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Coupling trade-offs and supply-demand of ecosystem services (ES): A new opportunity for ES management☆

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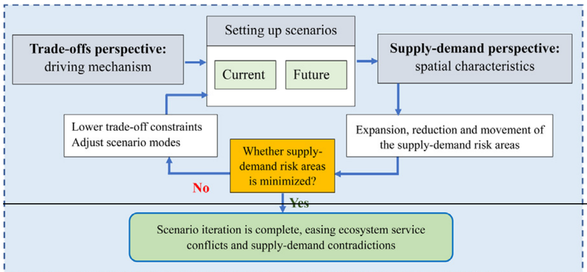
HIGHLIGHTS

- Two types of ecosystem services trade-offs are defined.
- The supply-demand risk area is defined according to ecosystem service flow.
- An analytic framework coupling trade-offs and supply-demand is proposed.
- The optimal land-use scenario is determined by scenario iteration.

GRAPHICAL ABSTRACT



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ABSTRACT

The trade-offs and supply-demand relations of ecosystem services (ES) are at the frontier of geographical and ecological studies. However, previous studies have focused on either trade-offs or the supply-demand aspects, while ES conflicts and supply/demand contradictions have not been comprehensively examined. The relationship between ES trade-offs and supply-demand is logically valid and studying the coupling of both can provide approaches for simultaneously alleviating ES conflicts and supply-demand contradictions. This study, based on a review of previous analyses of ES trade-offs and supply-demand dynamics, proposes a new analytic framework to couple them. First, we define two types of trade-offs based on the directions of growth or decline of the two services. We also define the supply-demand balance area and the supply-demand risk area according to the ES flow characteristics. Second, the mechanisms driving ES trade-offs are clarified, and land-use scenarios are set based on the mechanisms. Third, the supply-demand spatial characteristics of ES are analyzed, and supply-demand risk areas are identified. Finally, scenario iterations are performed to minimize the supply-demand risk area at an acceptable trade-off intensity to identify an optimal land use plan, which simultaneously alleviates ES conflicts and supply-demand contradictions. This analytic framework offers new opportunities for improving sustainable ecosystem management.

1. Introduction

Ecosystem services (ES) refer to the benefits that humans obtain directly or indirectly from ecosystems (Costanza et al., 1997). ES are fundamental to decision-making for sustainability (Inácio et al., 2020; Yang et al., 2020; Yin et al., 2021). The supply of ES is the capacity of an area to provide a bundle of ecosystem goods and services within a specified time (Burkhard et al., 2012). People often hope to maximize ES by regulation, but this is difficult because ES are not independent and may have complex non-linear relationships with unintentional trade-offs resulting from ignorance of interactions (Rodriguez et al., 2006). ES trade-offs refer to the enhancement of one type of ecosystem at the cost of reducing other ES (Millennium Ecosystem Assessment, 2005; Bennett et al., 2009). Trade-offs can be analyzed using multidisci-

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plinary theory and methods such as correlation analysis and production-possibility frontier (King et al., 2015; Li et al., 2018; Kathleen et al., 2019). The opposite of ES trade-offs is synergies where services either increase or decrease simultaneously (Bennett et al., 2009; Haase et al., 2012). This is a situation where the use of one service directly increases the benefits supplied by another service (Anna et al., 2017) or a "win-win" situation that involves a mutual improvement of both services (Haase et al., 2012). Therefore, "trade-offs" are more critical than "synergies" for balancing the natural resource allocations. Trade-off analysis provides a comprehensive and dialectical perspective for understanding the relationship between ES and has attracted attention in geography, ecology and sociology (Kanter et al., 2018). Recently, the study of ES trade-offs has become an important research area (Zheng et al., 2019; Ndong et al., 2020).

Demand of ES is the amount of ecosystem goods and services required or desired by human society in a particular area over a given period (Burkhard et al., 2012; Wolff et al., 2015). Supply-demand relationships can spatially describe the dynamic process of ES flowing from natural ecosystems to human social systems. Understanding these relationships help to identify the spatial differences between the supply and consumption of ES. Sustainable supply of ES is fundamental to the sustainability of nature and society. Humans use ES to meet demands and improve their well-being. Hence, the supply-demand relationship of ES has become an important research field (Bagstad et al., 2013; Wei et al., 2017; Schirpke et al., 2019; Shi et al., 2020; Laca, 2021).

