J. Geogr. Sci. 2016, 26(7): 953-968
DOI: 10.1007/s11442-016-1309-9

A review on trade-off analysis of ecosystem services for sustainable land-use management

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Abstract: Ecosystem services are substantial elements for human society. The central challenge to meet the human needs from ecosystems while sustain the Earth's life support systems makes it urgent to enhance efficient natural resource management for sustainable ecological and socioeconomic development. Trade-off analysis of ecosystem services can help to identify optimal decision points to balance the costs and benefits of the diverse human uses of ecosystems. In this sense, the aim of this paper is to provide key insights into ecosystem services trade-off analysis at different scales from a land use perspective, by comprehensively reviewing the trade-offs analysis tools and approaches that addressed in ecology, economics and other fields. The review will significantly contribute to future research on trade-off analysis to avoid inferior management options and offer a win-win solution based on comprehensive and efficient planning for interacting multiple ecosystem services.

Keywords: ecosystem services; trade-offs; land-use management; scale; integrated modeling; multi-criteria analysis; efficiency frontier

1 Introduction

Ecosystem services, which are broadly defined and extensively identified as the benefits obtained either directly or indirectly from ecosystems, are of great significance to human wellbeing. Ecosystem services flow into human society and provide fundamental life-support for human civilization. From clean water supply to erosion control, from food provision to climate regulation, from recreation to scenic beauty, all humans' life needed are provided by Earth's ecosystems (Daily *et al.*, 1997). Since the concept of ecosystem being put forward by Tansley (1935), the study of ecological system has gradually become a scientific framework, and has been further strengthened since the end of the 20th century. With varying attentions and perspectives, from the biological basis to economic concerns, the

Received: 2016-02-02 **Accepted:** 2016-03-15
Foundation: China National Natural Science Funds for Distinguished Young Scholar, No.71225005; The Key Project in the National Science & Technology Pillar Program of China, No.2013BACO3B00
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concepts and evaluations of ecosystem services have been evolved through various research projects (Costanza *et al*., 1998; MEA, 2005; TEEB, 2010; De Groot *et al*., 2010b). Most of these research efforts were concentrated on the evaluation and mapping of the biophysical or economic values of ecosystem services at different scales, and the impact mechanisms of human activities and natural changes (Li *et al*., 2013; Deng *et al*., 2013), shedding lights on the identification of the benefits that human society receive from the nature and providing information for decision making. Clarifying the current situation of ecosystem services is a prerequisite for further analysis and solutions identification.

In real world contexts, as a kind of human civilization, the land-use management activities have profoundly altered the ecosystems. Currently, there is a trend that an ever-large amount of ecosystem goods and services have greatly benefited humans. However, the capacity of global ecosystems for sustainable development is simultaneously degrading, leading to unintentional consequences that will potentially jeopardize the future land-use options (World Bank, 2008). Confronting the global challenges that land use changes substantially affect and alter ecosystem services, trade-off analysis on ecosystem services associated with decisions between land use alternatives has become the focus of land-use management (Ryffel *et al*., 2014). In order to avoid unwanted and possibly irreversible effects of land-use change, sustainable land-use management should assess and manage inherent trade-offs between meeting the site-specific immediate human requirements and maintaining the long-term ecosystem services provisions. Trade-offs will arise if particular land-use management decisions are made, which will result in changes of the types, magnitudes and interactions of ecosystem services. In addition, since each ecosystem service is not independent, but instead exhibits complex interactions, which will further lead to different environmental or socioeconomic outcomes related to different individuals or groups (Rodríguez *et al*., 2006). Over time, in spite of the great progress and success in the assessment of ecosystem services trade-offs, the practical application in land-use management decision is limited (Daily *et al*., 2009). The underlying reason is that most studies have been focused on one or a few services without considering the interdependence and highly non-linear relationships among the ecosystem services (Ring *et al*., 2010). Land-use management and decision makings with focus only on one type of ecosystem services without considering others will result in policy failure. In this sense, the understanding and knowledge about inter-linkages and potential trade-offs among different ecosystem services should be deepened and expanded to explore new insights in innovations related to institutions and governance (Elmqvist *et al*., 2013).

