecosystem services (ES) assessment (Scoping phase A).

Scoping phase (A): Determine the demand for the ES assessment Questions	Actions	Indicators (qualitative & quantitative)
Step 1: Specify and agree with stakeholders on problem		
Who are stakeholder groups and which problems are they concerned about? Are these problems caused by or linked to land use? Which socioeconomic or ecological drivers influence the problem? What are the spatiotemporal scales of the problem and who is affected? Are problems related to policies?	Consulting stakeholders, decision makers, and experts using participatory approaches, e.g., interviews, group consultations, surveys, and multicriteria analysis (e.g., Saarikoski et al. 2013*a*). Exploring available data and statistics on environmental and socioeconomic variables. Literature analysis.	Issues addressed in meetings and interviews with stakeholder groups, decision makers, and experts; Status and trends of environmental variables, e.g., water quality, habitat size, yield, climate, etc.; Status and trends in socioeconomic variables, e.g., income, health, access to resources, etc.; Size of affected area and population.
Step 2: Identify ES beneficiaries and select ES most relevant for decision making		
Which stakeholder groups or experts should be involved in ES identification and prioritization? Which ecosystems and ES are related to the problem? Which ES benefits are of particular importance to stakeholders? Are they part of a coproduced ES bundle? Who suffers from disbenefits / trade-offs? Which distributional challenges emerge?	Consulting stakeholders, decision makers, and experts on preferences for certain ES bundles and related trade-offs (e.g., Martín-López et al. 2014). Allowing flexibility for accommodating different knowledge types, values, and convictions. Adapting terminology and classification to stakeholder needs, while ensuring compatibility with common ES classification systems (e.g., Fisher et al. 2009, Haines-Young and Potschin 2012).	Types of benefits derived from ES, e.g., consumption, income, etc., types of disbenefits; Stakeholder groups and number of people benefiting from ES (beneficiaries and ES demand) or suffering disbenefits; Location and area of ecosystems that provide direct and indirect benefits to stakeholder groups (ES supply); Location and area of region that is benefiting from ES provision (ES demand); Importance of ES benefits for wellbeing of stakeholders and related disbenefits.
Step 3: Define information needs of decision makers		
Who is taking decisions on land use? Are stakeholders and decision makers aware of ES benefits and the positive and negative impacts of land-use decisions? Are there decision-making processes or policies for which ES information could be relevant? Would it improve decisions? If so, is there a window of opportunity for using ES information in current or upcoming land-use decisions? On what criteria are land-use decisions based so far (economic benefits, traditional rules, etc.) and by which group of decision makers? Does a link to ES exist (irrespective of the terminology used)? When in the decision process is what type of information needed by whom and for which purpose? Which level of detail is required? What are knowledge gaps related to the identified problems and ES? Are they relevant for the decision to be taken?	Using participatory methods (collaborative planning, workshops, consultations) for addressing complex land-use conflicts, involving relevant stakeholders, decision makers, and experts in identifying possible resolutions (Saarikoski et al. 2013*b*). Analyzing potential knowledge gaps, conflicting interests of stakeholder groups, and beneficiaries of ES information, e.g., empowerment of certain groups. Providing lessons learned in comparable decision contexts. For example, Garrick et al. (2009) compare how ES information influenced decisions on water management in two basins in the USA and Australia. Exploring historical data on information used in decision making. For example Wilkinson et al. (2013) compare historical changes in the use of ES information for urban planning in Melbourne and Stockholm.	Stakeholder groups involved in decision making and their respective interests; Stakeholder groups not involved and reasons for exclusion; Awareness of decision makers of identified problem and ES; Decisions or decision processes mentioned by decision makers; Social-ecological variables mentioned by decision makers to be of relevance; Timing of decision processes; Problems, decisions, and variables identified by the research team but not mentioned by decision makers, or only by subgroups.

Fig. 4. Problem-oriented approach for assessing ecosystem services (ES): the case of the LEGATO project on rice farming in Vietnam (Settele et al. 2013).

Scoping phase (A): Determine the demand for the ES assessment.			**Assessment phase (B): Analyze ES within social-ecological context and impacts of changes (e.g., in land use, policies, climate) on ES flow, benefits, and trade-offs.**					**Implementation phase (C).**
Step 1: Specify and agree with stakeholders on problem and relevant research question	**Step 2: Identify ES beneficiaries and select ES most relevant for decision making**	**Step 3: Define information needs of decision makers**	**Step 4a: Assess current management and alternative options**	**Step 4b: Assess role of biodiversity and ecosystem processes for provision of ES**	**Step 4c: Assess flow of ES and how changes in 4a and 4b impact ES flow**	**Step 4d: Determine ES benefits, values, and ES trade-offs**	**Step 4e: Account for impacts beyond land use and ES**	**Step 5: Synthetize and integrate information for decision support**
Rice farmers suffer from water pollution caused by the use of pesticides and frequent incidences of rice pests. Loss of land due to conversion for industry, settlement, and infrastructure. **Poverty:** Farmers have few or no alternative income sources. Production costs of rice farming are increasing due to use of artificial fertilizers and pesticides. **Development plans of** provincial government focus on promoting tourism and industry with little attention to sustainable farming practices. **Drivers:** poverty, water scarcity and pollution, pest infestations of rice farms, population growth, expansion of urban, and industrial areas.	**Rice farmers benefit from:** Provisioning ES: rice yield and biomass; Regulating ES: soil fertility, pest control, and pollination; Cultural ES: heritage, identity, aesthetics, education, and tourism. **Tourists benefit from** heritage of historical buildings and landscape, religious purpose of temples, pilgrimage; leisure from recreational ES. **Government** has leading role in modernizing rice production and managing transition from an agricultural society to urban, industrial society.	**Farmers require knowledge on alternative farming practices** that can: - reduce the use of artificial pesticides and fertilizers; - reduce water pollution; - promote natural pest control; - enhance soil nutrients; - reduce post-harvest losses (e.g., dryers, safe storage facilities). - increase farm-gate selling price (access to new markets). **Can natural pest control replace artificial pesticides and fertilizers while maintaining yields and income?** Identify **alternative income** sources, e.g., from tourism.	**Rice farming:** Assess role of already existing **traditional farming practices** for natural pest control, enhancing crop yields, and promoting soil nutrient cycles. Test and apply methods of **ecological engineering** that promote natural pest control. **Explore options for diversifying income:** Producing and marketing organic rice products; Engaging in tourism-based income generation; Developing tourism infrastructure to attract international tourists to cultural heritage and landscape amenities. Consider role of societal drivers in particular the potential impacts of **urbanization and industrialization** on future development of rice farming.	**Assessment of natural pest control:** Analyze species diversity of insects in rice fields for assessing the influence of different farming practices on the abundance of natural predators that control pests (e.g., damsel- and dragonflies). **Pollinators:** Assess abundance of pollinators in order to assess influence of biodiversity on productivity of crops other than rice (e.g., fruits). **Soil nutrients:** Conduct field experiments on decomposition and soil nutrient cycling. **Tourism:** Assess link between landscape structure and aesthetics value and recreation.	**Assess how farming practices:** **enhance yield** of rice, vegetables, fruits, nuts, spices, meat, pork, and chicken; **influence regulating ES such as** natural pest control, pollination, and functional diversity; **impact water quality** with relevance for domestic water use and health. **Applying ecological engineering** can potentially enhance natural pest control, enhance yields of farms, reduce need for artificial pesticides, and reduce water pollution. **Influence of land use on cultural services:** Traditional land-use practices are linked to cultural identity, social structures, and rituals connected to nature. Historical-cultural identity is supported by old temples and other historical sites.	**Beneficiaries of ES:** Rice farmers, millers, traders, consumers, employees in tourism, city dweller seeking recreation, government (taxes). **Potential benefits of changing farming practices to ecological engineering:** more stable rice yields, higher market value of organic rice, cost savings and health benefits from reduced use of pesticides, cleaner water, enhanced reputation of farmers from producing clean and healthy products, providing perspective to young farmers, stronger cultural identity and aesthetics value due to more diverse landscape, benefiting tourism (jobs, income). **Trade-off: farming competes with** industry offering jobs and income.	**Training** in ecological engineering can provide farmers with **capacity, awareness and skills** that are also of relevance in other sectors and enhance **diversification of income strategies.** **Reduction of dependency** on agro-chemicals allows more self-determined farming with potential to reduce costs. Socio-economic impacts of **industrial and urban development** are significant but are not assessed.	**Revise recommendations by regional government on rice farming.** **Revitalize traditional farming practices** that require less artificial fertilizers and pesticides, as this benefits pest control, water quality and income. **Enhance knowledge** on role of biodiversity for pest control. **Provide training** on ecological engineering in particular for young generation of farmers and decision makers. **Build capacity** for assessing trade-offs between different land-use options. **Guarantee long-term lease.** Enlarge fields. **Promote marketing of organic** farm products. **Communicate results** to intergovernmental organizations, e.g., Asian Development Bank (ADB).

