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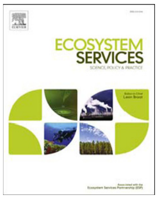

Towards systematic analyses of ecosystem service trade-offs and synergies: Main concepts, methods and the road ahead

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ABSTRACT

Ecosystem services (ES), the benefits that humans obtain from nature, are of great importance for human well-being. The challenge of meeting the growing human demands for natural resources while sustaining essential ecosystem functions and resilience requires an in-depth understanding of the complex relationships between ES. These conflicting ('trade-offs') or synergistic ('synergies') relationships mean that changes in one ES can cause changes in other ES. By synthesizing the growing body of literature on ES relationships, we identified the following four main study objectives: (i) the identification and characterization of co-occurrences of ES, (ii) the identification of drivers that shape ES relationships, (iii) the exploration of biophysical constraints of landscapes and limitations to their multifunctionality, and (iv) the support of environmental planning, management and policy decisions. For each of these objectives we here describe the key concepts, including viewpoints of different disciplines, and highlight the major challenges that need to be addressed. We identified three cross-cutting themes being relevant to all four main types of studies. To help guiding researchers towards more systematic analyses of ES trade-offs and synergies, we conclude with an outlook on suggested future research priorities.

1. Introduction

The importance of understanding relationships among ecosystem services (ES; Diaz et al., 2006; Braat and de Groot, 2012) is increasingly recognized by scientists and policy makers (e.g. Mach et al., 2015; Bennett et al., 2015). In general, three different types of relationships among ES have been identified: trade-offs, synergies and bundles. These relationships can result from two non-exclusive mechanisms (Bennett et al., 2009): (i) through common drivers that affect one or multiple services at the same time (e.g. land use change, climate change) or (ii) through direct interactions among services (e.g. reliance on the same ecosystem processes). The terms 'trade-off' (e.g. Sanon et al., 2012; Setälä et al., 2014) – and to a lesser extent 'synergies' – have received increasing attention, although they still lack an accepted definition (Deng et al., 2016). A trade-off describes an antagonistic situation that involves losing one quality of something in return for gaining another. In an economic context, a trade-off is commonly expressed as the opportunity cost of a decision alternative. Therefore, trade-off situations require choices or management decisions to be made between alternatives that cannot be achieved at the same time (Turkelboom et al., 2015) and that will result in changes of the types, magnitudes and interactions of ES (Deng et al., 2016). ES synergies have been defined 'as the positive response of multiple ES to a change in the driver' (Bennett et al., 2009), 'a situation where the use of one ES directly increases the benefits supplied by another service' (Turkelboom et al., 2015) or a 'win–win situation that involves a mutual improvement of both ecosystem services' (Haase et al., 2012).

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However, so far comparatively few studies have addressed ES synergies and an accepted definition has yet to manifest. Furthermore, ecosystem service bundles have recently been defined as 'sets of ES that repeatedly appear together across space or time' (Raudsepp-Hearne et al., 2010) and been the focus of a growing number of studies. Although the topic of ES relationships has been discussed previously (e.g. Villamagna et al., 2013; Grêt-Regamey et al., 2014), the importance of ES trade-offs, synergies and bundles has not yet been thoroughly examined.

The use of different terminologies in research focusing on ES relationships continues to be the source of misunderstandings. This has led to calls for better theoretical foundations (Bennett et al., 2009; Mouchet et al., 2014) and more syntheses of empirical examples (e.g. Raudsepp-Hearne et al., 2010; Turner et al., 2014). Considerable progress has been made towards these goals in the recent literature, and comprehensive methodological guidelines for assessing trade-offs between ES were first compiled by Mouchet et al. (2014). More specifically, Deng et al. (2016) recently summarized the tools and approaches that have been used for ES trade-off analyses in land use and management studies. Howe et al. (2014) conducted a comprehensive meta-analysis of ES relationships revealing how environmental or social conditions result in trade-offs between ES. In their recent quantitative review, Lee and Lautenbach (2016) showed that relationships between regulating and provisioning ES are dominated by trade-offs while synergies are mostly observed among regulating and cultural ES. However, the authors also note that – even though these patterns are consistently observed in their analysis – causality cannot be universally assumed.

The aim of this paper is to review the current scientific literature on ES relationships, focusing on trade-offs, synergies and bundles. We address different research objectives and the motivation why studies on ES relationships were performed. Based on the relevant literature, we identify the most prominent definitions and concepts, include viewpoints of different disciplines and highlight the major challenges for understanding ES relationships. Our aim was to cover a variety of applied approaches and to pinpoint the major cross-cutting themes. Ultimately, we aim to guide researchers towards areas that require future research and help developing more systematic analyses of ES relationships.