ES trade-offs and supply-demand issues have caught widespread attention in various disciplines. However, coupling these two aspects has rarely been attempted, which poses a challenge for simultaneously easing ES conflicts and supply-demand contradictions. Previous studies have mostly been performed from either the perspective of supply-demand relationships or that of trade-offs. The primary reason for the imbalance between supply and demand is the spatial mismatch between the location of natural resources and population and economic development. Therefore, it is necessary to find solutions from the perspective of ES flows (Zhang et al., 2021). The factors driving ES trade-offs include, for example, land use, climate change, management policy. Regulating these factors is one way to achieve effective management (Anna et al., 2017; Zheng et al., 2019; Dade et al., 2019). Some studies have explored the ES supply-demand matching method based on trade-off characteristics, in which trade-offs are used as preliminary preparation, constraints or regulations (Wang et al., 2019; Li et al., 2020). These studies have helped improve the understanding of the association between ES supply-demand dynamics and trade-offs.

There is an inherent relationship between supply-demand dynamics and trade-offs of ES. On the one hand, according to the definition of ES trade-off, the enhancement of an ES comes at a cost of reducing other ES, and the reduced services likely lead to the inability to meet demands due to insufficient supply (trigging a supply-demand contradiction), indicating that trade-off characteristics can affect the supply-demand relationship. On the other hand, the supply-demand relationship can also affect trade-offs. Taking food supply and demand conflict as an example, people might choose to convert forest and grass area into cropland to increase food supply. However, such a decision leads to soil erosion and a trade-off between food supply and soil conservation services. Thus, examining the coupling of trade-offs and supply-demand characteristics will help improve ES theory and provide potential solutions for simultaneously mitigating ES conflicts and supply-demand contradictions.

2. Identifying trade-off mechanisms and supply-demand spatial characteristics

2.1. Mechanisms influencing ES trade-offs

Identifying mechanisms is the core of ES trade-off research, and the basis for alleviating ES conflicts. Factors influencing ES include common and noncommon driving variables (Bennett et al., 2009). When there is a "positive covariation" between two services, changing the common driving variable can simultaneously increase the two services, achieving a "win-win" situation; when there is a "negative covariation" between two services, changing the common driving variable will exacerbate the trade-off relationship. For example, Biel et al. (2017) found that grassland invasion, as a common driving variable, contributes to coastal protection services, but inhibits seabird nesting, while habitat quality improvement and natural enemy control, as noncommon driving variables, can increase seabird populations but exert no impact on coastal protection. Feng et al. (2020) investigated the mechanisms driving the trade-offs between soil conservation and freshwater supply services in the Loess Plateau and found that construction land, arbor-shrub land and vegetation coverage are common driving variables for soil conservation and freshwater supply. They also found that slope gradient is a noncommon driving variable since it plays a leading role in soil conservation but has little or no significant impact on freshwater supply. In general, factors driving trade-offs can be classified into two categories: land use and climate change with land use being the most common driving factor over short periods (Zheng et al., 2019). Scientific analytical method is the basis for clarifying the trade-off mechanism. Several methods such as correlation analysis, classical regression analysis, quantile regression, piecewise linear regression, geographical weighted regression, redundancy analysis, geographic detectors, random forest analysis, structural equation modeling, Bayesian networks and data envelopment analysis are used. Their application allows investigators to identify the direction, intensity, speed and threshold of trade-offs responding to various driving factors (Feng et al., 2017; Wang et al., 2017; Kathleen et al., 2019; Feng et al., 2020; Forio et al., 2020; Sun et al., 2020; Su et al., 2021).