Although trade-offs analysis has become a hot topic in ecosystem services researches, few studies were conducted across disciplines. This study aims to explore the most frequent ecosystem services trade-offs associated with land-use practices and management, and compare techniques that measure trade-offs among ecosystem services across spatial and temporal scale based on comprehensive revisits to relevant researches. Firstly, we summarize the definitions and characteristics of ecosystem services trade-offs, then recognize trade-offs among ecosystem services at different scales. Subsequently, we elaborate the technics in different disciplines that are applied to investigate and measure the trade-offs for decision makings. Based on the review works, it will provide a comprehensive framework for future researches on ecosystem services trade-offs, which is critical to decision making for sustainable land-use management.

2 Trade-offs of ecosystem services

2.1 Definitions of trade-offs

Trade-off is a fundamental concept in economics, while being especially applied in an evolutionary context (Garland, 2014). In economic context, a trade-off is commonly expressed as the opportunity cost which is the preferred alternative when taking an economic decision, deriving from the idea that resources are scarce, which means to obtain more of one scarce resource, an individual or group collectively must give up some amount of another scarce good (De Groot *et al*., 2010a). In the ecosystem services context, the definition of trade-offs is mainly derived from the Millennium Ecosystem Assessment (MA), which is defined as management choices that intentionally change the services provided by ecosystems (MA, 2005a). In addition, The Economics of Ecosystems and Biodiversity (TEEB) described the trade-offs of ecosystem services as the way one ecosystem service responds to the changes in another service (TEEB, 2010). There are also some refined definitions of trade-offs, indicating the interactions among ecosystem services that result in the increasing provision of one ecosystem service at the cost of other services (Haase *et al*., 2012). Generally, trade-offs of ecosystem services occurs when human interventions enhance the output of an ecosystem service while negatively affect the provision of other services (De Groot *et al*., 2010a; Elmqvist *et al*., 2013).

2.2 Recognitions of trade-offs

Over time, socioeconomic development and human wellbeing are heavily relying on the provision of natural ecosystem services. On one hand, some of the ecosystem services functions are treated with priority and are intentionally modified due to their critical and important roles in the delivery of goods and services to support the human society, on the other hand, however, some of other services are ignored and damaged (Deng *et al*., 2011; Seppelt *et al*., 2013). Ecosystem is of extreme complexity and of great spatial and temporal variation in different ecological contexts. Identifying the specific trade-offs among different types of ecosystem services at different scales would help to convey information in a clear manner and provide decision-making framework about ecosystem services across geographic, ecological and socioeconomic dimensions (Ruhl *et al*., 2007; Tallis *et al*., 2008). In addition, it can also facilitate scientists and policy makers a better understanding of the potential consequences of unbalanced treatment of the ecosystem services in the process of land-use management (Haase *et al*., 2012).

2.2.1 Trade-offs in ecosystems

Considering the complexity and interactions of the ecosystems services for the human society, researches on the trade-off analysis between the provisioning and regulating services and investigations on the relationship of multiple ecosystem services and biodiversity are provoking. Agroecosystem is a good example in this case (Bennett and Balvanera, 2007; Nelson *et al*., 2008; Ring *et al*., 2010; TEEB, 2010; Elmqvist *et al*., 2013).

Agricultural land covers about 35% of the Earth's terrestrial surface (MA, 2005c), providing a series of provisioning (e.g., food, wood, and water), regulating (e.g., climate, carbon, and erosion), supporting (e.g., pollination, biodiversity/habitat), and cultural (e.g., recreation and education) services (Power, 2010). Over the past decades, humans changed the Earth's surface extensively for agriculture activities to meet the increasing demand for provisioning services, which severely affect the current and future generation of many regulating services and biodiversity (Bennett and Balvanera, 2007). For agroecosystem, the typical problem is that agricultural intensification and centralization related to the provisioning ecosystem services for higher macro-economic output usually reduce or damage other ecosystem services related to the ecosystem regulation and maintenance, as well as cultural services (Kirchner *et al*., 2015).