Step 2: Identify ES beneficiaries and select ES most relevant for decision making

Step 2 covers prioritization of ES according to their relevance to the identified problem, affected stakeholders, and the decision to be informed (Chan et al. 2012*a,* TEEB 2012; Table 1). Special attention should be given to diverging interests and the distribution of benefits and costs. To do so, it is critical to integrate a range of knowledge sources of multiple stakeholder groups, including farmers, indigenous peoples, decision makers in public administration and private businesses, but also researchers and experts with particular knowledge of the system. The focus on prioritized ES has the advantage of targeting ES assessments toward specific land-use problems, taking into account available capacities and resources. However, because many ES are coproduced in bundles with benefits and costs to different stakeholders, the analysis must not be limited to single ES, monetary benefits, or selected stakeholders, which would ignore ecological context and distributional effects.

For example in Vietnam, the involvement of different farmer groups and generations was needed to realize that traditional rice farming practices maintain species compositions that provide natural pest control, while artificial pesticides together with fertilizers cause water pollution and health issues. Thus, better understanding of farming practices that enhance natural pest control and reduce use of pesticides was identified to be the focus of the LEGATO project (step 2, Fig. 4). However, institutional issues can also play a role in prioritizing ES. Because of the relevance of rice farming for local and national economy, LEGATO sought contact to provincial governors, heads of administration, and national senators. Consequently, both direct and indirect beneficiaries of rice production were included among stakeholders. This helped reveal ES related to rice production, identify disciplinary overlaps, and fill gaps in the choice of decision makers to be involved.

There is the risk of overlooking ES or stakeholder groups that have not been prioritized in the first place, but are found to be important later in the assessment process. For example, in the INNOVATE project in Brazil, the relatively new and not yet generally recognized Watershed Committee was identified as an important stakeholder group after a series of expert consultations (step 1 and 3, Fig. 5). Furthermore, unexpected events can impact project priorities. During the course of the INNOVATE project a particularly strong drought triggered societal concerns over water quantity. Hence, ES related to water quantity increased in importance.

This decision-focused approach differs from the recommendation by Reyers et al. (2013), who suggest to assess the entire bundle of ES to address the full range of consequences and trade-offs involved in decision making. Although assessing the entire bundle of ES is certainly important for a complete trade-off analysis, it

Fig. 5. Problem-oriented approach for assessing ecosystem services (ES): the case of the INNOVATE project in the River São Francisco Watershed in Brazil.