2.2. Supply-demand spatial characteristics

The spatial representation of ES supply-demand relationships can be achieved through various approaches including: the expert knowledge-based supply-demand relationship matrix; multi-agent simulation system (SPANS) based on the ARIES modelling platform; public participation; questionnaire surveys; valuation methods; and the ecological footprint method (Burkhard et al., 2012; Tao et al., 2018; Koellner et al., 2019; Chen et al., 2020; Bing et al., 2021; Li et al., 2021). These methods have advantages and disadvantages. Since the ES supply-demand relationship exhibits diverse spatial characteristics, there are spatial mismatch and transboundary movement processes in the supply and consumption of ES. ES can flow to faraway places (outside the boundary) and people within the boundary can also use ES from other places. Thus, ES supply-demand based on flow features can be deemed to the final state for certain boundary. Based on the overall spatial characteristics of ES, Costanza (2008) classified ES flow into five categories: global non-proximity, local proximity, directional flow, in situ and user movement. Fisher et al. (2009) divided the space into ES production areas, benefit areas, and connection areas. The spatial flow of ES depends on different media, such as the atmosphere, rivers, organisms, soil and human movement (Koellner et al., 2019). The diversity of ES and their media mandate that the service flows have different forms and path lengths, causing them to exhibit different characteristics such as accumulation and dispersion, stability and non-stationarity, and periodicity and non-periodicity (Bagstad et al., 2013). Therefore, accurate identification of ES and their flow characteristics is key to understanding the ES supply-demand relationship and providing directions for sustainable management. For example, local supply capabilities of in situ service flows need to be strengthened, and directional service flows need to be rationally deployed to match resource supply and demand.

The characterization of ES flows allows the study of the supply-demand relationship to evolve from static analysis to dynamic simulation and has received extensive attention from various disciplines and international scientific cooperation platforms, e.g., the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

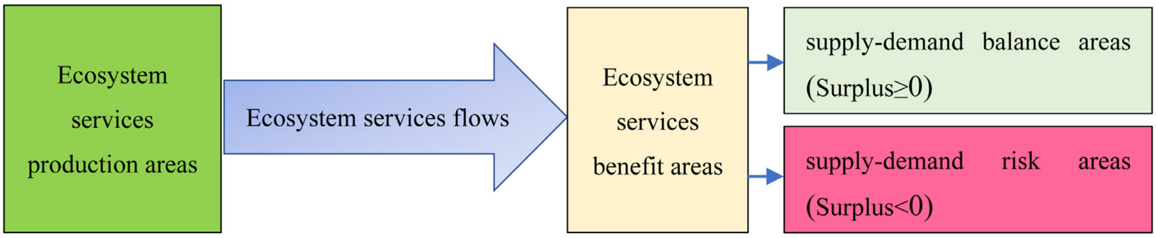

Fig. 1. Identification of supply-demand spatial characteristics based on ES flows.

(IPBES) (Koellner et al., 2019). Studies on ES flows have focused both on supply services (e.g., water resources, timber, food, medicines, genetic resources) (Li et al., 2017; Schröter et al., 2018; Lin et al., 2020; Miguel et al., 2020; Zhang et al., 2021) and on regulating service flows (e.g., soil conservation, carbon sequestration, windbreaks and sand fixation) (Xu et al., 2020). Supply-demand spatial characteristics based on ES flows can provide the foundation for resolving supply-demand contradictions.

2.3. *Rethinking the methods of quantifying trade-off intensity and supply-demand spatialization*

It has been difficult to reflect the development directions and relative advantages of ES by frequently used trade-off intensity indicators such as the root mean squared error and correlation coefficient, which are not conducive to elucidating the mechanisms driving trade-offs (Bradford and D'Amato, 2011; Kathleen et al., 2019; Schirpke et al., 2019). After the trade-off relationship between ES A and B is identified based on the growth and decline directions of A and B, we categorize trade-offs into two types: A-dominant trade-off (A increases and B decreases) and B-dominant trade-off (B increases and A decreases). We propose a trade-off intensity indicator as:

$$\mathrm{TR}_{\mathrm{AB}} = \frac{1}{2}\left(\sqrt{\left(\frac{\mathrm{ESA}_{\mathrm{T2}} - \mathrm{ESA}_{\mathrm{T1}}}{\mathrm{ESA}_{\mathrm{T1}}}\right)^2} + \sqrt{\left(\frac{\mathrm{ESB}_{\mathrm{T2}} - \mathrm{ESB}_{\mathrm{T1}}}{\mathrm{ESB}_{\mathrm{T1}}}\right)^2}\right) \times 100 \quad (1)$$

where:

$\mathrm{TR}_{\mathrm{AB}}$ is the trade-off intensity;
$\mathrm{ESA}_{\mathrm{T1}}$ and $\mathrm{ESA}_{\mathrm{T2}}$ are the ES values of service A at the T1 and T2 periods, respectively (T1 is earlier than T2);
$\mathrm{ESB}_{\mathrm{T1}}$ and ESB_{T2} are the ES values of service B at the T1 and T2 periods, respectively. $\mathrm{TR}_{\mathrm{AB}}$ is useful for describing the degree of ES fluctuation.