2. Methodology

This paper emerged from a series of monthly meetings among authors belonging to a multi-disciplinary team (with backgrounds in ecology, geography, environmental sciences, agricultural sciences, forest sciences, mathematics, economics and business administration) held between June 2015 and March 2016. The authors are involved in either (i) the development of methods for analyzing ES relationships or (ii) research on ES trade-offs, synergies or bundles in different case study regions. During the first phase of these meetings, key papers central to the literature on ES relationships (e.g. Bennett et al., 2009; Raudsepp-Hearne et al., 2010; Howe et al., 2014; Mouchet et al., 2014) and related literature that the authors were already familiar with were read by the team and then discussed in plenary. Based on these papers, the important concepts, methods and cross-cutting themes relevant to research on ES relationships were identified. In the second phase, authors split into teams and reviewed the scientific literature focusing on specific aspects (e.g. methods used to characterize ES relationships, stakeholder involvement). Progress and problems were reported back to the whole group during the monthly meetings. As a result of these discussions, we structure this paper along the following four research objectives that were prevalent in studies on ES relationships (see Fig. 1, Table 1):

(i) the identification and characterization of co-occurrences of ES, in particular those ES which are positively or negatively associated (Raudsepp-Hearne et al., 2010; Willemen et al., 2010; Turner et al., 2014);
(ii) the identification of drivers (González-Esquivel et al., 2015), environmental or social pressures (Martín-López et al., 2012) that shape ES relationships;
(iii) the exploration of biophysical constraints of landscapes and limitations to their multifunctionality, often using optimization approaches (Seppelt et al., 2013); and
(iv) the support of environmental/spatial planning, management and policy decisions (White et al., 2011; Kline and Mazzotta, 2012).

In addition, we identified three major cross-cutting themes that deserve special attention in analyses of ES relationships (Section 4). While some of these aspects have already been discussed elsewhere (e.g. Villamagna et al., 2013; Grêt-Regamey et al., 2014), their importance with respect to ES trade-offs, synergies and bundles has not yet been thoroughly examined. Finally, we synthesize possible important directions for future research on ES relationships (Section 5). Acknowledging the uncovered drivers and research gaps in future analyses will greatly advance our understanding of ES relationships.

3. Typology of case studies and main objectives

3.1. Identification and characterization of ES co-occurrences

The identification and characterization of ES co-occurrences provides insight into which ES are available at the same location, and whether the presence of one ES excludes another (Rodriquez et al., 2006). Indeed, many ES studies aim at identifying, characterizing and often mapping co-occurrences of ES (e.g. Raudsepp-Hearne et al., 2010; Willemen et al., 2010; Turner et al., 2014). For example, studies on ES bundles often focus on the most dominant ES at the landscape-scale (e.g. provisioning of crops, destinations of tourism, mapping of social-ecological systems or multifunctional bundles; Turner et al., 2014; Crouzat et al., 2015; Hamann et al., 2015; Queiroz et al., 2015). However, studies focusing on ES co-occurrence tend to neglect causal relationships and usually concentrate on either trade-offs, synergies or bundles without exploring the three together.

ES co-occurrences are typically assessed for a specific location or spatial unit at a given time. Therefore, such analyses provide snapshots of ES relationships and do not allow drawing generalized conclusions about the observed relationships or extrapolating them beyond the study area (Mouchet et al., 2014). To date, only few studies have analyzed ES relationships over time (but see Lautenbach et al., 2011; Renard et al., 2015), possibly due to the lack of monitoring data. A variety of statistical and computational methods have been used to detect and quantify spatial or temporal co-occurrences among ES (Mouchet et al., 2014). For example, pairwise correlation and statistical tests (see also Fig.1a, ①) are most commonly applied to identify the general direction and strength of trade-offs and synergies (e.g. in Ruijs et al., 2013; García-Llorente et al., 2015; Queiroz et al., 2015). Descriptive methods are also frequently employed to investigate ES relationships (more details in Lee and Lautenbach, 2016). ES bundles are often detected with the use of statistical clustering methods (e.g. K-means, Principal Component Analysis PCA; Raudsepp-Hearne et al., 2010; Queiroz et al., 2015). PCA either assists to understand the clustered results or provides input data to determine ES bundles (Hanspach et al., 2014; Turner et al., 2014). Illustration of ES bundles is often done using so-called spider diagrams or flower plots (Fig.1a, ②).