There are several studies explicitly analyzed the possible trade-offs among ecosystem services for agroecosystems. Specific trade-offs have been identified, such as the interactions between agricultural production and regulating services, e.g. sediment yield (Swallow *et al*., 2009) and carbon sequestration (Crossman *et al*., 2011). Biodiversity conservation is also commonly viewed as trade-off with agricultural production. Biodiversity is not equated to a specific ecosystem service or bundle. Most studies tried to investigate the trade-offs between biodiversity conservation and bundles of ecosystem services in agroecosystems. Barraguand *et al*. (2011) explicitly analyzed the trade-offs between valued agricultural production and biological conservation at the landscape scale. Mason *et al*. (2012) revealed that the investment directed into mitigating the impacts of agriculture on ecosystem services rather than biodiversity restoration would result in lower biodiversity. One research examined the potential trade-offs between agricultural production and biodiversity benefits, revealed that the benefit gained from an increase in biodiversity would outweigh the loss of returns from agricultural production (Dymond *et al*., 2012).

Little evidence and quantitative analysis on the interactions and linkages among ecosystem services bundles had been recognized as a major research gap regarding ecosystem services (Carpenter *et al*., 2009) and resulted in mixed conclusions (Bohensky *et al*., 2006). Recently, in order to provide implications for sustainable land-use management, researches on the types of interactions and the corresponding feedbacks among different ecosystem services are stimulated. For example, Brauman *et al*. (2007) revealed that water quality regulation services with other services, such as habit for biodiversity and climate regulation, can be co-delivered by vegetation, requiring the analysis of trade-offs among multiple services (Butler *et al*., 2013). It has been a major research priority to consider biodiversity conservation bundles and ecosystem services bundles during payment implementation (Wendland *et al*., 2010). In addition, some studies have revealed that when taking multiple services into consideration, the outcomes with maximized net gains of land-use management will be achieved more efficiently (Crossman and Bryan, 2009).

Intensive land-use change and management have been recognized as the major drivers that alter ecosystem services provision from agroecosystems (Sheng *et al*., 2011; Bryan, 2013). Wang *et al*. (2015) quantified the multiple ecosystem services in the Sanjiang Plain of China and concluded that the significant loss of ecosystem carbon stocks and natural habitats with grown food production was due to the extensive land conversion from natural wetlands to cultivated land. Similarly, Haines-Yong *et al*. (2012) confirmed a trade-off between the provisioning services ("crop-based production") and regulating services ("habitat diversity”). Also, during the process of ecological restoration, which converted the agricultural land back into natural ecosystems, trade-offs can be found among different ecosystem services, such as trade-off between biodiversity and salinity mitigation (Maron and Cockfield, 2008), between carbon sequestration and species conservation (Nelson *et al*., 2008), food production (Paterson and Bryan, 2012), and water supply (Chisholm, 2010). While, as humans play a critical role in managing the agroecosystem, political practices, socioeconomic incentives and technological progresses are likely to influence the quantity and quality of ecosystem services, which will further affect the direction of trade-offs (Nelson *et al*., 2009). Compared to the results of the research conducted by Wang *et al*. (2015), the study in the Loess Plateau of China by Lü *et al*. (2012) showed an opposite result, indicating synergy between food production and ecosystem carbon stocks with the conversions from farmland to woodland and grassland, which can be contributed to agricultural technological growth, improvement of agricultural management and production efficiency (Lü *et al*., 2012). Nelson *et al*. (2009) also identified that policy interventions could modify the negative trade-offs between commodity production and other ecosystem services and also biodiversity conversions. Maes *et al*. (2012) confirmed that there exist trade-offs among provisioning ecosystem services, regulation services and biodiversity conservation from agroecosystems, while he emphasized that trade-offs can be mitigated through specific management measures, such as increase cropping diversities and plant buffer strips. In this sense, trade-offs between agricultural production and other ecosystem services are not inevitable. Analysis on yields from agroecosystems indicated that with efforts on practice to conserve ecosystem services through measures, such as conservation tillage, crop diversification and biological control, ecosystem services trade-offs would be mitigated, with even improvements in yields (Badgley *et al*., 2007). These analyses suggest trade-off analysis should be incorporated into the land-use management decision making process, which can make a ‘win-win’ situation possible, where provisioning services are maintained and enhanced whilst other ecosystem services are supported.

