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生态系统服务研究在景观规划中的应用

APPLICATION OF RESEARCH ON ECOSYSTEM SERVICES IN LANDSCAPE PLANNING

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摘要

景观规划通过改变土地覆被类型和景观格局来调整空间结构和功能，进而影响生态系统服务。本文首先从土地覆被类型、景观格局与服务功能特性三个方面对景观规划与生态系统服务的关系进行分析，提出调控土地覆被类型可以改变服务类型、改变景观格局可以影响服务水平、调整服务功能特性可以影响服务发挥过程。随后，本文总结了生态系统服务评估、空间制图和情景模拟分析等研究方法在景观规划中的应用，认为生态系统服务评估是保证景观规划科学合理的手段；空间制图是辅助决策者做出合理判断的工具；情景模拟可供决策者直观地选择最优方案。同时，本文详细阐释了以上研究方法当前在绿色空间规划、生态保护红线划定、土地利用规划、生物多样性保护规划等景观规划中的应用实例。最后，本文对相关研究的现状和问题进行了总结，并提出未来应加快景观规划与生态系统服务之间关系的研究、依据生态系统服务构建动态复合的规划框架、推进景观规划中生态系统服务权衡–协同研究三项建议。

关键词

生态系统服务；景观规划；土地利用；景观格局；情景模拟

ABSTRACT

Landscape planning adjusts spatial structures and functions by altering the types of land use / land cover and the patterns of landscapes, and thus further impacts ecosystem services. This paper examines the impacts of landscape planning on ecosystem services and draws the conclusion that the control over the types of land use / land cover, the altering of landscape patterns, and the adjustment of landscape functional characteristics could change the type, quality, and performance of ecosystem services, respectively. Through an overall review on the application of ecosystem service evaluation, spatial mapping, and scenario simulation, this paper further concludes their roles in landscape planning: ecosystem service evaluation provides means to ensure scientific landscape planning; spatial mapping serves as a basis to the decision making; and scenario simulation visualizes all kinds of possibilities for an optimal choice. At the same time, such applications in landscape planning practices, ranging from green space planning, ecological conservation redline planning, land use planning to biodiversity protection planning, are exemplified. Finally, this paper summarizes existing research findings and limitations and proposes that future research is expected to study the relationship between landscape planning and ecosystem services, to build a dynamic composite planning framework that can improve ecosystem services, and to propel the research on the tradeoff-and-synergy among ecosystem services in landscape planning.

KEYWORDS

Ecosystem Services; Landscape Planning; Land Use; Landscape Pattern; Scenario Simulation

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1 引言

生态系统服务（ecosystem service）是指生态系统与生态过程所形成及所维持的人类赖以生存的环境条件与效用[1]，这一概念是由安·埃里奇等在“生态系统功能”（ecosystem function）、“自然服务”（nature service）、“环境服务”（environmental service）等相关概念的基础上提出的[2]。生态系统服务包括了人类从生态系统中取得的全部收益[3]，既涵盖物质生产、资源供给等有形服务，也包括休闲娱乐、文化历史价值等无形服务。生态系统服务主要分为供给服务、调节服务、支持服务与文化服务4个类型[4]，其中供给服务包含食物生产、水源和能源供给等；调节服务包含气候调节、水源涵养、雨洪调节等；支持服务包括生物多样性保护、生态系统生产力维系等；文化服务则包含休闲游憩、审美启智等。例如，森林生态系统可提供气候调节、水土保持等调节服务以及自然资源的供给服务；农田和耕地可为人类生存提供食物供给服务；水域、滩涂和灌草地则可提供水文调节服务[5]。

近年来，生态系统服务已成为了景观规划领域的研究热点。在理论研究方面，国内外学者多对某一项特定服务开展针对性研究，主要集中在降温服务、固碳释氧、雨洪调控、生物防治、景观美学、游憩等领域[6]。以此为基础，相关研究进一步探究了生态系统服务与景观格局[7][8]和生物多样性的关系[9]。在实践应用方面，研究多关注生态系统服务在景观规划管理[10]、土地利用[11]~[13]及城市规划[14]中的具体应用。本文旨在从生态系统服务与景观规划之间的关系入手，梳理生态系统服务在景观规划中的研究与应用进展。

2 景观规划与生态系统服务的关系

生态系统服务和景观规划的研究对象都是人类与生态系统，前者是人类从生态系统中获得的惠益，后者是为了满足人类需求而对生态系统做出的改造。提升生态系统服务是景观规划的目标，也是评价景观规划的重要依据。景观规划是保障生态系统服务产生和发挥效用的有效途径。具体而言，景观规划直接作用于城市用地类型和城市空间格局，通过改变土地覆被类型和景观格局来改变生态系统功能，进而影响生态系统服务的类型和分布，即景观规划通过改变服务的产生过程来影响生态系统服务；另一方面，景观规划以满足城市建设需求为

1 Introduction

Based on the concepts including ecosystem function, nature service, and environmental service, Ann Ehrlich et al. defined that “ecosystem services (ESs) are the conditions and processes, through which ecosystems, and the species that make them up, sustain and fulfil human life.”[1][2] ESs cover all benefits obtained by humankind from ecosystems[3], which include tangible services (such as material production and resource supply) and intangible ones (such as recreational, cultural, and historical values). ES has four types: provisioning, regulating, supporting, and cultural[4]. Provisioning services include food production as well as water and energy supply; Regulating services include climate regulation, water and soil conservation, and flood control; Supporting services include biodiversity protection, and ecosystem productivity maintenance; Cultural services include recreational and aesthetic significance. For instance, forest ecosystems provide regulating services such as climate regulation and water and soil conservation, while provisioning natural resources; Farming lands supply human beings with food; Water bodies, mudflats, shrubs, and grasslands regulate hydrological conditions[5].

ES has recently attracted wide attention in the field of landscape planning. In global academia, theoretical studies mainly focus on a particular type of service, such as cooling, carbon storage and oxygen release, flood control, biological control, landscape aesthetics, and recreational value[6]. Such findings have inspired more studies to explore the relationship between ES and landscape pattern[7][8] and biodiversity[9]. Most studies work on the ES applications in landscape planning and management[10], land use[11]~[13], and urban planning[14]. This paper reviews the research and applications of ES in landscape planning by starting from examining landscape planning’s association with ES.