Prior to calculation, data are categorized into three types according to the growth and decline of services A and B: A-dominated trade-off, B-dominated trade-off, and synergism where A and B change in the same direction.

Ecosystem services flow from the production area to the benefit area. After receiving external inflows, the benefit area is judged on whether it can meet service demands. If it can ((“supply amount” + “external inflows”) ≥ “demand amount”), it is defined as a supply-demand balance area. If it cannot ((“supply amount” + “external inflows”) < “demand amount”), it is defined as a supply-demand risk area (Fig. 1). This zoning not only considers spatial supply and benefit but also emphasizes whether human needs are ultimately met, thereby highlighting the impact of ES on human well-being.

3. Logical rationality of the correlation between trade-off intensity and supply-demand match degree

There are same driving variables (x_1, x_2, ..., x_i) for trade-off intensity and supply-demand matching as illustrated in Fig. 2, which is not only the intrinsic reason for the relationship between the two, but also the theoretical basis for the coupling framework we propose. Previous studies explain the logical rationality of the association between trade-off intensity and supply-demand matching. A case study of the Loess Plateau of China found that revegetation enhanced soil conservation and decreased water yield, and the trade-off intensity between the two increased (Feng et al., 2020). The decline of water yield aggravated the contradiction between water supply and demand, and the phenomena of dried soil layer and artificial forest degradation had happened (Feng et al., 2017). Zheng et al., (2019), using a watershed on China's Hainan Island, present a way for integrating ES trade-offs and approaches (“win-win”, “small loss-big gain” and “ES replacement”) to improve the match between ES supply and demand. Therefore, it is feasible to couple ES trade-offs and supply-demand.

4. Analytic framework for coupling ES trade-offs and supply-demand relationships

In this section, we propose an analytic framework for coupling ES trade-offs and supply-demand relationships (Fig. 3). First, land use scenarios are set up based on the mechanism driving a trade-off. Second, changes in supply-demand risk areas under different scenarios are identified. Finally, through scenario iteration, the supply-demand risk area is minimized within the acceptable range of trade-off intensity.

The detailed steps of this framework are as follows:

Step 1. Clarifying the influencing factors and thresholds of ES and their trade-offs

The direction, intensity, speed and threshold of ES and trade-offs responding to driving variables are clarified through geographic detectors, redundancy analysis, piecewise linear regression, quantile regression and other methods (Kathleen et al., 2019; Feng et al., 2020; Forio et al., 2020; Sun et al., 2020; Su et al., 2021). Then, the “common variables” that simultaneously drive the two ES, the “sensitive variables” that play a greater role and the “noncommon variables” that drive only one service, are identified. Finally, the response function of ES and their trade-offs to the variables are established (Fig. 4).

Step 2. Setting up land use scenarios

Land use configuration and conversion scenarios for different natural zones (e.g., precipitation and vegetation zones) and different environmental factor levels (e.g., slope gradient levels) are set up based on the influencing factors and thresholds of ES and their trade-offs. These are used in the simulation of ES trade-off and supply-demand spatial features (Table 1).

Step 3. Identifying supply-demand risk areas

This step involves three tasks. First, consists in identifying production areas and benefit areas: the area featuring greater ES supply than demand is identified as the supply area, while that with lower supply than demand is identified as the beneficiary area. Second task is describing ES flow from the supply area to the beneficiary area. Taking water yield as an example, it flows downstream from supply area due to water surplus. Surplus of water resource equals to the sum of water yield of the grid unit and upstream flow replenishment with water consumption being deducted. The third and final task is identifying the areas where the demand is still not met after receiving upstream water replen-