Scoping phase (A): Determine the demand for the ES assessment.			**Assessment phase (B): Analyze ES within social-ecological context and impacts of changes (e.g., in land use, policies, climate) on ES flow, benefits, and trade-offs.**					**Implementation phase (C).**
Step 1: Specify and agree with stakeholders on problem and relevant research question	**Step 2: Identify ES beneficiaries and select ES most relevant for decision making**	**Step 3: Define information needs of decision makers**	**Step 4a: Assess current management and alternative options**	**Step 4b: Assess role of biodiversity and ecosystem processes for provision of ES**	**Step 4c: Assess flow of ES and how changes in 4a and 4b impact ES flow**	**Step 4d: Determine ES benefits, values, and ES trade-offs**	**Step 4e: Account for impacts beyond land use and ES**	**Step 5: Synthetize and integrate information for decision support**
Water shortage during prolonged periods of drought causes **conflicts over water management between multiple stakeholders** across multiple scales. **Water uses include: Water withdrawal** by farmers for irrigation, by households and communal water suppliers for domestic use (drinking water), by local users, and **transferred** to distant user regions. **Minimum water flow required** for ecological processes, fishery, aquaculture, and navigation. **Water storage** for electricity generation from hydropower. Constructions of dams caused displacement of farmers to less fertile areas. **Lack of coordination between stakeholder groups** represented in the Watershed Committee).	**Maintenance of water flow benefits:** - domestic water use by households, - irrigation by farmers within and outside catchment, - hydroelectric power generation, - navigation, - ecological processes. **Maintenance of water quality** benefits domestic use, irrigation, livestock health, aquaculture, fisheries, and leisure. **Maintenance of soil fertility** benefits agricultural production. Negative effects from nutrient export to river. **Erosion control** benefits navigation and hydropower potential besides other.	**Watershed Committee** requires information for renewing its **water management plan**. The plan is developed for the next ten years and involves strategic decisions on water allocation. Information on options and effects of: - **distributing water** among different users, while **ensuring sufficient water flow and quality** for maintaining health of river ecosystem; - **reducing soil erosion** and nutrient export; - **identifying alternative income sources** related to tourism; - **coping with conflicts** in prioritization and decision making.	There is lack of **enforcing existing regulations** over water use or they show little effectiveness (e.g., water price not signaling its scarcity). Option 1: Enhanced **coordination** between stakeholder groups. Option2: Improve water **monitoring** for informing effectiveness of actions taken. Option 3: **Enhance existing water management** including sanitation. Option 4: **Protect and restore riparian vegetation** for controlling erosion and nutrient input. Option 5: **Enhance soil nutrients and adsorption capacity**. Option 6: **Diversify agricultural production** and aquaculture. Option 7: **Use income from water permits to** support and monitor current management and restoration projects.	Applying field measurements and hydrological and nutrient emission modeling for assessing: **Impacts of current and future land and water use** on water flow and quality; Options for **enhancing soil nutrients and reducing sedimentation**; Effect of land use on **water nutrients** (e.g., phosphorus); **Impact of reservoir management on macorphytes;** **Impacts of different land use intensities on biodiversity** (amphibians, and terrestrial plant species). **Considering the role of natural ecosystems** (e.g., riparian forests) for water provision and quality.	Hydrologic and hydro-economic models are used for assessing **water availability** under different water and land-use scenarios. The Watershed Committee aims at **conserving riparian and spring ecosystems as they are found to be of importance for water supply and quality.** This option is not only of ecological relevance but also highly political, since it has been promoted as alternative to the contested transfer of water out of the catchment. **Trade-off: Actions for soil improvement** may promote further conversion of natural vegetation (Caatinga reserves) to cropland with negative impacts on biodiversity and water availability.	Who are winner and loser of water and land management strongly depends on **negotiations and power relations among users.** Several water claims are mutually exclusive. **Farmers benefit** from irrigation and water for livestock production; **Fishermen** benefit from maintenance of water flow and quality for fish production. **Villages and towns** benefit from supply for domestic use. **Local and indigenous communities** benefit from intrinsic and spiritual value of natural landscape. **Companies** benefit from water for hydroelectric power generation, industries, mining, water diversion projects, transport (waterways), tourism. **Water shortage and erosion** has multiple **negative impacts and costs** to different users.	Water shortage and land degradation drives **migration to towns** for alternative income options. Construction of dams causes **expulsion of people** from the region. **Distant water users** benefiting from water transfer, while also involving equity concerns. **Change in traditional water use** also has **cultural effects** on local and indigenous people.	The project is developing water and land use models which test scenarios of different land and water management options for decision support. **Further recommendations to the Watershed Committee include:** Support **democratic, inclusive and transparent decision-making processes** allowing for effective participation of all stakeholder groups. **Harmonization of and easy access to existing water monitoring** programs, data and statistics. **Capacity building related to importance of riparian ecosystems:** assess and monitor ongoing restoration projects with careful consideration of ecosystem services.

is often constrained by the lack of resources and information. It is also not necessarily required in every decision context. For the case of the LEGATO project in Vietnam, for example, tourism and industrial development are likely to increase in importance for household income, but up to now they play a secondary role within the assessment, because the main focus is on enhancing pest control in rice farming systems (step 2, Fig. 4).

Whether the entire bundle of ES or only a subset of prioritized ES should be assessed is determined by the problem to be addressed (step 1), the different stakeholders and the decisions to be informed (step 3), and available methods and resources, including capacities, budget, and time. However, synergies and trade-offs involved in decisions and differences in preferences and impacts between stakeholder groups should be considered.

The perception of ES and related terminology can differ between stakeholder groups, localities, and cultural contexts. The ES concept can serve as an analytical tool for translating context specific terms into an agreed ES classification system (e.g., Haines-Young and Potschin 2012). For example, in stakeholder consultations of the LEGATO project, it was not the goal to educate stakeholders about the ES concept, but to collect their knowledge on the benefits they receive from ecosystems expressed in their own terms. The ES concept was then used to unify the various terms and enable synthesis and further analysis. Translation back into stakeholder-specific terms should be considered when disseminating results during the assessment process (e.g., in step 5).

Step 3: Define information needs of decision makers

Knowledge gaps in decision-making processes have to be addressed to ensure that an ES assessment generates relevant information (TEEB 2012; Table 1). Identifying options for integrating ES-related knowledge in ongoing decision-making processes supports the uptake of assessment results in decision processes (Ruckelshaus et al. 2015).

For example, the regional Watershed Committee of the São Francisco River in Brazil is in the process of developing a new water management plan for the next 10 years. In a series of stakeholder workshops, members of the committee identified gaps in understanding the impacts of decisions on water-related ES. Sharing knowledge among all stakeholders helped to build trust. As a consequence the Watershed Committee asked the INNOVATE project to contribute to filling the knowledge gaps. Thus, INNOVATE used hydrological models to inform about the amount of water available for irrigation, supply of drinking water, electricity generation, and critical ecological processes under different scenarios of decision making and climate change.

In the Tarim Basin in China, there is the need to generate a common understanding of impacts and trade-offs involved in decisions on land and water use across the region to inform the

Fig. 6. Problem-oriented approach for assessing ecosystem services (ES): the case of the SuMaRiO project in the Tarim River Basin in China (Rumbaur et al. 2015).