2.2.2 Trade-offs of ecosystem services at different scales

The recognition of trade-offs should be conducted at different scales. It is commonly acknowledged that ecosystem services trade-offs occur at different spatial and temporal scale (Rodríguez *et al*., 2006; Power, 2010) and vary across both space and time (Holland *et al*., 2011), which increase more uncertainty to be managed. In addition, trade-off analysis from other perspectives are also proposed to be of great significance to land-use management and decision making, such as trade-offs among different stakeholders (Ring *et al*., 2010) and the reversibility of ecosystem services (Rodríguez *et al*., 2006).

(1) *Trade-offs at time scale*. Trade-offs at time scale arises when policy-makers make choices between current and future benefits. Identifying such trade-offs can help policy-makers understand that management decisions should consider the long-term effects of preferring the short-term provision of one ecosystem services at the expense of future use of this same service or other services (Rodríguez *et al*., 2006). Rodríguez *et al*. (2005) elaborated a broad topic about the temporal trade-offs during decision makings, which revealed that there would be many important trade-offs between current use of nonrenewable resources and their future use. It was pointed out that slowly natural processes, such as soil formation, groundwater supply and genetic diversity generation that underlay supporting

services, were always being ignored since that they were difficult to be detected and quantified, which would seriously damage the long-run sustainable provision of ecosystem services (Rodríguez *et al*., 2005). For example, the collective activities of farmers to replace the original woody vegetation with pasture and corps for the short-term increase in agricultural production led to the water table being moved toward the surface, bringing salt upward through the soil, which finally resulted in land salinization in the long-term future (Greiner and Cacho, 2001; Briggs and Taws, 2003). Regarding the natural processes, there exist a great deal of uncertainties associated with large time lags in the feedback between changes in ecosystem process and other factors, posing much more difficulties in forecasting eventual outcomes and identifying the critical thresholds of ecosystem services (Holling, 1973; Rockström *et al*., 2009). For a balanced feedback loop during the resources management, the ability to recognize the trade-offs between current and future desirable states and 'time preferences' for ecosystem services becomes important and critical to make better decisions on land-use management (van den Belt *et al*., 2013).

(2) *Trade-offs at spatial scale*. Spatial trade-offs could be simply recognized as benefits here while cost there (Ring *et al*., 2010), it occurs spatially between different landscapes, ecosystems, communities and even countries. For example, the improvement in water productivity with more agricultural inputs in the upstream will consequentially impact the water quality regulation services and incur costs in the downstream (Pattanayak, 2004). Such trade-offs have been illustrated specifically in the agricultural production in the USA, where the highly intensive agriculture relied greatly on artificial fertilization and finally led to massive negative impacts on the fisheries in the Gulf of Mexico (Tilman *et al*., 2002; Cumming, 2005). Spatial trade-offs are also well-known in economics, the environmental economists use spatial externality to indicate the positive or negative effects of land-use management decisions on ecosystem services in extended areas than those ecosystem services of where the decisions incurred that cost or benefit (Tietenberg, 1988). For example, the extensive division of water from rivers for drinking or agriculture irrigation in the upper regions will trigger water scarcity in the regions lower down the watershed (Falkenmark, 2003), while the local cost to conserve the biodiversity will benefit the global (Ring, 2008). The need to account for the spatial effects outside traditional geopolitical boundaries when facing ecosystem services decisions has been recognized by many managers, while practically it was rare that managers would give consideration to large-scale benefit at the cost of local wellbeing. It implies that incentives are needed to encourage managers think broadly to integrate experiences of small-scale "win-win" solutions to solve large-scale and macro problems (Rodríguez *et al*., 2005).

(3) *Trade-offs among stakeholders*. Ecosystem services trade-offs among stakeholders mean that some stakeholders win while others lose, that is, one benefits from a particular ecosystem service at the cost of other individuals (Rodríguez *et al*., 2006). The UK National Ecosystem Assessment (UKNEA) defined such trade-offs as two outcomes: one is that the quality or quantity of an ecosystem service being utilized by one stakeholder was reduced or deteriorated due to others' utilization of that or other ecosystem services; the other one is that the utilization of ecosystem services by one stakeholder would lead to the decline of others' wellbeing (UKNEA, 2011). Different stakeholders derive wellbeing from a variety of ecosystem services based on their choices of development and management of particular