2 Impacts of Landscape Planning on ES

Both ES and landscape planning study humankind and ecosystems, with the former referring to the gains that human beings obtain from ecosystems and the latter focusing on altering ecosystems to meet human needs. Enhancing ES is a major objective of landscape planning and the basis of landscape planning evaluation. Landscape planning would ensure the production and performance of ES. Specifically, landscape planning changes the types of land use / land cover (LULC) and landscape patterns by adjusting urban land uses and spatial constitution, which would impact ecosystem functions, as well

目的赋予生态系统一定的服务功能特性，通过抑制或促进某种服务类型的发挥来影响生态系统服务。因此，景观规划对生态系统服务有着重要影响（图1）。

2.1 景观规划决定生态系统服务的产生过程

2.1.1 土地覆被类型决定服务类型

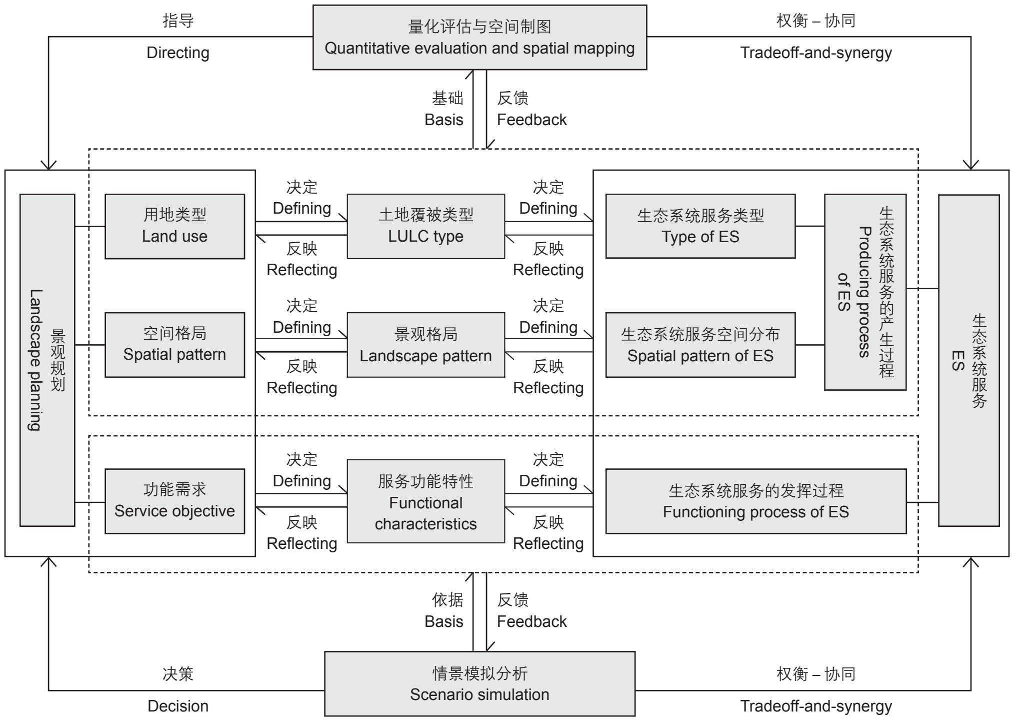
景观规划的重要内容之一是调控土地覆被类型，土地覆被类型的变化可对生态系统的物质交换、水土保持和生物循环等主要生态过程产生重要影响[15][16]，进而影响各项生态系统服务。大量研究表明，通过改变土地覆被类型可以实现生态系统服务类型的转换，例如，在自然林地向耕地转换的过程中，水源涵养和水质调节服务被削弱，粮食生产服务提高[17]；而在退耕还林过程中，粮食生产服务被削弱，水土保持服务提高[18]，实现了供给和调节服务的相互转换。在城市内部，随着建设用地的增加、农业用地和水体的减少，粮食生产和水文调节服务减弱、娱乐文化服务和废物处理能力增强，生态系统服务类型由供给、调节服务向文化和支持服务转移[19]。由此可知，景观规划通过调控土地

as the ES types and their distribution — In other words, landscape planning impacts ES by changing the producing process of services. At the same time, landscape planning facilitates or inhibits certain services of ecosystems to meet the needs of urban development. Therefore, landscape planning sees a close association with ES (Fig. 1).

2.1 Landscape Planning Defines the Producing Process of ES

2.1.1 LULC Types Define ES Types

A key component of landscape planning is to adjust LULC types. Such adjustments would significantly impact ecosystems' major processes such as substance exchange, water and soil conservation, and biosphere cycle[15][16], all of which would further impact ES. A number of studies have proven that alterations in LULC types would change ES types. For instance, a natural forest's regulating service in water conservation and water quality protection would be undermined when it is transformed into a farmland, with an enhanced food productivity[17]; when a farmland is reclaimed into forests, its food supply service undermines and regulating service in water and soil conservation increases[18]. Along with the growth of urban construction and the shrink of agricultural lands and water areas, a city's food production and hydrological regulation services would get degraded while its recreational and cultural services, as well as the waste treatment capacity, get strengthened, witnessing a shift of ES types from



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1. 生态系统服务与景观规划关系示意图

1. Relationships between ES and landscape planning

覆被类型可以实现各类生态系统服务的相互转换，这为基于生态系统服务的景观规划提供了理论支撑。

2.1.2 景观格局影响服务水平

景观规划的另一项重要内容是优化景观格局。不同的景观格局导致了生态过程和服务水平的差异性。在土地资源有限的情况下，科学的景观格局规划有利于生态系统持续且有效地提供服务。例如，傅伯杰等[20]比较分析了中国黄土高原不同的景观格局及其服务水平，得出土壤水分和养分保持服务发挥功效的优劣顺序是林地>草地>坡耕地；苏士亮等[21]认为景观格局的破碎化会导致生态功能的退化，进而导致服务水平的下降。此外，一些学者针对景观格局与生态系统服务水平的关系进行了量化研究。例如，王博娅等[22]对北京市海淀区进行了研究，结果显示，林地斑块占景观面积的比例与调节服务和支持服务水平呈明显的对数关系，而灌丛斑块的形状指数与生态系统服务水平呈指数关系。

综合来看，景观格局可通过改变土地覆被结构和空间特征来影响生态系统的服务水平。在景观规划实践中，需要结合景观格局分析方法对生态系统服务的空间特征展开量化分析和模拟预测，为景观规划提供科学依据。

2.2 景观规划影响生态系统服务发挥过程

景观规划可以根据人类需求促进或抑制不同生态系统服务的发挥，从而获取更多的经济、社会或生态效益。例如，通过改善农业生产条件、优化农业生产结构、改善生态环境等措施来提高耕地抵御自然灾害的能力[23]；为促进城市生态系统降温增湿服务的发挥，在景观规划中改变景观格局[24]、完善生态基础设施[25]、改变植被覆盖度和类型[26]、建立水体和绿地冷岛[27]；为保护生物多样性，俞孔坚等[28]以景观元素[29]为出发点对物种多样性保护进行规划；王志芳等[30]通过构建文化遗产廊道来促进文化服务的发挥。因此，景观规划是使生态系统服务满足人类动态需求的有效途径。

provisioning and regulating services into cultural and supporting ones[19]. Altogether, landscape planning would lead to ES shifts by changing LULC types, which paves the theoretical way for ES improvement through landscape planning.