Scoping phase (A): Determine the demand for the ES assessment.			**Assessment phase (B): Analyze ES within social-ecological context and impacts of changes (e.g., in land use, policies, climate) on ES flow, benefits, and trade-offs.**					**Implementation phase (C).**
Step 1: Specify and agree with stakeholders on problem and relevant research question	**Step 2: Identify ES beneficiaries and select ES most relevant for decision making**	**Step 3: Define information needs of decision makers**	**Step 4a: Assess current management and alternative options**	**Step 4b: Assess role of biodiversity and ecosystem processes for provision of ES**	**Step 4c: Assess flow of ES and how changes in 4a and 4b impact ES flow**	**Step 4d: Determine ES benefits, values and ES trade-offs**	**Step 4e: Account for impacts beyond land use and ES**	**Step 5: Synthetize and integrate information for decision support**
Irrigation of cotton causes land **degradation** and increases the risk of **desertification**. **Melting glaciers** of Tien Shan Mountains are main water source. Water flow from glaciers is expected to decline after 2050 due to **climate change.** **Overuse of irrigation** is having multiple negative impacts on ecosystems including: **salinization** of soils and river water, **changes in ground water** level, soil degradation leading to **productivity loss of agricultural land,** degradation of natural forests. **Loss of natural forest** causes **biodiversity loss**, reduction in storm protection, and increase in **wind erosion** and sand drift.	**Most important ES of the Tarim River Basin include:** **Water** for agriculture, industry, households, and natural ecosystems; **Fiber:** 40% of Chinas cotton is produced in the region, heavily relying on water for irrigation. **Food:** water sustains irrigation agriculture and livestock. **Natural forests provide storm protection and erosion control,** mitigating sand drift, sandstorms, and desertification. **Habitat** for 60% of global population of Euphrat poplar (*Populus euphratica*). **Trade-off in water use for irrigation** vs. water needed for maintaining natural vegetation.	Information on ES is requested by **institutional stakeholders in Xinjiang Region:** **Water Resources Bureau** and **Tarim River Basin Management Bureau:** How does climate change impact glacier melt, water flow, and future water availability? **Agriculture Department:** How can salinization of soils be reduced? **Forestry Administration:** How do changes in groundwater impact natural forests? **Environmental Protection Department**: What are options for reducing salinization and desertification?	**Comparing impacts of different scenarios of climate change and land use on hydrology and socio-economy:** **Climate change:** Assessing impact of a) extreme, b) moderate, and c) low rise in global temperature on hydrology of the Tarim Basin. **Land use and socio-economic scenarios**: a) maximizing cotton production versus b) complete protection of natural vegetation and c) mosaic landscape of cotton production with natural vegetation. **Testing alternatives to cotton production:** Indian hemp (*Apocynum sp.*) is a salt tolerant plant that can be used for fiber production. It can be used for restoring saline soils. Economically viable production is being tested.	**Assessment of:** **Climate change** using climate models for predicting changes in precipitation and temperature; **Hydrology** using model MIKE HYDRO for computing water discharge, water use, and allocation. **Agricultural changes** using agro-economic models for comparing productivity of cotton on "healthy" soils and on saline soils with the productivity of the alternative fiber plant *Apocynum sp.* **Forest changes** analyzing state of forests on shallow and deep ground-water levels, forest distribution, and use of fuelwood. **Desertification** analyzing area affected.	**Assessing impact of changes in climate and land use on ES flow:** **Water provision** from glacial melt compared with water demand for irrigation agriculture, maintenance of natural ecosystems. **Fiber production:** Compare yields of cotton with *Apocynum sp.* **Fuelwood:** Assess harvest of fuel wood in riparian forest. **Storm and erosion control by forests:** Assess avoidance of sand drift, soil erosion, sandstorm, and avoided damage to infrastructure (e.g., roads). **Habitat:** Asses species composition of forests, comparing different stages of forest use and degradation. **Recreation:** Assess aesthetic appreciation by visitors.	**Water provision** benefits agriculture, industry, domestic use (e.g., drinking water). **Fiber from cotton provides** income to small private and large state farms and large-scale investors. **Fuel wood** is used by households for heating and cooking. **Storm protection, erosion control by forests:** estimating avoided damage to roads. **Provision of habitat** species abundance. **Aesthetics:** benefits to tourism. **Trade-offs:** *Apocynum sp.* finds lower acceptance by farmers than cotton as production is more expensive providing less income. Farmers prefer alternative water-intense crops e.g. Chinese dates.	External effects are not addressed in this study but include: Water use and environmental impacts by **other economic sectors** such as oil and gas mining; Impact of desertification on **other regions and infrastructure;** **Health effects** by dust due to wind erosion; Potential **land-use conflicts** effecting minorities; Effects of land use and land degradation on **migration**.	**Findings include:** By 2060 glaciers are likely to have disappeared due to climate change, which is likely to lead to a **decrease in runoff** and water shortage in the Tarim River (Sorg et al. 2012). Based on models a **Decision Support Tool (DST)** is developed allowing institutional stakeholders to **evaluate possible consequences** of scenarios of land and water use. **Impacts of different scenarios on ES provision are rated** (good, medium, poor); The **DST has mainly educational purposes;** **Simple solutions do not exist.** Decision involves trade-offs in agriculture and nature conservation. The DST can inform decision making on likely impacts on ES provision.

development of the five-year-plan at a national and provincial level. The SuMaRiO project involves multiple institutions at regional level, each with competing interests and responsibilities in managing water distribution, agricultural production, forests, and biodiversity conservation (step 3, Fig. 6). Adequate and sensitive management of tensions is critical for developing a concerted strategy for the entire Tarim Basin. Hydrological models operating at a basin scale were chosen to better understand the effects of different options for water distribution and land use (step 4). Based on this, a decision support tool was developed, allowing institutions to test different decision scenarios (step 5). The assessment process also contributes to enhancing transparency and communication among different stakeholder groups.

In Vietnam, rice farmers and authorities expressed their interest in low-cost measures for stabilizing or enhancing rice yields, reducing pre- and postharvest losses, in particular through pest control, reducing water pollution from pesticide use, enhancing soil nutrients, and improving income and livelihood. The LEGATO project compared traditional and conventional farming systems for biological pest control, rice yields, nutrient cycling in soils, and impacts on water quality (step 4, Fig. 4). The analysis of the ecological processes related to biological pest control required species sampling over several growing seasons. This focus mainly determined the design, spatial scale, and timing of the assessment. Interactions with other practices that affect the farming system, e.g., tourism or forestry, were also investigated.

Careful consideration of the actual information needs by decision makers is important to ensure that ES assessments apply indicators and methods, which provide the type and detail of information required for a specific decision. At the same time, the expectations of stakeholders and decision makers about what an ES assessment can deliver need to be kept realistic to ensure that assessment results are used appropriately and that misinterpretations and disappointments are avoided.

Assessment phase (B)

Step 4: Analyze ES within social-ecological context and impacts of changes, e.g., in land use, policies, climate, on ES flow, benefits, and trade-offs.

The previous steps provide the focus for the social-ecological analysis in step 4, which is divided into five substeps compatible with other SES approaches (Fig. 2): the assessment of current and alternative management options (4a), ecological factors relevant for producing ES (4b), the flow of ES (4c), ES benefits and trade-offs (4d), and impacts beyond land use and ES (4e; Table 2).

Table 2. Examples of questions, actions, and indicators for assessment phase (B).