services, which are strongly influenced by lots of factors, such as their beliefs, preferences and experiences over time (McShane *et al*., 2011). Trade-offs occur among different ecosystem services due to inherent biophysical constraints in time and over space, then the divergent preferences on ecosystem services of different stakeholders will trigger conflicts (Martín-López *et al*., 2012). For instance, land use activities in terrestrial ecosystems impact the water regulation services through hydrological processes, then it will arise the conflicts among a range of associated stakeholders that depend on terrestrial ecosystems and aquatic ecosystems (Silvestri and Kershaw, 2010). In this case, reconciling stakeholders' divergent preferences over ecosystem services with explicit recognition of the nature of biophysically based trade-offs is crucial to identify sustainable solutions (King *et al*., 2015). With stakeholders' preferences being valued and added into the trade-off analysis, it makes the values intrinsic to ecosystem services (Brauman *et al*., 2007), and most researchers recently thought that the values as sources of conflicts that should be separated with biophysical constraints (Mouchet *et al*., 2014; Yahdjian *et al*., 2015). Especially, Cavender-Bares *et al*. (2015) presented a sustainability framework that characterizes ecosystem services trade-offs in terms of two dimensions of ecosystem service conflicts: biophysical constraints, and divergent preferences and values of stakeholders. The framework enables the identification of driving factors of and direct visualization of trade-offs due to stakeholders' preferences at spatial or temporal scale (Cavender-Bares *et al*., 2015). King *et al*. (2015) further evaluated the utility of the framework for ecosystem services trade-off analysis with critical insights to clarify conflicts among stakeholders under different scenarios.

(4) *Trade-offs in terms of reversibility*. Reversibility of ecosystem services means the possibility of disturbed ecosystem service being reversed back to its original state once the perturbation ceased (Rodríguez *et al*., 2005). In addition that trade-offs effects can be felt over time and spatial scale, indeed, some trade-offs may be irreversible. Regarding that the ecosystem services may be changed irreversibly, the importance of thresholds has been highlighted in the Millennium Ecosystem Assessment (MA, 2005b). When a system crosses a threshold due to persistent or strong environmental or socioeconomic drivers, it will trigger great costs to society due to the irreversible loss in critical natural capital (Farley, 2012). Ring *et al*. (2010) interpreted the thresholds as resilience, which stands for a system's ability to adapt to the perturbations and stay persistent without changes. Further, considering the thresholds, they put forward four types of non-linear dynamics in ecosystems. It includes: a system with 'no-threshold effect', where it is revisable no matter how the changes in the controlling variables; a system with 'threshold, no alternate attractors', where slight changes in controlling variables will significantly alter the system while it is still revisable if changes pass the threshold; a system with 'threshold, alternate stable state', where it may be irreversible with large changes in the controlling variables that pass the thresholds; and a system with 'irreversible threshold change', where the changes shall not exceed thresholds to avoid irreversible situations (Ring *et al*., 2010). The existing of thresholds and relevant irreversible dynamic changes may curse various problems for sustainable development of socioecological systems, e.g. application of fertilizer in agricultural production that exceeds the thresholds will pose negative impacts on water quality. While with recognition of the thresholds, better management measures can be taken to shift the trade-off thresholds, such as that precise agriculture will achieve greater crop yield with same inputs, while with less damages to

ecosystems (Cavender-Bares *et al*., 2015). Thus, being aware of how far-reaching the effect, whether the effect is reversible, and how quickly can it be reversed, managers can make decisions appropriately to mitigate negative effects and even achieve “win-win” situations (Rodríguez *et al*., 2005).

In dealing with the trade-offs in the context of ecosystem services, there exist multiple interactions and linkages among services at different scales that should be taken into consideration at first place, such as processes and management interventions of different stakeholders across various spatial and temporal scale. In addition, variations in the thresholds of ecosystems are closely related with the reversibility, making it difficult to estimate the ecological status. Facing the above issues, managers should complement their decisions with trade-offs at multiple spatial, temporal and stakeholder scales into consideration, with recognition of the threshold to minimize the negative effects of trade-offs.