2.1.2 Landscape Patterns Impact Service Qualities

Another key component of landscape planning is landscape pattern improvement. Ecological processes and service qualities vary among different landscape patterns. Scientific planning of landscape patterns of limited land resources enables the ecosystem to deliver sustainable and efficient services. By comparing different landscape patterns and their ES performance on the Loess Plateau of China, Fu Bojie et al.[20] concluded that the conservation service of moisture and nutrient contents is in order of forest > grassland > slope farmland. Su Shiliang et al.[21] held that a landscape in a fragmented pattern would cause a degradation of its ecological functions and a poor service quality. Moreover, the association between landscape patterns and ES qualities are also quantitatively studied. Wang Boya et al.[22] explored the relationship between landscape patterns and ES performance of Haidian District of Beijing. The findings reveal that the proportion of forest patches in the study area is logarithmically correlated with its regulating and supporting service performance, and the shape index of the bush patches and ES are exponentially related.

To sum up, landscape patterns impact ES performance by changing the LULC structure and spatial characteristics. Quantitative analyses and simulation prediction of spatial characteristics of ES need to be combined with landscape pattern analyses so as to assist landscape planning.

2.2 Landscape Planning Impacts the Functioning Process of ES

Landscape planning is conducted to promote or inhibit the functioning process of ES in order to meet human needs for greater economic, social, and ecological benefits. For instance, a farmland's resilience to natural disasters can be strengthened by improving agricultural productivity and structure and enhancing ecological conditions[23]. Adjusting landscape patterns[24], improving ecological infrastructure[25], increasing vegetation coverage and diversity[26], and creating water bodies and cold islands in urban green spaces[27] all help cool and moisturize the city. Yu Kongjian et al.[28] proposed conservation plans of species diversity with landscape elements[29]. Wang Zhifang et al.[30] argued that building cultural heritage corridors would improve landscapes' cultural services. All these studies have proven that landscape planning is an effective means for ecosystems to meet the changing needs of human beings.

3 生态系统服务研究方法在景观规划中的应用

生态系统服务的量化研究为景观规划提供了科学分析依据[31]。近年来，量化评估、空间制图、情景模拟等方法被广泛应用于生态系统服务的价值评估、空间分布特征和规划预测研究中，这些研究成果也为规划者改变土地覆被类型、调整空间格局和制定相关保护规划提供了依据，有助于指导可持续发展指标体系的制定[32]。

3.1 生态系统服务评估在景观规划中的应用

根据规划目标的不同，景观规划可分为两类：一类用于识别关键空间类型，保护生态安全；一类力求提升综合效益，确保可持续发展。传统的生态系统服务评估通过对不同生态系统的同一服务能力或同一生态系统的不同服务类型进行比较，来评估生态系统服务水平，其评估方法根据不同的核算媒介分为物质量评估、价值量评估和能值评估[33]。而在景观规划领域，生态系统服务评估通常分为稀缺性评估和综合性评估两类。

3.1.1 生态系统服务稀缺性评估

生态系统服务稀缺性评估是指对生态系统中的不可替代资源（如物种多样性）以及不可逆过程（如土壤形成过程）进行评价。理查德·科勒特[34]认为，经济作物收入的增加不能抵消食物生产减少的损失；华方圆等[35]的研究表明，东亚地区单一人工林总面积的增加无法提供同面积天然林的多种服务。稀缺性评估旨在准确描述或评价生态系统提供某种服务的能力，评估其相较于稳定状态的差距，可指导生态系统的合理保护与开发，规避损害生态系统服务的短期经济行为。这是对科学利用生态系统的指导，也是保证生态安全的重要前提。其目前通常采用物质量评估结合定性描述的方法，以多样性和生产力等作为评价指标。

生态系统服务稀缺性评估在景观规划中的应用主要体现在识别关键空间类型、构建安全格局和划定生态保护红线等方面，目前的研究多集中在快速城市化区域[36]、干旱区[37]、湿地[38]、地质灾害频发区[39]等生态敏感区。汤峰等[40]借助生态系统服务价值当量评估来确定生态源地并构建生态安全格局；彭建等[41]采用物质量评估法对固碳服务和水土保

3 Application of Research Methods of ES in Landscape Planning

Quantitative study of ES helps develop scientific analyses of landscape planning[31]. Methods such as quantitative evaluation, spatial mapping, and scenario simulation have been widely used for exploring benefit evaluation, studying spatial distribution characteristics, and developing planning scenarios. Such research provides guidelines for adjustments of LULC types and spatial patterns and the formulation of protection plans, helping decision-makers establish an indicator coordinate of sustainable development[32].

3.1 Application of ES Evaluation in Landscape Planning

Landscape planning aims either to identify key spatial types and protect ecological security, or to improve the overall benefits and facilitate sustainability. Conventional approaches evaluate ES performance by comparing a particular kind of ES among different ecosystems or different kinds of ESs in a particular ecosystem, through varied evaluations on mass, value, and energy according to varied criteria. In landscape planning, ES evaluation is mainly applied as scarcity evaluation and comprehensive evaluation.

3.1.1 Scarcity Evaluation of ES

Scarcity evaluations of ES study the irreplaceable resources (such as species diversity) and the irreversible process (such as soil formation) in ecosystems. According to Richard Corlett[34], income increase of industrial crops cannot offset the decrease in food production. Studies by Hua Fangyuan et al.[35] revealed that the increase of the total cultivation area of a single-species afforestation cannot provide the diverse services delivered by a same-sized mixed natural forest. Scarcity evaluation is to accurately describe or assess the capabilities of the ecosystem to deliver a certain kind of ES and figure out the gap with its optimum. Such evaluations help decision-makers improve protection and development plans, avoiding ES degradation or loss for shortsighted profits. This helps make the best use of ecosystems and ensure ecological security. The combined approach of mass evaluation and qualitative description is mostly adopted, with diversity and productivity as the evaluation indicators.