Assessment phase (B): Analyze ecosystem services (ES) within social-ecological context and impacts of changes, e.g. in land use, policies, climate, on ES flow, benefits, and trade-offs.		
Questions	Actions	Indicators (qualitative & quantitative)
Step 4a: Assess current management and alternative options		
What are historical and current land-use practices and which policies and institutions influence change? How are future changes expected to influence land use and ES provision? What formal and informal policies, norms, and rules influence land-use decisions? Which drivers influence land-use practices and policies, e.g., cultural or economic drivers? What are potential alternative land-use options and policies? Which freedom of choice do local farmers have?	Analyzing how policies and institutions influence land-use practices to identify options for improving resource use and governance (e.g., Rathwell and Peterson 2012). Providing evidence from success stories in other regions to identify alternative options. For example Goldman et al. (2008) found that using ES information had a positive influence on the success of conservation projects. Developing social-ecological models and scenarios of future changes together with stakeholders and decision makers for understanding drivers for ES provision and likely trade-offs (e.g., Reed et al. 2013).	Types of land-use practices and change over time; Laws, regulations, and financial mechanisms such as subsidies, taxes, or fines; Institutions governing land use; Developments in market price of crops and market access; Formal regulations, e.g., related to pesticides and nutrients use; Traditional and informal rules, e.g., on cropping cycles, types of crops used; Cultural rules and norms, e.g., rites related to land use; Level of decision making, by individual farmer or by central government.
Step 4b: Analyze role of biodiversity and ecological processes for provision of ES		
Which elements of biodiversity and ecosystem processes are important for ES provision over an extended period of time? How do land use and other relevant drivers impact biodiversity and ecosystems, e.g., changes in population, policies, markets, and climate? What are likely impacts of alternative land-use options and policies on biodiversity and ecosystem processes?	Choosing methods that resonate with decision makers and adapting them to particular information needs to ensure credibility of ES data for decision making. For example, mapping and modeling of ES can be targeted to specific stakeholder needs (e.g., Petter et al. 2012, Crossman et al. 2013). Using in-situ field measurements for monitoring biodiversity and ecosystem processes, e.g., species presence or hydrological monitoring. Analyzing historical trends in land use and conditions of ecosystems using remote sensing.	Mapping forest area and assessing species composition, e.g., for estimating potential for carbon storage and biodiversity conservation; Model influence of drivers on biodiversity and ecological processes relevant for ES provision; Presence or absence of species important for pest control; Sediment content in river water, e.g., as indicator for role of vegetation for water quality and erosion.
Step 4c: Assess flow of ES and how changes in 4a and 4b impact ES flow		
How do biodiversity and ecosystem processes contribute to the provision of ES? How do changes in land use and other drivers influence ES flow, e.g., changes in population, policies, markets, and climate? How would alternative land-use options and/or policies impact ecosystems and ES flow?	Assessing impacts of changes in management on ES flow, using integrative methods and tools, including socioeconomic and ecological models (e.g., Bagstad et al. 2013). Modeling impacts of land-use change on ES flow such as erosion, sediment load, nutrient concentration in water or water availability (e.g., Villa et al. 2014). Assessing impact of changes in crop growth on yield or changes in species composition on spread of pests. Assessing impact of changes in forest use on carbon stocks, availability of wood for fuel and construction, bush meat, medicinal plants, etc.	Water flow in river under different land use, land cover, or climate scenarios; Comparing crop yield for different stages of soil degradation; Abundance of pests in relation to species composition; Water quality, e.g., nutrient or sediment content, for different scenarios of land use and cover; Erosion control by vegetation for different land-use scenarios; Carbon sequestration by forest under different forest management options.
Step 4d: Determine ES benefits, values, and ES trade-offs resulting from changes in 4a-4c		

(con'd)

Who are ES beneficiaries? Who are recipients of disbenefits? What are the ES benefits? What are the ES disbenefits? Which social and cultural values are affected positively and negatively by the service/disservice? Which socioeconomic values are affected among the different stakeholder groups? What human inputs, e.g., knowledge, skills, resources, costs, etc., are required for accessing ES? Which indicators and methods for assessing the benefits/disbenefits of ES are relevant and meaningful to different stakeholders and decision makers?	Assessing benefits and disbenefits of ES bundles for different stakeholder groups and land-use types (Raudsepp-Hearne et al. 2010, Goldstein et al. 2012, Martín-López et al. 2014). Using multicriteria-analysis and cost-benefit analysis to account for both qualitative and quantitative ES information in assessing the impacts of land-use changes on human well-being (e.g., Sijtsma et al. 2013). Assessing impacts on social and cultural values such as status, sense of place, social relations (e.g., Chan et al. 2012*a, b*). Assessing monetary and nonmonetary values of ES (e.g., Christie et al. 2012, Viglizzo et al. 2012). Mapping cultural ES (e.g., Plieninger et al. 2013).	Impact of changes in crop yield on income and status of farmers and decision makers; Impact of changes in pests on yield, income, and subsequent changes in land management; Impacts of changes in water availability on water user, e.g., changes in water price, changes in crop yield; Health benefits, e.g., due to improvement in water quality; Health damage cost; Impact of changes in forest cover on erosion, hunting success, carbon stocks; Changes in water treatment costs; saved costs of sediment removal from reservoirs for hydropower production.
Step 4e: Impacts beyond land use and ES		
Which other sectors or institutions beyond land use are affected by changes in ES flow and benefits/disbenefits? Which cultural and social impacts occur because of changes in ES,e.g., impacts on traditions, norms, rituals?	Analyzing impacts on education, social norms, traditional practices, rituals, social structures. Identifying links to other sectors and infrastructure related to energy, transport, communication, etc. Assessing changes in distribution of wealth and income, political stability and social security, self-determination vs. transfer dependency.	Educational benefits and capacity building because of assessment process; access to new knowledge and technology; Behavioral changes of land user, e.g., crowding out effects (Rode et al. 2015); Changes in access to infrastructure, markets, and communication; Income distribution patterns; Changes in the hierarchies of social structures.

Step 4a: Assess current management and alternative options

Identifying policies and management options requires an understanding of the current land-use policies and practices within their socioeconomic and cultural context (Cowling et al. 2008, Ostrom 2009, Chan et al. 2012*a*). Within ecological limits, landscapes offer a range of potential land-use options and configurations. Which of the land use options are implemented and which of the ES benefits are appropriated and by whom partly depends on the ability of the different stakeholder groups and beneficiaries to influence land-use decisions (Spangenberg et al. 2014*b*). Social, cultural, and economic processes shape ES generation, with power relations, property and access rights, investments of time, labor, and resources determining the ES potential realized across a landscape.