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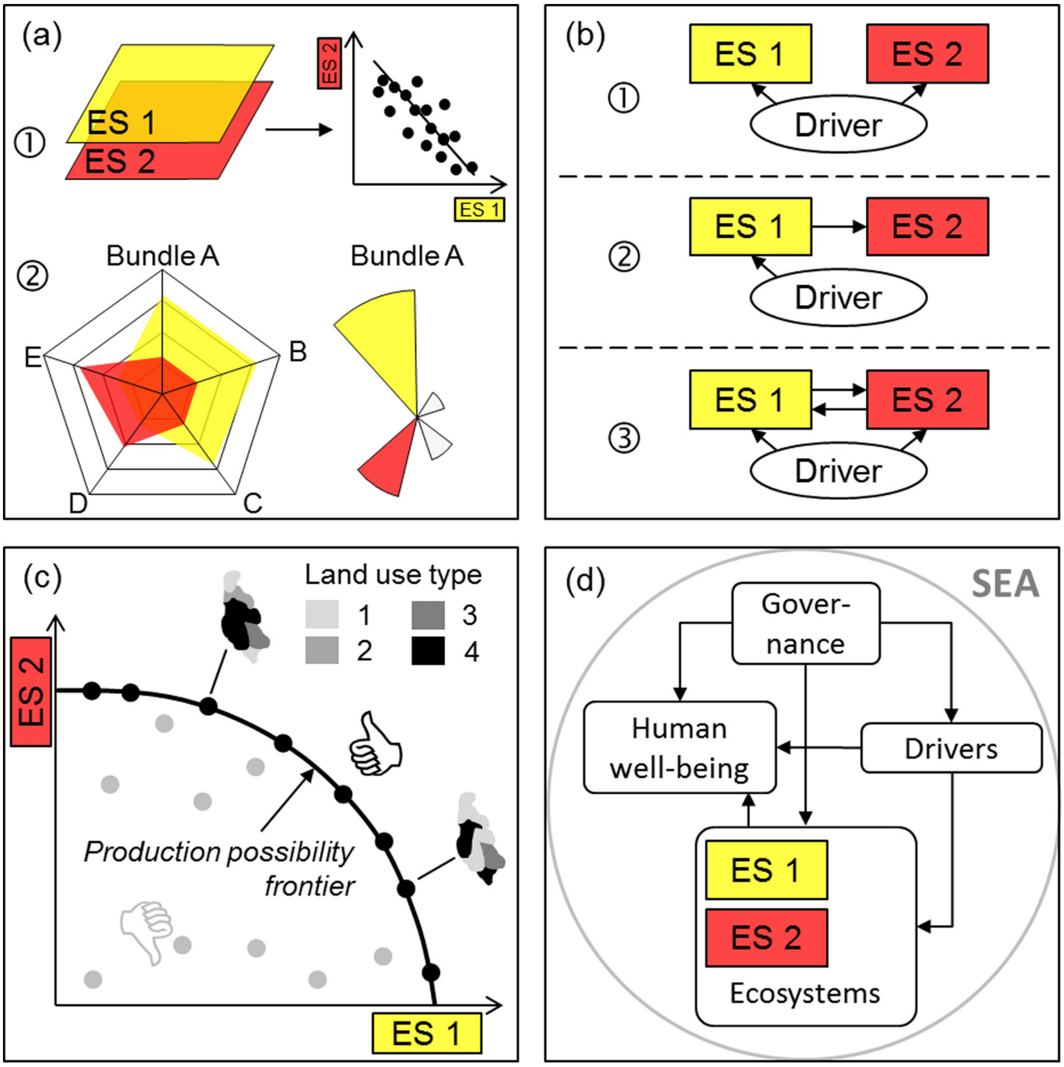

Fig. 1. The four major research objectives of studies on ES relationships. Each of the boxes represents one of the research objectives we identified in this review: (a) The identification and characterization of ES co-occurrences: ① Spatial overlay of ES maps and correlation analysis, ② Illustration of ES bundles using so-called spider diagrams (showing multiple bundles A–E) or flower plots (for bundle A); (b) the identification of drivers, environmental or social pressures and underlying mechanisms: ① Common environmental or socio-economic drivers lead to or reinforce the observed trade-offs or synergies, ② Direct interactions between ES lead to trade-offs or synergies, ③ Combined effects of ① and ② (modified from Bennett et al., 2009); (c) the exploration of biophysical constraints of landscapes and limitations to their multifunctionality: The production possibility frontier (connected black points) represents the Pareto optimal supply of multiple ES given a landscape's capacity. Spatially-explicit solutions (maps) may be obtained by coupling models with optimization techniques. All grey points inside the frontier can be produced but are inefficient because more of one or multiple ES could be provided; (d) the support of environmental planning, management and policy decisions: potential integration of multiple ES in decision-making, illustrated by Strategic Environmental Assessments (modified from Partidario and Gomes, 2013).