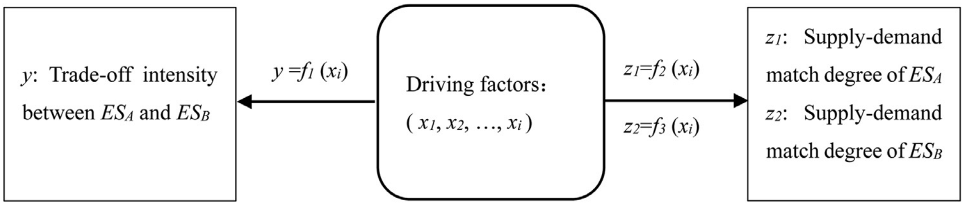

Fig. 2. Intrinsic reasons for the correlation between trade-off intensity and supply-demand match degree ($y = f_1\ (x_i)$, $z_1 = f_2\ (x_i)$, $z_2 = f_3\ (x_i)$ is the response function).

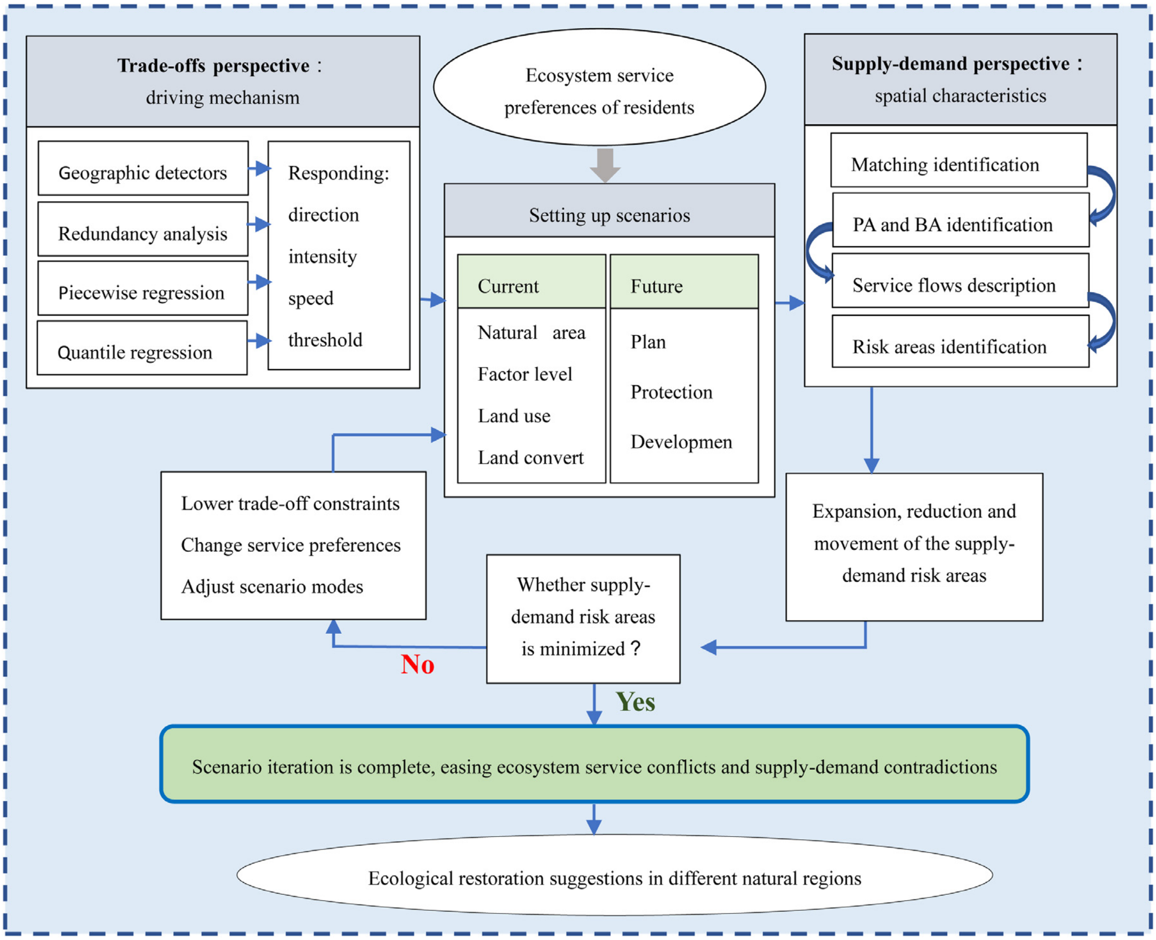

Fig. 3. Analytic framework coupling ES trade-offs and supply-demand relationships (PA: production areas, BA: benefit areas).