In landscape planning, scarcity evaluations of ES are mostly used for key spatial type identification, security pattern construction, and ecological protection planning. Most existing research concentrates on eco-sensitive regions, including rapidly urbanized regions[36], arid areas[37], wetlands[38], and the areas that suffer from frequent geological disasters[39]. Tang Feng et al.[40] evaluated the value equivalents of ES to identify the regional

持服务进行量化，来确定生态源地并构建云南省生态安全格局；凡非得等[42]采用层次分析法和多因子综合评价法建立评价体系，对桂西北喀斯特地区的生物多样性保护、土壤保持、水源涵养、石漠化控制和产品提供5项服务进行评价，为生态功能区划提供了重要依据；香宝等[43]、朱立晨等[44]、杜悦悦等[45]也进行了相关探索。

3.1.2 生态系统服务综合性评估

大多数生态系统都受到人类活动的影响，以致其服务能力降低，进而威胁到人类自身的利益。生态系统服务综合性评估是指在景观规划中对各类生态系统服务进行全面评价，通过将不同的服务类型转化为统一的客观标准进行比较或叠加，从而协助诊断问题和支撑决策，辅助规划者制定可持续发展规划的指标体系[46]。

不同的景观规划实践所运用的评估方法有所不同，其中指标评价法、价值评估法和模型评估法应用较多。指标评价法是通过对不同指标的量化分级来为景观规划提供有效信息的评估方法，其指标选择灵活，并可通过问卷调查等方式对较难被量化的文化服务进行描述分级，应用范围广泛。毛齐正等[47]根据评价内容、数据获取差异以及研究尺度的不同，总结了常用的评价指标及相应的数据获取方法；李锋等[48]选取6类指标来评估扬州市绿地系统的生态系统服务，诊断其问题，并将评估结果应用于景观规划的多个阶段；美国盖恩斯维尔[49]以及柏林、萨尔茨堡、赫尔辛基、斯德哥尔摩等欧洲城市[50]也用该方法进行了生态系统服务评估的实践。

价值评估法[33]是以货币统一衡量不同生态系统服务的价值，以便于生态系统服务综合价值的评估、促进环境核算，包括当量因子法、费用支出法、市场价值法、机会成本法、影子工程法、旅行费用法和条件价值法等[51]。谢高地等[52]制定了中国陆地生态系统服务价值当量表，随后大量学者针对不同类型的生态系统服务进行了评估研究[53][54]；李巍等[55]采用旅行费用法进行了九寨沟风景区自然资源游憩价值评价；

ecological sources and build the ecological security pattern. Peng Jian et al.[41] adopted mass evaluation methods to quantify the services of carbon fixation, soil conservation, and water conservation to identify the regional ecological sources in Yunnan Province, China and build the ecological security pattern. Fan Feide et al.[42] employed the Analytic Hierarchy Process and the multi-factor comprehensive evaluation method to establish an assessment system in order to evaluate biodiversity protection, soil and water conservation, stony desertification control, and product supply of the karst landform in northwest Guangxi Zhuang Autonomous Region, China, providing a guideline for the eco-function zoning. Xiang Bao et al.[43], Zhu Lichen et al.[44], and Du Yueyue et al.[45] have made similar explorations.

3.1.2 Comprehensive Evaluation of ES

Most ecosystems on the planet have been impacted by human activities, which have disturbed the delivery of ES and threatened human well-beings. By comparing or adding up all sorts of ES with a uniform criterion, a comprehensive evaluation of ES is to describe the overall ES level of an ecosystem, assist problem-finding and decision-making, and help develop an indicator coordinate to improve the ecosystem's sustainability[46].

In landscape planning practice, evaluation methods vary from case to case, among which indicator evaluation, monetary evaluation, and modeling evaluation are commonly used. Indicator evaluations can quantify ES in varied indicator coordinates, among which quality-rating systems like questionnaires are particularly helpful to address cultural services that are difficult to be quantified. Mao Qizheng et al.[47] summarized a number of common indicator coordinates and related data collecting methods by reviewing the differences in evaluation objectives, data obtaining, and application scales. Li Feng et al.[48] identified the problems of the green space system of Yangzhou, China by evaluating its ES under six indicator categories, which offered a guideline for the entire process of landscape planning. This method has also been applied in similar research in Gainesville, the United States[49], as well as Berlin, Salzburg, Helsinki, Stockholm, and other European cities[50].

Monetary evaluation[33] is to quantify different ES in a same currency value, which would help estimate the overall value of ES and environmental accounting with methods like equivalent factor method, expense accounting method, market pricing method, opportunity-cost method, shadow project approach, travel expense method, and contingent valuation method[51]. Xie Gaodi et al.[52] developed the service equivalents for China's terrestrial ecosystems, which has inspired the academia to

表1：基于社会-生态数据的生态系统服务制图的数据获取方式分类总结
Table 1: Criteria used to classify the types of approaches used to map ES supply based on social-ecological data