3.2. Identification of drivers, environmental or social pressures that shape ES relationships

Drivers, i.e. the factors that cause ES relationships to develop or change (Bennett et al., 2009), often have positive and/or negative effects on multiple services at once (e.g. fertilization may increase agricultural yield but negatively affect pollination). When identifying drivers quantitative as well as qualitative methods may be employed. Uni- or bidirectional interactions among ES often emerge from the same underlying ecological functions or functional traits that are relevant to several ES (Mace et al., 2012). Neighborhood effects (e.g. pollination from natural habitat has positive effects on productivity; Klein et al., 2003) also play an important role for ES relationships. However, one may also come across non-causal co-occurrence of ES or 'no effect relationships' (Mouchet et al., 2014). These can also be an artifact of ES mapping techniques because several ES may co-occur in the same spatial unit (e.g. within a district, see Section 3.1) although at finer scale they do not spatially overlap.

Common drivers of ES trade-offs and synergies can be identified using a variety of statistical approaches, such as regression methods or machine-learning techniques (Mouchet et al., 2014). For example, Renard et al. (2015) identified socioeconomic and biophysical drivers behind the relationships of nine ES by using redundancy analysis. Alternatively, spatio-temporal simulation models (e.g. InVEST (Tallis and Polasky, 2009) and ARIES (Villa et al., 2014a)) may be used to simulate drivers and functions for ES provision. Recently, the process-based watershed model SWAT (Arnold et al., 1998), which simulates the impact of land use and land management on water- and soil-related processes and crop yield, attracted growing attention for studying ES trade-offs (Logsdon and Chaubey, 2013; Francesconi et al., 2016).

In addition to these quantitative methods, interviews (Palomo et al., 2011; Kari and Korhonen-Kurki, 2013) and focus group

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Table 1
The main objectives of recent studies on ES relationships. While these objectives are not mutually exclusive, they differ regarding their typical research questions, important concepts and methods as well as the major challenges they pose.

Main objective	Typical (research) questions	Important concepts	Relevant methods	Recent achievements & major challenges
Identifying and describing ES co-occurrences	Are ES provided or can be used simultaneously in the same location or at the same time? Does the presence of one ES exclude the presence of another? Which locations exhibit similar ES combinations?	ES bundles	Pairwise correlation coefficients and statistical tests Combination of multivariate analyses like PCA and K-means cluster analysis	Increasing awareness of temporal changes in ES co-occurrences Need to consider spatial autocorrelation of ES indicators
Identifying drivers, environmental or social pressures and their underlying mechanisms	What are the important drivers for ES relationships? Is the similarity in ES relationships between localities explained by a similar combination of drivers?	Distinction of two principal mechanisms (common drivers and direct interactions)	Statistical, quantitative analysis of empirical data Process-based simulation models Qualitative methods (e.g. interviews, focus group discussions)	Need for further empirical studies, in particular considering neighborhood effects Selection of appropriate system boundaries remains open
Exploring biophysical constraints of landscapes and limitations to their multifunctionality	What is the capacity of a landscape to provide different ES at the same time (balancing ES provision)? Where (and how strong) are the trade-offs among conflicting objectives?	Economic concept of production possibility frontiers (PPFs)	Data-driven empirical approaches, simple mathematical models or spatially explicit, process-based models Heuristic and meta-heuristic optimization approaches	Great potential of combining scenarios with the findings of optimization approaches (to support decision-making) Challenge of combining multiple ES models to derive PPFs Challenge of integrating biophysical focus with analysis of stakeholders' preferences for ES
Supporting environmental planning, management and policy decisions	What are planning or management solutions that evaluate potential trade-offs and minimize conflicts between multiple land uses and ES? What is the foreseeable impact given a certain initiative, measure, plan etc.?	Human wellbeing Rational choice	Environmental Impact Assessment (EIA) Strategic Environmental Assessment (SEA) Cost-benefit-analysis (CBA) Multi criteria analysis (MCA)	Integrating the perspectives of beneficiaries/providers and winners/losers in traditional planning approaches Facilitating integration of sectoral planning (e.g. traffic, nature conservation, housing) Challenge of generating standard values for decision-making

discussions (Abunge et al., 2013) are used to identify drivers of changes in ES availability. These approaches unravel the interplay of factors that cause ES trade-offs and identify 'winners and losers' of ES relationships (see also Section 4.3). Even the combination of quantitative and qualitative techniques may be useful for the study of drivers for ES trade-offs, synergies and bundles. For example, by combining ecosystem and participatory models for exploring socio-ecological dynamics and discursive scenarios, Daw et al. (2015) identified ES trade-offs and their drivers and evaluated their perception by stakeholders.