Table 1
Setting up current and future land use scenarios under different natural zones and environmental factor levels

	Scenario	Natural zone A Environmental factor B (level 1)	Environmental factor B (level 2)	…	Environmental factor B (level *i*)
Current scenarios	Scenario 1 Scenario 2 … Scenario *n*	Including the following scenarios: arbor forestland, shrub forestland, grassland, farmland-converted grassland, farmland-converted arbor forestland, arbor forestland-converted shrub forestland, arbor forestland-converted grassland, grassland-converted farmland and other land use configuration and conversion methods and the upper and lower limits of different types			
Future scenarios	Protection scenario Plan scenario Development scenario	Future land use changes are simulated from three perspectives, i.e., strengthening ecological and environmental protection, maintaining the current pace of development, and highlighting social and economic development, and then the changes in ecosystem service supply-demand risk areas are further simulated to determine the optimal future scenario.			

ishment, i.e., areas with negative water surplus, as supply-demand risk areas; and areas with positive surplus as supply-demand balance areas (Fig. 1).

Step 4. Determining the optimal land-use scenarios

Optimal land-use plans to alleviate ES conflicts and supply-demand contradictions for different natural regions and environmental levels are achieved by minimizing the supply-demand risk areas with acceptable trade-off intensities. The land use plan in the proposed analytical framework considers "ES relationship coordination" at the natural level and "ES supply-demand balance" at the social welfare level. We believe that this framework can break through the bottleneck of ES regulation theory.

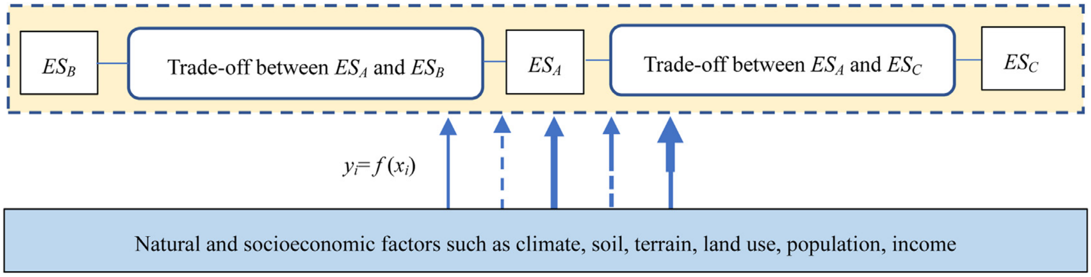

Fig. 4. Impact mechanisms of ES and their trade-off (ES_A, ES_B, ES_C are the ecosystem service A, B, C, respectively; y_i represents ecosystem services and their tradeoffs; x_i represents natural and socioeconomic factors; solid arrows and dotted arrows represent positive and negative effects, respectively; the thickness of the arrow represents the size of the effect; an arrow with varying thickness or both solid and dotted lines indicate the presence of an influence threshold; $y_i = f(x_i)$ is the response function).

5. Conclusions

In this study, we presented an analytic framework that couples trade-off mechanisms and supply-demand spatial characteristics. Using this framework overcomes cognitive limitations and provides a holistic understanding of the association between service conflict and supply-demand imbalance during ecosystem service flows from the natural environment to human well-being. Therefore, it has the potential to simultaneously alleviate trade-off and supply-demand contradictions. To implement this framework, first, we proposed a new trade-off quantification indicator. Second, we defined the areas where the demand cannot be satisfied after the external inflow is received as the supply-demand risk areas. Third, we set up land use scenarios through the mechanisms driving trade-offs. Finally, we used scenarios iteration to screen for the optimal land use mode and achieved the goal of simultaneously decrease ecosystem service conflicts and supply-demand contradictions. The method for trade-offs quantification and of supply-demand spatialization has been improved in this analytic framework, and the mechanism of trade-offs and spatial characteristics of supply-demand can be coupled through scenario iterations. This framework provides a new gateway for scholars to deepen the research on ecosystem services, and helps to promote the sustainable management and support decision-making regarding ecosystems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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