分类标准 Criteria	分类 Categories considered	内容 Rationale
数据来源 Availability of data sources	一手数据 Primary data	实地调研采集得到的数据，包括测绘数据、调查结果、访谈或人口普查资料 Maps derived from sampling in the field (e.g., field data, surveys, interviews, or census data)
	二手数据 Secondary data	无法经由实地调研采集或验证的既有数据，包含地图数据、遥感数据、社会经济数据和数据库或全球统计数据等综合数据信息 Maps derived from readily available information not verified in the field (e.g., cartographical data, remote-sensed data, socio-economic data, and mixed sources or databases like global statistics)
数据类型 Types of data sources	生物物理数据 Biophysical data	用地类型、遥感、地形、水文和气候数据 Land cover, remote-sensed, topographical, hydrological, and climate data
	社会经济数据 Socio-economic data	道路地图、人口地图、照片和人口普查数据 Road map, population map, photos, and census data
	综合数据来源 Mixed sources	数据库（如奥尔森全球碳储存地图、联合国粮食及农业组织报告等全球统计数据）、相关文献、调查报告和调研数据 Database (global statistics, e.g., Olson's global map of carbon storage and FAO reports), bibliography, surveys, and field data
空间尺度 Scales	斑块尺度 Patch	10 ~ 10^2 km^2
	局地尺度 Local	10^2 ~ 10^3 km^2
	区域尺度 Regional	10^3 ~ 10^5 km^2
	国家尺度 National	10^5 ~ 10^6 km^2
	全球尺度 Global	> 10^6 km^2
方法 Methods	文献查询 Look-up tables	利用用地类型文献资料中现有的生态系统服务评估值 Use of existing ES values from the literature to land cover classes
	专家咨询 Expert knowledge	专家基于地块提供某种生态系统服务的潜力，对不同用地类型进行排序 Experts rank land cover types based on their potential to provide specific ES
	因果关系分析 Causal relationships	整合不同层级的、与生态系统过程和生态系统服务相关的既有知识，创建一个新的生态系统服务指标层级 Incorporate existing knowledge about different layers of information related to ecosystem processes and the services to create a new proxy layer of the ES
	一手数据的外延推导 Extrapolation of primary data	参考地图数据（通常是用地类型）对实地调研数据的数据库进行权重处理 Field data databases weighted by cartographical data (generally land cover)
	回归分析 Regression models	将生态系统服务的实地调研数据作为响应变量，将指标（如生物物理数据和从GIS获取的其他信息源）作为解释变量 Employing field data of ESs as response variables and proxies (e.g., biophysical data and other sources of information obtained from GIS) as explanatory variables

注释
表格出处：参考文献[63]。
Note
Source: Ref. [63].

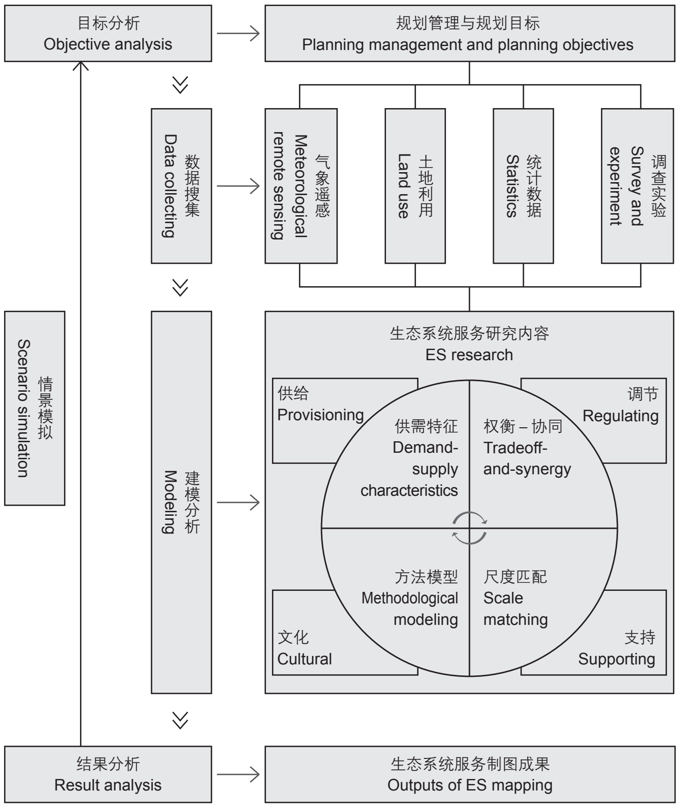
刘亚萍等[56]运用条件价值法和旅行费用法对武陵源风景区的游憩价值进行了评价。

模型评估法通过建立与生态系统服务相关的参数输入和输出模型对生态系统服务进行评估，该方法可以使各项评估结果在空间上展示出来，便于空间规划，其中InVEST模型、Aries模型和SolVES模型应用广泛[57]。李屹峰等[58]采用InVEST模型对北京市密云水库流域的生态系统服务进行评价，研究了土地利用变化对服务的影响；程丹阳等[59]采用SolVES模型对上海市黄浦江两岸滨水空间的社会价值进行量化，为可持续的滨水空间景观规划提供了科学依据。

总之，生态系统服务综合性评估可通过统一量纲的方法对不同的服务类型加以综合评估，以此来调整生态系统服务类型结构，并为景观规划提升生态系统综合效益提供指导。

2. 生态系统服务制图流程示意（图片来源：参考文献[17]）

2. Mapping process of ES (Source: Ref. [17])



2 © 傅伯杰，张立伟

3.2 生态系统服务制图在景观规划中的应用

生态系统服务制图是指结合不同生态系统服务分析方法和模型工具，利用空间制图手段来表达特定时间与空间尺度内生态系统服务的种类、数量、分布特征、相互关系以及发展变化可能性，以进行分析与预测的定量描述方法[60]。其方法和类型经过玛利亚·琼斯·马丁内兹–哈末斯和帕特里夏·巴尔万尼拉[61]、本杰明·巴哈德等[62]的发展，由朱塞佩·普里格等[63]基于生态和社会数据进行了总结（表1）。傅伯杰和张立伟对生态系统服务制图流程进行了归纳（图2），将其主要分为4个阶段，其中建模分析阶段是整个流程的核心[60]，现多采用InVEST、Aries、Mimes和SolVES[64]等工具。将生态系统服务制图方法应用于景观规划，既可直观定量地展示生态系统服务的现状综合特征，又可供规划者、决策者及其他利益相关者模拟未来特定时空尺度下生态系统服务的发展变化情景，为规划决策提供依据。

目前，生态系统服务制图方法在景观规划中的应用主要集中在供需制图和权衡–协同情景分析制图两方面。生态系统服务供给–需求制图是通过将供给和需求量进行叠加运算形成供需关系图，进而作为景观规划决策的依据。董丽青[65]通过供需关系图来探讨“引黄入晋”工程南干线生态系统服务的分布特征和影响因素；刘文平等[66]以北京市海

conduct more quantitative research on different ES types[53][54]. Li Wei et al.[55] used the travel expense method to estimate the recreational value of the natural resources of Jiuzhaigou Scenic Reserve, China; Liu Yaping et al.[56] studied the recreational value of the Wulingyuan Scenic Area through a combination of contingent valuation method and travel expense method.

Modeling evaluation is to build models for ES-related parameters input and output models, which can map out different sorts of evaluation results in a same spatial system, largely facilitating further spatial planning. Common models include InVEST, Aries, and SolVES[57]. Li Yifeng et al.[58] used the InVEST Model to evaluate the ES of the watershed of Miyun Reservoir in Beijing to study the impact of land use changes on ES performance. Cheng Danyang et al.[59] employed the SolVES Model to quantify the social value of the Huangpu Riverfront in Shanghai, providing a reference for sustainable landscape planning of urban waterfront.