3.3. *Exploration of biophysical constraints of landscapes and limitations to their multifunctionality*

Exploring the biophysical constraints of landscapes and limitations to their multifunctionality and ES trade-offs is commonly achieved through production possibility frontiers (PPFs) (Arthaud and Rose, 1996; Kline and Mazzotta, 2012; Cavender-Bares et al., 2015a). PPFs, also called 'efficiency frontiers' (Polasky et al., 2008; Nelson et al., 2008), originate from the concept of Pareto-optimality. This allocates ES in a way that no increase of one ES is possible without decreasing another. When considering two competing ES, the trade-off is simply the slope of the PPF at any point, i.e. the rate at which one service must be reduced to provide more of another service. Using PPFs, ES trade-offs and synergies can be distinguished due to the nonlinear nature of ES (Lester et al., 2013).

PPF studies mainly differ in how they approximate PPFs (e.g. data-driven or optimization approaches). Moreover, mathematical models have been applied to illustrate PPFs (Cavender-Bares et al., 2015a; King et al., 2015). Some authors (e.g. Crossman et al., 2013; Logsdon and Chaubey, 2013; Duku et al., 2015; Turner et al., 2016) also use spatially explicit models such as InVEST or SWAT (Section 3.2) to explore the multifunctionality of landscapes. Beyond the use of scenarios, PPFs can be approximated by coupling models to heuristic or metaheuristic (search or optimization) algorithms. For example, Polasky et al. (2008) combined the results of a set of biological and economic models in order to maximize biodiversity conservation objectives for given levels of economic returns (and vice versa). Lautenbach et al. (2013) identified optimization-based trade-offs among crop yields and water quality/quantity indicators by coupling SWAT with the Non-dominated Sorting Genetic Algorithm (Deb, 2002). This algorithm is one of the most frequently used genetic procedures to approximate Pareto optimal solutions (Malczewski and Rinner, 2015). In the context of multi-objective land use optimization, other algorithms have been also used (reviewed in Memmah et al., 2015).

3.4. *Support of environmental planning, management and policy decisions*

To define different likely changes in land use and resulting effects on ES synergies and trade-offs, most planning and management studies consider either scenarios on climate and policy change (e.g. Bateman et al., 2013), specific land use planning scenarios (e.g. Goldstein et al., 2012) or develop their own participatory scenario planning frameworks (e.g. Palomo et al., 2011; Daw et al., 2015).

Environmental Impact Assessments, that evaluate the likely environmental impacts of a proposed development project prior to decision making, and Strategic Environmental Assessment Frameworks, which aim at incorporating environmental consequences early on, use economic valuation of environmental impacts and cost-benefit analysis (CBA) to derive

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recommendations for mitigating trade-offs. This is done, for example, by valuing changes in ES or by assessing potential costs for offsetting environmental impacts. In some instances CBA is required by law. Nevertheless, there is growing concern whether such utilitarian frameworks do cover all relevant environmental impacts or are appropriate to assess ES trade-offs (Spash, 2008; Vatn, 2009; Kenter et al., 2015). Deliberative valuation and multi-criteria analysis offer solutions to this concern (Lienhoop et al., 2015; Mastrangelo et al., 2014).

4. Cross-cutting themes

4.1. Distinction between supply and demand

Quantitative studies that assess and map the relationship between the supply and social demand of ecosystem services are still scarce (but see Castro et al., 2014; Quintas-Soriano et al., 2014). Studying trade-offs between ES, however, requires conceptual clarity with respect to differences between supply of and demand for ES (Kroll et al., 2012), which are connected via 'ES flow' (i.e. actual use; Villamagna et al., 2013). Wolff et al. (2015) distinguish two components of demand: the actual consumption of ES versus the potentially greater desires of society (see also Geijzendorffer et al., 2015). Expanding on Mouchet et al. (2014) we identify four ways to quantify ES relationships:

1. 'Potential supply': the maximum biophysically possible ES supply of a landscape. Other than Villamagna et al. (2013) in their definition of 'capacity', we do not include social constraints here. Example: The amount of wood growing during a given time period.
2. 'Actual supply': the actual ES supply by a landscape to local or distal beneficiaries, which may be considerably smaller than the potential supply. Example: The amount of wood harvested during a given time period.
3. 'Actual demand': the fulfilled demand for an ES by stakeholders. Actual supply and actual demand balance out only if there is no supply and delivery of the considered ES from outside to the study area. Example: The amount of wood used by beneficiaries during a given time period.
4. 'Potential demand': the expressed demand for an ES by stakeholders in terms of actual allocation of scarce resources (Geijzendorffer et al., 2015), similar to the desires or preferences introduced by Wolff et al. (2015). Example: The amount of wood desired by beneficiaries during a given time period.