3 Quantification analysis of trade-offs

Management of the complex socio-ecological system requires tools to depict trade-offs among ecosystem services. As reviewed above, the major barriers to effective management contribute to that services trade-offs differ across time and space, and that different groups of stakeholders possess different preferences for services. To deal with the barriers, researches in different disciplines have applied a variety of tools and approaches to quantitatively analyze these ecosystem service trade-offs. For a comprehensive knowledge of tools and approaches, we conduct a review of how ecosystem services trade-offs being analyzed at different scales from various perspectives.

3.1 Mapping trade-offs via correlation analysis and cluster analysis

GIS-based spatial mapping analyses are frequently applied to provide detailed information on ecosystem services indicators and further assist to understand and visualize potential trade-offs (Kirchner *et al*., 2015). For example, Maes *et al*. (2012) confirmed trade-offs between multiple ecosystem services and biodiversity with GIS-based spatial mapping and correlation analysis in Europe. Similarly, Maskell *et al*. (2013) identified intensive trade-offs between soil carbon storage and above-ground net primary production based on maps and pairwise correlations. The two examples above just investigated the trade-offs among multiple ecosystem services across space with no changes at time scale. While in practical terms, trade-offs are usually identified in response to land-use changes under particular management actions and measures or designed scenarios over time. Jiang *et al*. (2013) mapped changes in agricultural production, carbon storage and biodiversity, and further conducted spatial statistic analysis on the trade-offs at landscape scale in the UK during 1930-2000. In addition, trade-off analysis is mostly conducted from the perspective of biophysical supply side, while studies are scarcely conducted to assess and map ecosystem services trade-offs from the aspect of social demand side. To address both biophysical supply and social demand sides, Castro *et al*. (2014) identified ecosystem services trade-offs based on correlation analysis, both on the supply and the social demand sides, and analyzed spatial mismatches among the ecosystem services on biophysical, socio-cultural and economic dimensions within a spatial unit (Castro *et al*., 2014).

Correlation analysis of the trade-offs based on mapping simply identifies the interactions between pairs of ecosystem services, while trade-offs and synergies are more generally found within the bundles of services, indicating that a more integrated perspective on bundles of services is required for trade-off analysis among ecosystem services (Haines-Young *et al*., 2012). Regarding the interactions among ecosystem services bundles, cluster analysis was mostly applied. Cluster analysis based on mapping is a powerful tool to identify ecosystem service bundle types and analyze ecosystem services trade-offs and synergies (Raudsepp-Hearne *et al*., 2010). Especially, it is a more appropriate way when prior knowledge about what the trade-offs involve is not available (Medcalf *et al*., 2014). Raudsepp-Hearne *et al*. (2010) applied the concept of ecosystem service bundles to analyze interactions among ecosystem services, in which cluster analysis determined the provision of all 12 ecosystem services and grouped the 137 municipalities into six data clusters. Also, Haines-Young *et al*. (2012) explored the trade-offs between the selected services with cluster analysis, in which seven spatially explicit clusters were distinguished with distinct evolutionary trajectories of ecosystem services.

GIS-based spatial mapping with accompanied correlation or cluster analysis on the interactions among ecosystem services is a useful tool to provide specific information for trade-off analysis. Nonetheless, it is criticized that there are some shortcomings, such as less focused on biodiversity, mostly dominated at regional scale, and rarely considered detailed bottom-up economic modeling of land-use management (Kirchner *et al*., 2015).

3.2 Integrated modeling for trade-off analysis

In comparison with the widely applied GIS-based tool for spatial ecosystem services trade-off mapping analysis, integrated modeling approach can deal with some shortcomings raised above, which not only allows for a spatially explicit quantification of the ecosystem services changes over time and space (Huber *et al*., 2013), but also can link disciplinary data and models to clarify complex interactions between the human society and the ecosystems (Falloon and Betts, 2010; Laniak *et al*., 2013). Recently, the integrated modeling approach has been widely applied in the assessment of trade-offs in ecosystem services (Nelson *et al*., 2009; Polasky *et al*., 2011; Willemen *et al*., 2012). For example, Briner *et al*. (2012) designed an integrative modeling framework–Alpine Land Use Allocation Model (ALUAM), which not only specifically considers the spatial scale at which decisions are made, but also the economic interdependencies among ecosystem services. Further, they applied the ALUAM to evaluate spatially explicit trade-offs among food provision, protection against natural hazards, carbon sequestration, and biodiversity in a mountain region in the Swiss Alps within designed scenarios (Briner *et al*., 2013).