To sum up, comprehensive evaluation can realize an overall estimation of all types of ES under a uniform quantitative criterion, so as to improve ES structures and enhance its overall benefits through landscape planning means.

3.2 Application of ES Mapping in Landscape Planning

ES mapping is a quantitative description that combines multiple analysis approaches and models to represent ES varieties, amount, distribution characteristics, interrelations, and future possibilities within specific periods and spatial realms through spatial mapping approaches[60]. Developed by Maria Jose Martinez-Harms and Patricia Balvanera[61], as well as Benjamin Burkhard et al.[62], the methods and types of ES mapping are summarized by Giuseppe Pulighe et al.[63] based on social-ecological data (Table 1). Fu Bojie and Zhang Liwei summarized the process of ES mapping into four steps (Fig. 2), with modelling analysis as the core[60] where tools including InVEST, Aries, Mimes, and SolVES[64] are now most widely employed. ES mapping in landscape planning visualizes the quantified overall ES level and informs planners, decision-makers, and other stakeholders with ES scenarios in particular spatial and temporal scales.

ES mapping is mostly adopted as supply-demand mapping and tradeoff-and-synergy scenario mapping. The ES supply-demand mapping is to overlap ES supplies and demands and identify the gaps so as to provide a reference for landscape planning decision-making. Dong Liqing[65] employed the supply-demand mapping to explore the ES distribution characteristics and impact factors of the southern artery of the Project of Diverting Water from the Yellow River to Shanxi. Liu Wenping et al.[66] developed the supply capacity map of the urban biodiversity protection service in the

淀区为例，基于城市生物多样性保护服务，绘制了生态系统服务供给能力图，直观展现了生态系统服务的空间分布情况，为保护规划提供了重要参考。生态系统服务的权衡—协同是指人们对某种生态系统服务的消费利用导致与之相关的生态系统服务的增加或减少[60]。权衡—协同情景分析制图可以从时间、空间和可恢复性等方面来分析不同情境下生态系统服务的变化情景，从而有助于制定综合效益最大化的景观规划方案。目前针对权衡—协同情景分析制图的研究以简单的统计分析为主，其定量化和模型化的研究亟需加强[67]。

综上，生态系统服务制图是综合使用实地调查、数据分析、空间制图、模型模拟等多种方法，辅助决策者做出合理判断的有效工具。但其仍需在制图流程的规范性、数据来源的全面性、数据分析的可靠性、模型工具的综合性，以及规划决策的有效性方面进行加强。

3.3 生态系统服务情景模拟在景观规划中的应用

生态系统服务情景模拟是指借助数据分析或模型模拟等方式，营建出若干描述生态系统服务格局变化特征、生态保护状况或社会经济发展状况的情景，来分析生态系统服务价值、相互关系及可能产生的发展变化[68]。在景观规划的实际应用中，通常采用模型对生态系统服务的综合特征进行全面描述，包括基于经验的统计模型（如WaterGAP）、动态模型（如IMAGE、EwE）、一般均衡模型（如GREEN、GTAP）、局部均衡模型（如IMPACT）及综合模型（如CLUE-S）等[69]。近年来，由斯坦尼斯劳·阿拉姆和约翰·凡·纽曼提出、海伦·考莱利斯应用在城市研究中[70]的元胞自动机模型（CA）已被越来越多地应用于当前的相关研究中并指导景观规划决策。例如，吕国屏等[71]基于CA-Markov模型对贵州省普定县的喀斯特地貌区不同土地覆被类型及景观格局情境下的生态系统服务价值展开了动态模拟；黄焕春等[72]基于改进后的Logistic-CA模型对天津市滨海地区扩张的多情景下生态系统服务的空间格局特征展开了模拟预测和分析。由此可以看出，生态系统服务情景模拟能够有效预测并展示出土地覆被类型、空间结构、保护管理状况等方面的变化及其对生态系统服务的可能影响，为决策者提供直观、综合的参考信息，这对于生态系统保护与景观规划管理有突出的辅助作用。

Haidian District of Beijing, which visualized the ES distribution in the study area, shining a significance for biodiversity protection planning. ES tradeoff-and-synergy refers to the ES increase or decrease resulted from human's ES consumption[60]. The tradeoff-and-synergy scenario mapping analyzes the ES changes among different preconditions in time, space, and restorability to formulate landscape planning schemes with maximum benefits. Existing studies on this mapping are still on simple statistics. Quantitative and modeling analyses should be strengthened with future efforts[67].

Above review suggests that ES mapping is a tool for landscape planning that combines multiple analysis methods including field investigation, data analysis, spatial mapping, and modelling simulation. However, it also sees expectations to make the mapping process more standard, data more multi-sourced, analyses more scientific, modelling more inclusive, and planning decisions more effective.

3.3 Application of ES Scenario Simulation in Landscape Planning

ES scenario simulation is to analyze and predict ES values, interactions, and possible changes with methods like data analysis and modelling simulation, by creating a series of scenarios that visualize the characteristics of ES pattern changes, ecosystem protection conditions or the level of social-economic development[68]. In landscape planning practices, the models that are used to represent the overall ES characteristics include empirical statistics models (such as WaterGAP), dynamic models (such as IMAGE and EwE), general equilibrium models (such as GREEN and GTAP), local equilibrium models (such as IMPACT), and comprehensive models (such as CLUE-S)[69]. Over the past few years, the Cellular Automata (CA) proposed by Stanislaw Ulam and John von Neumann and applied by Hellen Couclelis in urban studies[70] is more commonly found in relevant studies and landscape planning decision-making processes. For example, Lv Guoping et al.[71] conducted a dynamic simulation of the ES value in different scenarios of varied LULC types and landscape patterns in the karst region of Puding County, Guizhou Province, China with the CA-Markov model. With an improved Logistic-CA model, Huang Huanchun et al.[72] predicted and analyzed the ES spatial characteristics of different scenarios of the coastal area of Tianjin, China under the backdrop of aggressive urban expansion. Examples discussed above suggest that ES scenario simulation works well to predict and visualize the changes in LULC types, spatial structures, and protection and management situations, as well as the possible impact of such changes on ES, providing visual and comprehensive references for decision-makers for ecosystem protection and landscape management.