Combining these four different ways of quantifying ES demand and supply can reveal hot-spots of diverging or converging demand and supply for a single ES. This information can be highly relevant for management decisions. For example, comparing the potential supply and the actual supply provides information on usage intensity, while comparing actual supply and actual demand may quantify locally realized ES flows (Bagstad et al., 2013). Ignoring the conceptual differences between the four types of ES supply and demand in analyzing ES relationships may therefore dilute results. However, studies on ES relationships typically overlook this distinction. They rather make use of available data, thereby using information on actual demand and potential supply. Actual supply is often quantified for regulating (e.g. carbon sequestration in kgC/ha) and provisioning services (e.g. crop yield in t/ha), whereas cultural services are mostly quantified as potential local demand (e.g. by combining population density and accessibility; Ziv et al., 2016) or potential supply (e.g. number of tourist attractions that can be visited; Raudsepp-Hearne et al., 2010) rather than actual supply (for instance number of visitors in national parks).

4.2. Consideration of scale effects

ES have complex dynamics that operate across spatial and temporal scales (Hein et al., 2006) and ignoring scale effects involves the risk of misinterpretation of ES co-occurrences. However, with respect to analyses of ES relationships, scale issues are not sufficiently represented (but see Rodriquez et al., 2006; Barnett et al., 2016).

This is directly related to the role of scale for identifying drivers and underlying mechanisms (Section 3.2), where, for instance, macroeconomic policy of food price subsidies can cause land use changes at the local scale that affect the supply of ES at the local scale (Scholes et al., 2013). Scales also play an important role in studies that aim at exploring the biophysical constraints of landscapes and limitations to their multifunctionality (Section 3.3). The higher the complexity of the modeled system (i.e. number of ES considered) and the larger the size of the study area, the higher is the probability that the relevance of different ES varies spatially within the study area. This may lead to a distortion of the trade-off simulations and wrong conclusions. Overall, appropriate consideration of spatio-temporal scales represent a core challenge – mostly due to often very long time lags between human action and environmental effects and the high complexity of systems in which ES are embedded (Underdal, 2010). Moreover, additional studies are needed that (i) combine the rigor of small-scale studies with the breadth of broad-scale assessments (Nelson et al., 2009) and (ii) assess ES relationships during different time periods (Holland et al., 2011). Frameworks enabling the visualization of trade-offs due to stakeholder's preferences at specific spatial or temporal scales (e.g. Cavender-Bares et al., 2015a) may greatly advance the current state-of-the-art.

4.3. Consideration of winners and losers

Almost every land-use change divides stakeholders into winners and losers. Three possible types of winner-loser relationships have been identified: (i) winners and losers can be part of the same community; (ii) winners and losers can be spatially separated (see also Section 4.2); (iii) winners and losers can be temporally separated (e.g. they could live at different times). Usually, analyses of ES relationships miss this issue because they focus on biophysical aspects, or because they view the demand side in aggregated terms only (Berbés-Blázquez et al., 2016). When trade-offs between ES are involved (Kovács et al., 2015), social relationships between stakeholders, institutions and governance structures are highly relevant and co-determine the option space for the management of multifunctional landscapes. If these issues are ignored, conflicts can ensue (Wittmer et al., 2006; Berbés-Blázquez et al., 2016). In a typical economic analysis of land-use change, the focus is solely on aggregated net benefits – but this obscures the fact that not all stakeholders benefit. In extreme cases, this can mean that seemingly 'optimal' land-use options violate the rights or cultural norms of the community (Daw et al., 2015).

If co-occurrence of ES (Section 3.1) is analyzed on the basis of demand data, underlying social relationships can determine the direction of co-occurrence. For example, a trade-off between agricultural production and biodiversity is often found in landscapes dominated by large-scale industrialized agriculture, even though traditional agriculture involved a positive relationship between the two. To disentangle such changes, historical analyses of ES relationships can be very helpful (Berbés-Blázquez et al., 2016; Dittrich et al., 2017). Historical analyses can also help illuminate the relevance of drivers and their links to social structures.

The sole focus on the biophysical potential for multifunctionality (Section 3.3) can obscure the importance of social factors, such as taboo trade-offs (Daw et al., 2015) or lexicographic preferences/

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incommensurable values (Temper and Martinez-Alier, 2013) – describing situations in which certain trade-offs are considered socially unacceptable and are therefore rejected. Such unacceptable trade-offs can impose limits to multifunctionality which go beyond biophysical constraints.

The identification of winners and losers is particularly relevant in studies aiming at environmental planning and management (Section 3.4), where the failure of taking into account distributional effects can have profound societal consequences and even backfire (e.g. Daw et al., 2015). When stakeholders are located in different spatial units, there is a high chance that they focus on different ES derived from the same landscape (Gantioler et al., 2010; Hicks et al., 2013; Suwarno et al., 2015). Such situations call for a disaggregated perspective: even if the net benefits of a land-use change are positive, losers may still exist who rationally oppose the changes (Daw et al., 2011). In the case of temporal mismatch between winners and losers, one of the groups usually cannot be involved in the decision making process. One option for dealing with this conundrum is intertemporal discounting, which is, however, a rather controversial and value-laden issue (Arrow et al., 2014; Heal and Millner, 2014). In other contexts, small-scale deliberative institutions (focus groups, citizens' juries) can be used to expand the perspective of stakeholders and to include the interests of future generations (O'Neill, 2001) (Table 2).