In the Tarim River Basin in China, land-use decisions are centralized but involve multiple government institutions (Land and Resources Bureau and departments of Agriculture, Forestry, and Environmental Protection) that make decisions at the regional level following guidelines by the central government. Complex trade-offs exist in land and water use for cotton production, hydropower generation, forestry, and conservation of natural habitats (e.g., Feike et al. 2015). To better understand the impacts of different land-use options, scenarios were developed including climate change with high and low water availability, and land use with different intensities of cotton production and nature conservation. In field experiments, alternatives to irrigation-intense cotton production were tested using the salt-tolerant plant *Apocynum* sp. This plant is suitable for fiber production and can be used for the restoration of degraded agricultural soils. Throughout the assessment process interviews and discussions with stakeholders informed the development and testing of the different options.

In the case of the São Francisco watershed in Brazil, analyses of past and current water governance found that comprehensive water policies already exist for addressing water distribution issues, especially at the federal level. However, the implementation and enforcement of these policies is weak and the water monitoring is inadequate to measure the effectiveness of policies. INNOVATE addressed these immediate information needs of the Watershed Committee by developing guidance on implementation of existing policies and improving water monitoring (step 5).

LEGATO's ES assessment compared traditional and conventional rice farming systems for factors that impact income and livelihoods of farmers. This included institutional settings and world views that may guide different land management decisions, biological pest control, rice yields, and nutrient cycling in soils (step 4a, Fig. 4).

In the case of the SuLaMa project in Madagascar, decisions of farmers and smallholders are largely based on traditional knowledge (step 4a, Fig. 3). Crops are primarily cultivated for subsistence, with surpluses being traded as a source of income. Besides crops, livestock plays an important role for people's livelihood. It provides a fallback resource in periods of crop failures and also determines social status. Current land use leads to ecosystem degradation and encroachment in the Tsimanampetsotsa National Park. This situation is aggravated by cattle thieves driving farmers to graze their livestock in forested areas. Thus, the SuLaMa project analyzed the drivers of degradation, their impacts on biodiversity and ES provision, and explored options of more sustainable land use. Besides others, this includes fodder production for livestock as means for reducing grazing pressure and the use of home gardens as means of diversifying sources of income.

Step 4b: Assess role of biodiversity and ecosystem processes for provision of ES

In this step, ecological processes and biodiversity indicators relevant for the provision of the prioritized ES are identified and analyzed. This includes biophysical measurements, modeling of ecological processes, and biodiversity assessments as well as characterization of relevant drivers. Again, multiple sources of knowledge should be taken into account including scientific, traditional, and indigenous knowledge. Biophysical assessment methods are numerous, and factors influencing the choice of methods include: the type of biophysical indicators required for addressing the information needs, available expertise and resources, available data, and extent to which primary data have to be measured in the field.

In the Tarim Basin in China, the SuMaRiO project used the hydrological model MIKE HYDRO for estimating water discharge and allocation for irrigation. Cotton yields on intact soils were compared with yields on degraded soils, and productivity of the more salt-tolerant crop *Apocynum* sp. were tested in the field to inform model simulations of alternative crop production. Methods of forest monitoring were used to assess how forest biodiversity and its role for erosion control are impacted by changes in groundwater levels.

In INNOVATE, the hydrological model SWIM and the nutrient emission model MONERIS were calibrated and adjusted for the São Francisco River. The MAgPIE model was used to estimate future land use under climate change. Hydro-economic analysis was performed for a subregion of the catchment. A species distribution model of the semiarid Caatinga vegetation was set up with Maxent. Although these models mainly use secondary data, primary data on biodiversity and alternative land use options were collected in the field.

LEGATO in Vietnam analyzed the role of biodiversity for pest control, conducting inventories of species, e.g., of parasitoids or damsel- and dragonflies, that control pests. Impacts of fertilizers and pesticides on ecological processes were investigated via field inventories of pollinators, native and alien plant species, soil organisms, and nutrient cycles. This was accompanied by surveys among farmers to assess productivity of rice fields for the different farming systems. The analysis of the ecological processes was the main factor determining the design, spatial scale, and timing of the assessment.

Step 4c: Assess flow of ES and how changes in 4a and 4b impact ES flow

In this step, the interplay between social (4a) and ecological factors (4b) and their role for the production and flow of ES is assessed. A causal relationship between ecological factors and the provision of ES is often anticipated, but it is rarely proven or quantified (Carpenter et al. 2009, Reyers et al. 2013). Proxy indicators are often used in cases where direct measurements of ES are missing or for simplifying the analysis, e.g., changes in forest cover as proxy for carbon sequestration. Additional validation is required in case proxies are used to transfer results across different sites.

Given the complexity involved in social-ecological systems, computer-based models are often the first choice for analyzing climate-change impacts, drivers of land-use change, their impacts on ES flow, and alternative land-use scenarios. This is in particular true for large-scale assessments as undertaken by INNOVATE and SuMaRiO (Figs. 5 and 6; e.g., Krysanova et al. 2015). Validating models based on empirical data and discussing their plausibility with scientists and stakeholders is critical to ensure that model outputs provide relevant information for decision making. In the Tarim Basin in China, hydrological modeling combined with stakeholder consultations helped inform decision makers about potential impacts of land-use decisions on water availability. Through this process the relevance of forest conservation for protecting infrastructure and agricultural land from desertification was communicated to respective stakeholders.

Field surveys and experiments allow ground truthing the assumptions on ES flows. In Madagascar, the SuLaMa project used household surveys to analyze the relevance of ES for household income, including yields of different crop varieties, productivity of home gardens, fodder production using Samata (*Euphorbia stenoclada*), and use of wild plants. Inventories of insect species in rice fields in Vietnam elucidated the benefits that local communities obtain from traditional farming practices that support natural pest control (LEGATO, Fig. 4).

Step 4d: Determine ES benefits, values, and ES trade-offs

Valuation of biodiversity and ES depends on the perception of stakeholders that benefit from ES or suffer disbenefits (Görg et al. 2014). There are multiple values that stakeholders can attach to biodiversity and ES, including social, cultural, and economic (monetary and nonmonetary) values (Chan et al. 2012*a,* TEEB 2012). Demonstrating these values with analytical methods in quantitative and qualitative terms can be a challenge; in particular, when it comes to spiritual and cultural values, public goods, and future generations. The types of values to be assessed and the choice of methods and indicators should be tailored to each specific decision.