4 景观规划实践中的生态系统服务研究应用

景观规划是通过调整空间结构和功能来协调人与自然关系的手段，具体包括绿地规划、生态保护红线规划、生物多样性保护规划等。目前，生态系统服务的指标体系、量化评估、空间制图和情景模拟等内容已被应用于多种规划实践中。

绿地规划是将自然与城市相融合，有效地发挥生态系统服务功能，促进城市可持续发展的规划途径。崔朝伟等[73]基于生态系统服务评估了北京市绿地现状，确定了可提升的潜力地块和需整治的问题地块；张婷雯[74]基于生态系统服务量化评估和空间制图，以湖南省长沙市为研究区域，将之分为核心区、缓冲区、过渡区和低敏感区，进而确定了绿地的重要性等级和保护优先等级；萨拉·米罗等[75]借助生态系统服务分析模型对底特律城市绿色基础设施的规划选址进行了探究，以实现社会可持续发展和城市生态韧性的最大化；苏珊·弗兰克等[76]以德国东部萨克森州瑞克兰市的格罗本海尼尔自然保护区作为研究区域，对生态系统服务评估方法在景观空间格局规划层面的应用进行了探索，并通过情景模拟研究了生态系统服务与景观格局之间的关系，为绿地结构优化提供了更好的指导。

生态保护红线划定主要根据区域内各类生态系统服务的能力及其对区域可持续发展的作用和重要性进行分级，明确其空间分布。李晓翠等[77]将生态系统服务重要性纳入生态适宜性评价框架中，将湖北省鄂州市生态保护红线区划分为一级、二级管控区，并提出分区管理措施，为中小型城市生态保护红线划定提供了科学方法；杨姗姗等[78]结合生态系统服务重要性和生态敏感性评价对江西省生态保护红线进行划定；肖甜甜等[79]对海岸带区域生态系统服务进行了价值当量评估，并识别出价值热点作为重点保护区、价值冷点作为生态脆弱区，从而提出围填海区域景观生态保护红线的划定方法。

在土地利用规划中，生态系统服务的量化评估和情景模拟分析可以帮助规划者识别不同土地覆被类型和土地利用模式下生态系统的综合效益，从而协助规划者制定可持续的土地利用决策。拉斯·科斯彻

4 Application of ES Research in Landscape Planning Practice

Landscape planning, including land use planning, green space planning, biodiversity protection planning, and ecological conservation redline planning, is a means that coordinates the relationship between human beings and the nature by adjusting spatial structures and functions. For now, the indicator system, quantitative evaluation, spatial mapping, and scenario simulation of ES have been widely applied in landscape planning practice.

Green space planning is to integrate city with nature and leverage ES performance to boost sustainable urban development. Cui Chaowei et al.[73] evaluated the existing ES level of the green space in the urban area of Beijing and identified the plots with potentials and those need to be improved. Zhang Tingwen[74] took Changsha, a Chinese city, as the study area and divided it into the core area, the buffer area, the transitional area, and the less sensitivity area through quantitative ES evaluation and spatial mapping, in order to identify the importance and protection priority of the city's green space. Sara Meerow et al.[75] used ES analysis models in the site selection of green infrastructure in Detroit for a sustainable social development and a stronger ecological resilience of the city. Susanne Frank et al.[76] applied the ES evaluation methods into the landscape spatial pattern planning for the Großenhainer Pflege in Reikland of Saxony in eastern Germany, studying the relationship between ES and landscape patterns through scenario simulations to improve the green space structure.

The planning of ecological conservation redline grades ESs and defines their distribution by the capacities of all ES types, as well as their importance to the sustainability within a region. Li Xiaocui et al.[77] integrated the importance of ES into the eco-suitability evaluation framework, according to which two-level eco-protection zones of E'zhou, Hubei Province, China are identified and related management guidelines are proposed, providing a scientific demonstration for similar practices in small- or medium-sized cities. Yang Shanshan et al.[78] conducted the ecological conservation redline planning for Jiangxi Province, China through evaluations on regional ES importance and ecological sensitivity. Through ES equivalent evaluations, Xiao Tiantian et al.[79] identified the key protection areas and eco-vulnerable areas in coastal areas, and proposed the classification methods of landscape ecological conservation redline determination for the reclamation areas.

For land use planning, the quantitative evaluation and scenario simulation of ESs help planners comprehend the overall

等[80]以德国瑞克兰市为例进行了土地利用管理与生态系统服务综合评价的研究，并将评估结果与情景模拟结合，协助决策者完成土地利用规划和选址。刘耀林等[81]在土地利用规划、退耕还林及耕地可达性规划中引入生态系统服务价值评估，并以湖北省武汉市东西湖区为例验证了优化模型的有效性。

生态系统服务的量化评估和预测还可应用于生物多样性保护等方面，以辅助生态系统保护规划的制定。提雅・川克等[82]认为适度干扰的生物多样性保护有利于维持某些濒临灭绝物种的可持续性，使生态系统服务达到最大化。吴祖南等[83]通过分析深圳市域河流1988~2008年间生态系统服务对生物多样性保护价值的时空动态，提出了将生态系统服务评估与景观连续性分析相结合，并应用于生物多样性保护和景观规划的方法。

5 总结与展望

本文从土地覆被类型、景观格局与服务功能特性三个方面对景观规划与生态系统服务的关系进行了阐述，得出调控土地覆被类型可以改变服务类型、改变景观格局可以影响服务水平、调整服务功能特性可以影响服务发挥过程。本文还总结了生态系统服务评估、空间制图和情景模拟分析等研究方法在景观规划中的应用，认为稀缺性评估是保障生态安全的基础，综合性评估是保证可持续发展的有效手段，空间制图是辅助决策者做出合理判断的工具，情景模拟则可直观地供决策者选择最优方案。在规划实践层面，学者已对生态系统服务研究在绿地规划、生态保护红线划定、土地利用规划、生物多样性保护规划等景观规划中的应用展开了广泛探索。最后，结合当前的研究与问题，本文对生态系统服务研究在景观规划中的应用提出以下建议：

（1）加强景观规划与生态系统服务之间关系的研究

现阶段的研究表明，土地覆被类型和景观格局是改变生态系统服务类型、影响生态系统服务水平的重要因素。景观规划手段不仅可以从整体上对生态系统服务总量进行调整，还可以改变各服务类型的

benefits of ecosystems in different LULC types and land utilization modes to make smarter decisions on land use sustainability. Lars Koschke et al.[80] evaluated the land use management and the overall ES level of Reikland, Germany. Combined with scenario simulations, the evaluation results played a role in land use planning and site selection. Liu Yaolin et al.[81] introduced the ES valuation into land use planning, reforestation, and farmland accessibility planning, and tested the validity of the improved model in the case of Dongxihu District of Wuhan, Hubei Province, China.