5. Directions for future research

5.1. Novel methods to account for spatial dependence in ES relationships

In most studies on ES co-occurrence (Section 3.1), spatial information is considered implicitly, meaning that spatially structured indicators of ES are referenced with their geographic locations but the dependence among neighboring sites is not accounted for. However, clustering algorithms can be used to visualize ES co-occurrences when identified groups of ES combinations are projected back onto maps. For example, Self-organizing maps (SOMs) can add important advantages as they account also for the topology of the input data (Wehrens and Buydens, 2007). SOMs have already been used widely in environmental sciences (e.g. Václavík et al., 2013; Levers et al., 2016) and were listed as a promising, novel approach for ES trade-off analysis by Mouchet et al. (2014). In contrast, accounting for spatial information explicitly is more challenging but can help us better describe and understand ES co-occurrences. We suggest that spatially-explicit methods deserve more attention in the future, as they can directly address spatial interactions between the study location and its surrounding area and allow determining the strength and significance of ES bundling. Surprisingly, only few trade-off studies applied such methods so far (e.g. Delzeit et al., 2016), whereas promising applications in related topics can be found. In one of the few examples, Kehoe et al. (2015) used the Local Indicator of Spatial Association (LISA; Anselin, 1995) to quantify the relationship between thirteen indicators of agricultural land-use intensity and measures of biodiversity at a global scale. This analysis allowed identifying areas where the focus on a single provisioning ES (e.g. food production) can be in potential conflict with biodiversity conservation.

5.2. Integration of stakeholders

For all four prevalent research objectives (see Sections 3.1–3.4), we see an increasing need to integrate stakeholders. Deliberative and participatory methods are seen 'as key ingredients for the ES paradigm to gain traction in science and policy arenas' (Martinez-Harms et al., 2015). Stakeholder engagement is important not only to define scenarios of alternative future management of natural resources (Daily et al., 2009), but also for the improvement of methods to assess ES and for the establishment of programs for long-term monitoring of biodiversity and ecosystem attributes (e.g. Gardner, 2010). From a (socio-)economic perspective, however, it is still difficult to consider future costs and benefits associated with ES trade-offs. Recently developed deliberative valuation approaches ask stakeholders to anticipate their children's needs and to consider these in their valuation of ES trade-offs (Lienhoop and Völker, 2016).

Decision-making tools, such as environmental cost-benefit- and multi-criteria-analysis, may be used to analyze the impacts of land-use decisions on stakeholders. Exploring the viability of land-use options using multi-criteria optimization (Section 3.3) requires integrating the biophysical focus with the analysis of stakeholders' preferences for ES (Mastrangelo et al., 2014). This may happen either before (*a priori*), during (interactive) or after (*a posteriori*) the optimization process (Coello Coello et al., 2007). While *a priori* approaches limit the search space for feasible

Table 2
Relevance of the three cross-cutting themes that we identified with respect to the four main objectives of studies on ES relationships.

	Distinction between supply and demand	Consideration of scale effects	Consideration of winners and losers
Identifying and describing ES co-occurrences	Missing distinction not problematic as such, as long as the different conceptual backgrounds for quantification are clearly stated	Ignorance of spatio-temporal scales involves the risk of misinterpretation of ES co-occurrences in space and time	If occurrence is analyzed on the basis of demand, winner-loser constellations can affect the direction of ES co-occurrence
Identifying drivers, environmental or social pressures and their underlying mechanisms	Drivers cannot be identified correctly if no distinction between supply and demand is made	Large-scale drivers (policies) can cause land use changes at the local scale. These may lead to changes in the supply of and relationships between ES at other scales	Winners and losers can have different influence on drivers and are key to understand social pressures
Exploring biophysical constraints of landscapes and limitations to their multifunctionality	Focusing on either supply or demand facilitates these complex analyses and eases interpretation of results	Increasing complexity (number of objectives and/or size of the modeled system) poses challenges for optimization algorithms to progress towards Pareto optimality. It may also lead to varying relevance of different ES (objective functions) at different scales	Conflicts and taboos impose restrictions upon multifunctionality of landscapes which go beyond biophysical potentials
Supporting environmental planning, management and policy decisions	Mixing supply and demand will limit the practical values of such analyses	Formal planning procedures currently often ignore the impact of land-use decisions on stakeholders beyond the spatio-temporal scale considered Scale effects are particularly important as long time lags may occur between human action and environmental effects	Management changes may lead to the emergence of new conflicts; alleviation of existing winner-loser conflicts as additional objective of management