Although increasing in popularity, monetary valuation of ES is not necessarily required or useful in every decision context. Alternative and complementary methods for addressing social and cultural values can be more relevant to decision makers (Limburg et al. 2002, Daily et al. 2009, Abson and Termansen 2011, TEEB 2012, Chan et al. 2012*b,* Ruckelshaus et al. 2015, Sijtsma et al. 2013). Multicriteria analysis is an option for integrating qualitative and quantitative information on values in decision making (e.g., Fontana et al. 2013). There is also an increasing number of tools for data integration (Bagstad et al. 2013).

In particular, traditional land-use practices cater multiple values. Rice farming in Vietnam is not only a source of food and income, but it is deeply interlinked with local culture and traditions, which developed around rice farming over generations. Hence, in the LEGATO project, alternative rice-farming practices were not only evaluated for their benefits in terms of income and environmental impacts, but also for their impacts on local culture and identity. Rice farming systems based on traditional knowledge are expected to account for ecological processes, using locally adapted crop varieties, which require less input of artificial fertilizer and pesticides. Such systems are expected to enhance natural pest control, thus requiring less chemical inputs, which in turn reduces related costs and benefits water quality. Traditional farming is also promoting a sense of place by strengthening local traditions and social bonds (Tekken and Settele 2014). This has potential benefits for tourism, which brings new income sources to the region, but can also exert stress on traditions and social bonds. Accessing markets for organic products can potentially provide a long-term perspective also for younger rice farmers.

Similarly, in Madagascar, land-use practices are strongly linked to local culture through traditional knowledge and religious beliefs. Besides analyzing crop yield, food availability, and cash income, the SuLaMa project also accounted for cultural values involved in each of the analyzed land-use practices. Wild plants do not only serve as food or medicine but also fulfil important roles in traditions and rites. The number of livestock determines the social status of households, providing an incentive to increase livestock numbers, which can enhance grazing pressure.

In the case of watershed management addressed by INNOVATE in Brazil and SuMaRiO in China, ES valuation targets more long-term investment decisions across regional scales. Stakeholders were asking for quantitative information on water flow, crop yield, costs of water provision, costs of ecosystem degradation, and impacts on income. ES valuation was used to identify the winners and losers of different watershed management strategies. In the Tarim Basin in China, SuMaRiO project assessed the ecological and economic potential of *Apocynum* sp. as an alternative to cotton production (Thevs et al. 2012). The value of natural forests for reducing wind erosion and desertification was analyzed by estimating avoided costs from reduced loss in agricultural land and reduced infrastructure maintenance, e.g., cleaning sand from roads.

Step 4e: Account for impacts beyond land use and ES
Decision making within the assessed social-ecological system can have external effects on other social-ecological systems (Ostrom 2009). Shifts in land use can impact stakeholder sectors and land-use systems within and outside the study region. Valuation of ES can have impact on cultural values or behavior. For example, introducing monetary values as an argument for conservation of biodiversity can replace cultural and intrinsic motivations for conservation (crowding-out effects; Rode et al. 2015).

In the assessment of watersheds in Brazil (INNOVATE) and China (SuMaRiO), it is recognized that changes in land and water use greatly impact migration of people in and out of the region, although it is not the central focus of the assessment. The INNOVATE project acknowledged plans for artificial water transfer to regions outside the watershed and the severe impacts this can have on the future development of the entire catchment. Because of the lack of transparency regarding the details of these plans, this factor is subject to speculation. In the Tarim Basin in China, mining of oil and gas is an important water user, but this sector was beyond the scope of the SuMaRiO project because of limited resources and political reasons. Although cattle theft is a major problem in Madagascar, it was not the focus of the SuLaMa project to assess behavioral changes of cattle thieves in response to changes in cattle production. In Vietnam, industrial development impacts income opportunities, causing migration of young people to cities and a decline in farming population. This issue is documented by the LEGATO project but not assessed in detail because these drivers are beyond the project's influence.

Although such external effects cannot always be analyzed in detail, it is critical to recognize their existence. They substantiate the discussion of uncertainties of the findings and help in embedding the findings of ES assessments into the larger decision context.

Implementation phase (C)

Step 5: Synthetize and integrate information for decision support
Step 5 focuses on the use of ES information for decision support based on the synthesis of information generated in the previous steps (Table 3). The outcomes of ES assessments depend on the information needs defined in scoping phase A and need to be adapted to the particular ecological, socioeconomic, and cultural context. Assessment results can help change stakeholder perspectives and trigger changes in the management of biodiversity and ES (Ruckelshaus et al. 2015). Whether this change is for better or worse depends on how the information is used and by whom. Avoiding the fact that ES information leads to adverse impacts, e.g., the commodification and exploitation of nature (Turnhout et al. 2013, Schröter et al. 2014), requires broad stakeholder participation and transparency in defining and using ES information (Chan et al. 2012*a,* Jax et al. 2013).

Integrating ES information into decision making and changing land management to more sustainable practices require adaptive management (Cowling et al. 2008), involving an iterative and participatory process of prioritizing management actions, monitoring their performance, and adjusting management practices in accordance with the defined objectives (Martinez-Harms et al. 2015). The outcome can be as unique as the assessment process itself, depending on the specific social-ecological context. Hence, guidance on integrating ES information into decision making can only remain general. However, science-practice partnerships, involving close collaboration of practitioners and scientists from outset of the assessment, can help generate user-inspired and user-relevant knowledge that promotes effective management on the ground (Ntshotsho et al. 2015).

In the INNOVATE project, guidelines for the watershed management of the São Francisco River in Brazil were discussed with stakeholders to improve water monitoring and inform existing policies and restoration efforts. Collaboration with local and regional research organizations ensures capacity building for

Table 3. Examples of questions, actions, and indicators for implementation phase (C).

Implementation phase (C) Questions	Actions	Indicators (qualitative & quantitative)
Step 5: Synthetize and integrate information for decision support		
How to communicate the generated ecosystem services (ES) information, so it is adopted by stakeholders? Are there windows of opportunities for bringing assessment results to the attention of key decision makers, institutions, or including it in public debates? How can the generated ES information trigger changes in policies and practices? How to ensure that these changes improve the sustainability of land use? Are there important knowledge gaps that require an iteration of assessment steps?	Promoting science-practice partnerships from the start to enable codesign of user-inspired and user-relevant knowledge (Milner-Gulland et al. 2010, Ntshotsho et al. 2015). Promoting use of assessment results through user-adapted decision support tools such as participatory models, maps, guidelines, user-targeted publications, and web sites (e.g., Liekens et al. 2013). Consulting stakeholders, decision makers, and experts on the use of ES information. Establishing monitoring system for tracking positive and negative changes. Repeating assessment steps if necessary.	Awareness of stakeholder groups on availability of ES information, e.g., through the use of assessment results or published reports. Monitoring of qualitative and quantitative changes in ES using indicators, e.g., for water quality, sediment load, crop yield, carbon stock, etc. (e.g., Feld et al. 2009). The type of ES information and tools used by stakeholders in decision processes.

future assessments in the region. Supporting ongoing restoration and conservation projects with data on biodiversity and land use may pave the way for a more careful consideration of natural resources in decision making. Recommendations are provided in writing, presented in live events, and discussed and refined during stakeholder consultations. These efforts can also support the development of more transparent and democratic decision-making processes for water management.