Among the integrated modeling tools, the most currently available and applied tool is the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) (Nelson *et al*., 2009; Tallis *et al*., 2011), which was designed to inform decisions about resources management and planning. Nelson *et al*. (2009) applied InVEST to investigate the trade-offs between biodiversity conservation and ecosystem services under stakeholder-defined scenarios of land-use/land-cover change in the Willamette Basin. It showed that such trade-offs varied in different scenarios, suggesting that analyzing trade-offs between ecosystem services did great favor in more effective, efficient, and defensible decision makings (Nelson *et al*., 2009). Goldstein *et al*. (2012) revealed the trade-offs between carbon storage and water quality and also between environmental improvement and financial returns under seven land-use planning scenarios based on InVEST, which support the implement of the plan for diversified agriculture and forestry management. However, Jackson *et al*. (2013) pointed out that InVEST was widely applied at large scale and with coarse resolution, in comparison, they designed the Polyscape tool, which can be used to disentangle spatially explicit ecosystem services trade-offs to support landscape management, from individual field scale through to catchments scale. Further, they compared the similarities and dissimilarities among different tools, such as Artificial Intelligence for Ecosystem Services (ARIES) tool, Envision tool, and the framework and models developed within Multiscale Integrated Earth Systems project (MIMES) (Jackson *et al*., 2013).

There has been great advances in the development and application of integrated modeling approach for ecosystem services and trade-off analysis, while comparing the dissimilarities among the integrated modeling tools, it can be noted that, considering the spatial differences and regional heterogeneities, there still exist space and opportunities for innovations on multi-scale and multi-regional integrated modeling frameworks for ecosystem services trade-off analysis at a higher spatial resolution (Crossman *et al*., 2013).

3.3 Multi-criteria analysis of trade-offs

Ecosystem management will inevitably involve conflicting objectives, trade-offs, uncertainties and conflicting value judgments (Sanon *et al*., 2012), making it a complex process for policy design for ecosystem management. To address above interdisciplinary and complex problems, multi-criteria analysis, as a tool that can take both ecological and socioeconomic criteria into consideration, is mostly applied to conduct ecological economic analysis (Huang *et al*., 2011; Fontana *et al*., 2013). Multi-criteria analysis had been applied in various disciplinary researches and recently been broadly introduced and utilized to solve the problems in ecosystem services management (Daily *et al*., 2009; Nelson *et al*., 2009). For example, Cheung and Sumaila (2008) applied the multi-criteria analysis to explore the trade-offs between conflicting conservation and socioeconomic objectives for tropical marine ecosystems management.

Traditional multi-criteria analysis deals with only the implicit trade-offs through introducing the weights expressed by the stakeholders (Van Huylenbroeck, 1997), to enhance the transparency, Sanon *et al*. (2012) assigned numerical values for ecosystem services to elaborate and quantify the trade-offs between the stakeholder's objectives based on a participatory approach (Sanon *et al*., 2012). In addition, combining the Geographical Information System (GIS) with multi-criteria analysis, Nguyen *et al*. (2015) proposed a spatial multi-criteria analysis, which integrates ecological aptitude, environmental impact and socio-economic feasibility criteria in a step-wise procedure to analyze objectives that affected by spatially-distributed diagnostic factors. Further, Vollmer *et al*. (2015) demonstrated an application of a four-step spatial multi-criteria analytical approach that involves scenario development, ecosystem service quantification and mapping, preference weighting, and optimization to maximize preferred ecosystem services while minimizing cost, which can support decision making for efficient polices to manage ecosystem services.

3.4 Trade-off analysis based on production theory

Multi-criteria analysis has a long history of being applied to analyze the trade-offs in ecosystem services, in parallel, the production theory developed by the economics discipline has also been applied to production of ecosystem services (Barbier, 2007) and to examine services trade-offs (Naidoo and Ricketts, 2006). Production theory is a subfield of microeconomics that concerns trade-offs between different inputs for production, i.e. considering the process of different inputs being converted into different outputs (Varian and Repcheck, 2010). A production theory analysis can be linked not only to the ecosystem services with market value as inputs in the production function, but also to the others not connected to market output (Chee, 2004; Barbier, 2007). As that not all services can be simultaneously maximally delivered to humans, thus stakeholders must make decisions according to their preferences, then when applying production theory to ecosystem services trade-off analysis for decision making, the key principle is to achieve the sustainable and efficient delivery of multiple interacting services to human society (Tallis *et al*., 2008).