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solutions prior to the optimization, e.g. by defining constraints (Cao et al., 2011), interactive optimization techniques allow stakeholders to adjust the solution of the algorithm in an iterative fashion, directing the optimization towards results that accomplish his/her preferences best (Eikelboom et al., 2015). *A posteriori* approaches are most commonly used to evaluate PPFs generated by evolutionary algorithms, (Deb and Köksalan, 2010). They allow stakeholders to select their preferred solutions once Pareto optimal land use and management solutions have been estimated. However, the timing at which stakeholder preferences get involved into the exploration process most likely impacts the shape of the trade-off curve, an issue which has not yet been accounted for in the literature.

Following these suggestions for methodological innovations, we see great potential in the combination of PPFs with utility functions that describe the contribution of ES to the well-being of individuals (Kline and Mazzotta, 2012; Bateman et al., 2013; Cavender-Bares et al., 2015a). There is a need for more research in this direction and comprehensive analyses, which could lead to a combination of different assessment methods taking into account the cultural, socio-economic and institutional specificities of the investigated case. A typical procedure is the (biophysical) identification/quantification of ES, followed by economic valuation, and qualitative/deliberative/participatory assessments (Martín-López et al., 2014; Hattam et al., 2015). Finally, to best support decision making and finding sustainable solutions (e.g. King et al., 2015; see also Section 3.4), more research is needed on how to combine policy-driven and stakeholder-based scenarios with the findings of optimization approaches (e.g. Seppelt et al., 2013; Gaddis et al., 2014).

5.3. Integration of ES relationships in planning and management

Available methods and tools for the characterization of ES relationships at hand (see Sections 3.1–3.3) are not being implemented or insufficiently applied in environmental planning, management and policy. As an exception, Arkema et al. (2015) applied the ES framework to design a national management plan for Belize's coastal zone through iteration of spatial modeling and stakeholder engagement. The coastal management plan was endorsed by the Belizean government in February 2016. Key methodological challenges in the field of environmental planning and management are the integration of different forms of values (biophysical, economic, insurance, social, etc.) for evaluating trade-offs (often called 'integrated valuation') and the adequate consideration of cultural ES. So far, relatively little empirical evidence has been collected on the extent and outcomes of public engagement as it is being carried out (Spangenberg et al., 2015). A recent review by Rega and Baldizzone (2015) suggests that public involvement has indeed the potential to positively influence both SEA and decision-making, although authors point to the need to support this from the policy side by stronger legal frames, higher requirements and improved technical guidance for participation. Other aspects that need to be strengthened are the integration of the ES framework into existing concepts of planning and the science-policy-interface in order to deliver scientific information on ES trade-offs to inform policy assessment, design and implementation (e.g. Goldstein et al., 2012; Förster et al., 2015).

6. Final remarks

From the growing body of literature on ES relationships we identified four major research objectives of such studies as well as three cross-cutting themes that deserve more attention. Researchers need to reflect more on their selection of ES considered so that they are representative and relevant for the case study area (i.e. ultimately dependent on the demand of stakeholders; Spangenberg et al., 2014) and to avoid biases regarding trade-offs and management decisions. Commonly analyzed trade-off curves will convey a different message depending on which component of ES supply and demand (see Section 4.1) is considered. Also the choice of methods used to determine ES relationships may influence the observed directions (as reviewed in Lee and Lautenbach, 2016).

Providing multiple ES in parallel and maximizing ES synergies are not necessarily goals to pursue. Instead, land use history (e.g. von Wehrden et al., 2014) as well as societal relevance (Robards et al., 2011) will greatly influence observed trade-offs and practical decisions on how to choose appropriate land use and management options. If there is no additional demand by stakeholders or society, increasing the supply of a certain ES might not be needed (Spangenberg et al., 2014). Other important, yet commonly ignored topics are temporal lags and intergenerational inequities, thresholds and nonlinear system dynamics (Cavender-Bares et al., 2015b). So-called ecosystem disservices, which are negative economic, health and well-being effects of ecosystems (von Döhren and Haase, 2015; Shackleton et al., 2016), may become especially relevant for trade-off analyses.

Finding and describing positive and negative co-occurrences of ES is only the first step towards understanding ES relationships. To be able to support management decisions, we need to identify drivers and underlying mechanisms and develop a holistic understanding of the complex socio-ecological systems we are dealing with. Although the number of ecological/environmental process-based models is increasing, our knowledge on interactions and feedbacks in complex socio-ecological systems is still limited. We believe that comprehensive analyses of ES relationships may ultimately provide the base for the implementation of sustainable management strategies.

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