The decision support tool developed by the SuMaRiO project in China supports institutions at the national and provincial level in testing different scenarios of land and water use (Siew et al. 2014). The tool has mainly educational purpose and allows the involved institutions to better understand possible impacts of land-use decisions on ES. Although it is a simplification of the watershed, the tool supports institutions in developing an improved understanding of the complexity of the system and general trends across the watershed.

Enhancing the use of home gardens has been identified by the SuLaMa project in Madagascar as a viable option that improves income of local households and increases resilience to environmental disturbances, e.g., pests and droughts. Local acceptance of this strategy is expected to be high because it builds on existing land-use practices and benefits women in particular. With regard to potential alternative strategies for crop and fodder production, more investigation is needed to get a better understanding of possible adverse impacts, e.g., an increase in livestock production could cause conflicts over scarce water resources. Modern farming practices were previously introduced by development organizations but subsequently abandoned for the lack of local acceptance, indicating complex social-ecological challenges involved in establishing alternative land-use practices.

Educating and training farmers and government officials in ecological engineering is identified by the LEGATO project as an important component of supporting rice farmers in Vietnam. "Farmer field schools" and "entertainment education" including soap opera episodes on radio and TV (Escalada et al. 1999, Heong et al. 2008, 2014) proved to be effective tools for education about the practices of ecological engineering. Furthermore, based on the ES assessment, policy advice was developed for regional and national government departments to better integrate knowledge on biodiversity and ES in rice farming policies. Provincial administrations insisted on the participation of representatives of the agricultural administration in farmer training to build capacity for repeating the training on a province-wide scale. In addition, the project participants were frequently consulted for advice on provincial development plans. Despite this success, the generated information can become irrelevant to decision makers, for example, if other issues on the political agenda become more relevant, or in case of mismatch of competencies between project partners.

DISCUSSION AND CONCLUSION

Initiatives like the SLM Program and PECS aim at applying ES assessments to inform decisions on specific land-use problems. However, simply generating ES information does not guarantee its relevance for decision making (Laurans et al. 2013). Often science-driven ES assessments focus only on biophysical functions (Honey-Rosés and Pendleton 2013), ignoring diversity in ES benefits and information needs by decision makers. Social and political processes in the provision and distribution of ES and resulting social, distributional, and economic impacts are often not analyzed. The presented problem-oriented approach was developed to better target ES assessments to specific information needs by decision makers. The approach builds on the analysis of empirical experience of four place-based ES assessments (Fig. 1) and existing ES frameworks (Fig. 2).

The presented approach stresses the need to: (a) identify land-use problems (step 1) and related information needs by decision makers (step 3) from the outset of the assessment process, and (b) focus on decision-relevant ES information throughout the assessment process (step 2 and step 4).

Step 1 and step 3 are useful for focusing ES assessments on land-use problems from a stakeholder point of view within a particular local or regional decision context. This promotes both engagement of relevant stakeholders and the building of trust between stakeholder groups. Trust among stakeholders is important for sharing knowledge but also for acknowledging relevant knowledge gaps. This includes, for example, local knowledge on diversifying crop production as a means of building resilience to droughts and pests in Madagascar (SuLaMa, Fig. 3), and knowledge on the relevance of local practices for enhancing resistance of rice farming to pests in Vietnam (LEGATO, Fig. 4).

Targeting the assessments on priorities relevant for decision making (step 2 and step 4) helps to integrate ES information into ongoing policy processes (step 5). For example, the SuMaRiO project (Fig. 6) informs the development of the five-year-plan for the Tarim Basin in China about ES trade-offs involved in cotton production. Having a clear focus on decision-relevant land-use problems from the outset of the assessment enhances the probability that the generated ES information will be integrated in the decision process.

The presented approach also facilitates the establishment of partnerships with decision-relevant institutions, the development of a common understanding of the issues at stake, and the building of trust between stakeholders involved in the assessment. For example, it enabled the INNOVATE project (Fig. 5) to establish a close working relationship with the Watershed Committee of the São Francisco River in Brazil, allowing effective communication of information needs of decision makers to the scientists conducting the ES assessment. This also allows the transfer of assessment findings back to relevant stakeholders and decision makers, highlighting where regional and national policies and development priorities override interests of local land user.

The clarity of problems and information needs is also important to agree on assessment goals and the type of decision support that an ES assessment can realistically deliver within a given context and with available resources. The process of codesign with stakeholders allows identifying opportunities for the ES assessment to provide a meaningful contribution to a specific decision-making process. This is important to clarify limitations and avoid overly ambitious expectations. ES assessments can trigger changes in decision making, in particular, if they are linked to ongoing decision-making processes. The development of decision support tools and guidelines can be useful in promoting this process. Nevertheless, the impact of technical decision support tools should not be overestimated because decision processes are often complex negotiations dependent on multiple factors that are beyond the scope of an ES assessment.

ES assessments are unlikely to deliver ultimate solutions to the identified problems. When ES assessments become part of a political process, they can contribute to solutions but also trigger new conflicts. For example, the INNOVATE project identified that the ES assessment can help making decisions on water management more transparent and thereby facilitate stakeholder involvement in water management. However, more transparency in decision making is not always wanted by all stakeholders or decision makers.

Nonetheless, achieving a shared understanding of the role of ES within the social-ecological context can already be beneficial for the decision-making process. Designing ES assessments is a learning process where the design is refined and re-adjusted in the course of the assessment process and in response to newly acquired knowledge. To paraphrase Albert Einstein, assessments should be as simple as possible, but no simpler. We recognize that step-wise approaches are a simplification of the process required to fully understand the complexities involved in social-ecological systems (Rogers et al. 2013). However, our approach is meant to provide pragmatic guidance for making ES assessments more policy-relevant by focusing the design of assessments on particular land-use problems, stakeholder priorities, and information needs to explore options for more sustainable land management.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/7804

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