Quantitative assessment and prediction of ESs can also be applied in biodiversity protection planning practice. Teja Tscharntke et al.[82] argued that moderate intervention in biodiversity protection is conducive to certain endangered species to avoid being extinct, and to maximize the ES performance. Cho Nam Ng et al.[83] proposed a method that combines ES evaluation with landscape continuity analyses for biodiversity protection and landscape planning after examining the spatio-temporal changes of ES values in biodiversity protection of the rivers within Shenzhen City from 1988 to 2008.

5 Conclusions and Prospects

This paper reviews the association between landscape planning and ES in respects of LULC types, landscape patterns, and functional characteristics, drawing a conclusion that the control over LULC types, the altering in landscape patterns, and the adjustment of functional characteristics could change ES types, quality, and performance, respectively. Also, the paper examines the application of ES evaluation, spatial mapping, and scenario simulation in landscape planning practices and further concludes that scarcity evaluation serves as a scientific basis for biological security; comprehensive evaluation is an effective means that guarantees sustainability; spatial mapping aids planners to make reasonable decisions; and scenario simulation visualizes varied possibilities and informs decision-making processes. A large number of studies have explored the application of ES research in planning practices such as green space planning, ecological conservation redline planning, land use planning, and biodiversity protection planning. Based on existing research findings and limitations, this paper proposes the following suggestions on the application of ES research in landscape planning:

(1) To strengthen studies on the association between landscape planning and ES

Existing studies reveal that LULC types and landscape patterns greatly matter ES types and qualities. Landscape planning can not only adjust the total ES amount, but also impact the composition and distribution of different ES types. Current research has mainly focused on the qualitative and quantitative studies on the impact

构成和空间分布。目前，针对土地覆被类型与生态系统服务之间定性和定量关系的研究比较充足，而探讨景观格局如何影响生态系统服务的研究较少，建议未来的研究应结合生态学理论，探究景观格局对生态系统服务的影响机制；结合实际案例研究，将定性描述转为定量评估，加强生态系统服务科学在景观规划实践中的应用。

（2）依据生态系统服务构建动态复合的规划框架

风景园林学是一门循证的科学，合理的价值导向和科学的规划流程是景观规划的工作基础。现有的规划方法和模型多从城市规划角度出发，关注空间格局和政策等因素，对生态、社会和文化相结合的系统框架研究较少。以满足人类需求为目标的生态系统服务研究为景观规划提供了理论基础和实践依据。生态系统可以根据时空差异或需求差异提供相应的服务，因此应将时间、空间和需求纳入景观规划框架中，通过对评估方法、评估指标的调整，结合生态系统服务制图，对不同时空条件下的生态系统服务展开模拟分析，充分考虑多种生态系统服务及其相互关系的影响，选择可处理复杂动态空间系统的模型工具，以制定可以满足不同发展阶段、不同生态系统、不同规划目标的动态复合框架体系，从而有效指导景观规划与决策。

（3）推进生态系统服务权衡—协同研究及其在景观规划中的应用

目前，景观设计学领域内对单一生态系统服务评价及其与空间规划的关系研究较多，然而针对多种特定、细分的生态系统服务间权衡—协同关系的研究较少。其主要原因有四：一是评估各生态系统服务价值的数据获取难度较大；二是较难根据复杂的决策目标和有限的可获得数据形成可量化的评估指标；三是因缺乏评估多种生态系统服务价值的统一指标体系和方法，不同区域范围、不同种类生态系统服务的评价结果尚不具备可比性；四是对多种生态系统服务进行空间制图的难度较大，凭借现有空间分析工具不易识别权衡—协同的类型与范围。未来应深入研究影响不同生态系统服务间关系的因素和作用机制，完善生态系统服务权衡—协同的研究方法，并发展空间制图与模型模拟等分析手段，使生态系统服务研究与景观规划设计更有效地对接。**LAF**

of LULC types on ESs, but the impact of landscape patterns on ESs has been less studied. More studies are expected to explore the impact mechanism of landscape patterns on ESs through a perspective of Ecology; besides, combining authentic case studies, with a shift from qualitative descriptions to quantitative evaluations, more efforts are needed to strengthen the application of ES-related sciences into landscape planning practices.

(2) To establish a dynamic, composite planning framework for ES improvement

Landscape Architecture is an evidence-based discipline, and landscape planning embraces rational valuation and scientific process. Current planning methods and models concentrate more on spatial patterns and policies with a lens of urban planning, with less framing studies on the integration of ecological, social, and cultural considerations. ES research that aims at enhancing the overall human well-beings provides theoretical and practical bases for landscape planning. Ecosystems function differently due to the spatio-temporal variety and the assortment of human demands. Thus, a dynamic, composite planning framework conceived to address different stages, ecosystems, and planning objectives can be established by adjusting evaluation methods and indicators; conducting simulations under different temporal and spatial scales through a combination with ES mapping; making comprehensive analyses of multiple ES types and the interactions among them; and, properly selecting models that can process dynamic complex spatial systems. Such a framework would better guide landscape planning and decision-making processes.

(3) To encourage ES tradeoff-and-synergy studies and related applications in landscape planning

In the field of Landscape Architecture, most current research converges on studying one certain ES and its relationship with spatial planning, while few studies explore the tradeoff-and-synergy among multiple ES types, or specific kinds of one ES type. Reasons are: 1) the difficulty in obtaining data of the valuation of different ESs; 2) the difficulty in drawing quantitative evaluation indicators under complicated objectives or with limited available data; 3) the lack of uniform indicator coordinates or methods to assess the value of different ES types makes the cross-evaluation of varied ES types or in varied regions impossible; and, 4) the difficulty in spatial mapping of multiple ES types and identifying the tradeoff-and-synergy types and ranges with existing spatial analysis tools. In future, the academia needs to endeavor to explore the impact factors and mechanisms among different ES types, improve the methods on ES tradeoff-and-synergy study, and strengthen analyses like spatial mapping and modeling simulation, in order to better bridge ES research with landscape planning and design practice. **LAF**

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