The Cobb-Douglas Production functions are the most widely used types to depicts the production theory (Chisasa and Makina, 2013), while it cannot cope with the complex systems that with multiple inputs/multiple outputs production systems that influenced by natural resources, external environmental attributes, and the preferences of land managers. To address the multiple-inputs/multiple outputs production functions, the efficiency frontier method has become popular (Grosskopf *et al*., 1992), which can be traced back to the ideas put forward by Farrell (Farrell, 1957). Specifically, the productive efficiency is treated as a relative concept, which can be illustrated as Pareto-efficient options for optimal utilization of two or more services, where the system cannot increase one service without sacrificing other services (Nelson *et al*., 2008; Polasky *et al*., 2008).

In recent years, the efficiency frontier analysis has been utilized in a variety of researches to examine trade-offs between different ecosystem services, especially in agro-ecosystems (Bekele *et al*., 2013; Balbi *et al*., 2015; Mastrangelo and Laterra, 2015). Lester *et al*. (2013) conducted a review on the ecosystem services trade-off analysis framework that based on economic theory, and summarized six common types of ecosystem service interactions based on the insights gained from frontier shapes, including non-interacting services, direct trade-off, convex trade-off, concave trade-off, non-monotonic concave trade-off, and backward S trade-off. All the frontier shapes focus on two dimensions, which are the easiest ways to visualize, while the concept and logit can be applied to trade-offs in multiple dimensions as well (Cavender-Bares *et al*., 2015). For example, to deal with the conflicts between the production of marketable ecosystem goods and the provision of non-marketed ecosystem services in agro-ecosystems, Bekele *et al*. (2013) combined the Soil and Water Assessment Tool (SWAT) model and the productive frontier analysis to analyze a 6-dimensional trade-offs between three provisioning services and three regulating services, which confirmed that provisioning and regulatory services aggregately formed a linear to convex ecological-economic production possibilities frontiers. The efficiency frontier is an effective method to judge the biophysical constraints of the ecosystem services production system, which combines with the information about value of services from stakeholders' perspective, and further identifies optimal management approaches that yield the greatest net benefits, while the problem that there may exist uncertainty about the production frontier and values still remains to be dealt with (Cavender-Bares *et al*., 2015)

4 Conclusions

For ensuring sustainable land-use management, it is critical to conduct trade-off analysis of ecosystem services closely associated with land-uses, which allows the decision-makers to better understand the corresponding consequences of different choices and achieve a solution to long-run sustainable development of socio-ecological systems.

Trade-offs arise when biophysical constrains change or humans make management interventions, which will change the types, magnitudes and interactions among services provided by ecosystems. Investigations on the trade-offs among individual ecosystem services and biodiversity are mostly provoked, further analysis on the interactions among ecosystem services bundles has also gained great achievements. On one hand, intensive land-use change and management are recognized as the major factors affecting ecosystem services provisions and incurring trade-offs, on the other hand, the major barriers that inhabit the sustainable resource planning and management contribute to ecosystem services trade-offs at different scales, which can be classified in terms of temporal and spatial scale, stakeholders' preference, and the degree of irreversibility. Thus, taking the ecosystem services trade-offs at different scales into consideration during decision-making is important for sustainable land use management to avoid negative effects and achieve synergetic outcomes.

In dealing with the problem of ecosystem services trade-offs, a wide variety of analytical tools and approaches have been developed and applied for management decisions, including the assessments that explicitly linked spatial information on service supply to conduct correlation or cluster analysis, the integrated modeling framework for the systemic assessment, and also approaches based on the multi-criteria decision theory and economic production theory. While, evaluation of trade-offs is complex due to the multiple dimensions, interactions, variations and uncertainties with different physical units across time and space, thus quantifying the non-linear dynamics of trade-offs between ecosystem services in the social-ecological systems driven by both biophysical drivers and management decisions still remains a big challenge for sustainable land-use management.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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