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森林生态系统服务多功能性: 概念、指标和经营模拟模型

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摘要:森林生态系统同时提供多种功能和服务的能力，被称为森林生态系统多功能性，可分为生态系统功能多功能性和生态系统服务多功能性。近年来，生态学领域对生物多样性与多功能性关系机理、多功能性驱动因子等进行了大量研究，这些研究持续成为热点。然而，这些研究成果在实际应用，尤其是在指导森林经营实践方面，尚显不足。森林经营一直以实现多种功能或服务的最大化为目标，但目前还缺乏与生态学中多功能性理论研究的有机联系，迫切需要将二者结合。本文对国际国内森林生态系统服务多功能性的概念、指标、评价方法、经营模拟和优化模型进行了综述，认为预测森林生态系统服务及多功能性、在森林经营单位层面实现多功能性最大化是将来的研究方向。因此，需要加强森林经营模型模拟研究，寻找减少不同服务间冲突、增加协同（即增加多功能性）的经营策略，回答森林经营和气候变化如何影响生态系统服务间的权衡和协调关系及其时空变化等理论和实际问题。

关键词: 森林生态系统服务多功能性; 森林生长模型; 权衡–协调关系; 多目标优化

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Forest ecosystem service multi-functionality: definitions, indicators and simulation models for forest management

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Abstract: Forest ecosystem multifunctionality (FEMF) is defined as the ability of forests to simultaneously provide multiple ecosystem functions and services. FEMF could be classified as ecosystem function multifunctionality and ecosystem service multifunctionality. In recent years, a large number of studies have been carried out in the field of ecology on the relationship between biodiversity and multifunctionality, as well as on the driving factors of multifunctionality, and have continued to be a hot topic. However, these research results are still insufficient in terms of application, especially in guiding forest management practices. Maximization of multiple functions and services has been the goal of forest management, but the involvement of FEMF in forest management is still limited, and it is urgently needed to strengthen the integration. This paper summarizes the definitions, indicators and optimization models for the FEMF linked with forest management. We concluded that the future direction will focus on the prediction of the change of forest services and FEMF, and the realization of FEMF maximization at forest management unit level. Emphasis should be given to forest management modelling and simulations to seek the most effective

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management strategies to mitigate trade-offs and enhance synergies of ecosystem services, and answer theoretical and practical questions on how forest management and climate change affect the balance and coordination between ecosystem services, as well as their spatiotemporal changes.

Key words: forest ecosystem service multi-functionality; forest growth model; tradeoff and synergy relationship; multiple-objective optimization

森林具有多种功能已经成为共识，联合国千年生态系统评估将人类从生态系统获得的所有惠益称为服务，并将生态系统服务分为供给（provisioning）、调节（regulating）、文化（cultural）和支持（supporting）4 大类[1]。自生态系统多功能性概念提出以来，国际上在度量指标、评价方法、生物多样性与多功能性关系、多功能性驱动因素、模型预测和经营规划方面都取得了很多进展，成为近年来的研究热点[2]。实际上，森林的多功能利用有悠久的历史，且人们对森林提供的多种服务需求表现出多样和增加的趋势。由于森林生态系统服务之间有权衡（trade-off）和协同（synergy）关系，如何通过森林经营发挥森林生态系统的多功能性仍然存在挑战和不确定性[3−6]。我国也在森林生态系统服务和功能评价指标等领域开展了相应的工作[7−9]，对多功能性的测度[10−11]、多功能性与生物多样性的关系也进行了研究和综述[2,12−16]，这些工作主要从生态学的角度进行。我国还在多功能森林经营领域开展了诸多研究[17−19]。由于缺少专门针对森林生态系统服务的具体指标与模型分析，使得森林生态系统多功能性很难在森林经营中得到体现，需要进一步将森林生态系统多功能性理论与森林经营进行有机结合，从而更好地实施多功能森林经营[20]。因此，本文从森林经营角度，对森林生态系统多功能性的概念、指标、量化方法和经营优化模拟模型进展进行综述，以期为我国的森林多功能经营研究提供参考。

1　森林生态系统服务多功能性概念

生态系统多功能性（ecosystem multifunctionality）的概念起源于为了满足人们的多种需要有必要管理不同用途的土地，因为这些需求或用途往往存在冲突[21]。实际上，林业上提出的多用途（multiple use）、多目标（multiple objective）、多功能（multi-functional）都与多功能性类似。出现的定义包括：“生态系统的综合功能”“同时提供多种生态系统过程”“景观提供多种惠益的潜力”“生态系统对多重生态系统功能的支持能力”等[22]。虽然多功能性被广泛定义，但关于多功能性概念背后的理论和度量指标非常复杂，在实践中的应用还存在很多问题，多功能性的指标选择具有主观性且很难解释[23]。对生态系统多功能性的研究分为两个方向[22]：一是探究群落生物属性（主要是生物多样性）与整体生态系统功能之间的关联性，即生物多样性–生态系统功能关系研究；二是研究景观在实现多种土地利用目标方面的能力，即土地管理研究。前者属于基础研究，后者则偏向于应用研究。相应地，上述两个方向对多功能性有不同的定义和测度。据此 Manning 等[22]提出了两个概念：生态系统功能多功能性（ecosystem function multifunctionality）和生态系统服务多功能性（ecosystem service multifunctionality）。前者被定义为生态系统内发生的生物、地球化学和物理等过程的组合；后者被定义为与人类需求相关的多种生态服务的同时供给，国内有学者也将其定义为生态系统多服务性（ecosystem multiserviceability 或 multi-servicing ability）[16]。尽管在森林经营中采用“多服务性”更为准确，但由于“多功能（多目标）”为森林经营中约定俗成的表达，为便于接受和方便应用，本文仍采用森林生态系统服务多功能性这种表达。实际上，生态系统的功能是提供服务的基础，他们对服务产生直接或间接的影响。因此，森林生态系统的多功能性本质上是指生态系统同时提供多种功能或服务的能力。虽然将功能的多功能性和服务的多功能性进行区分有助于理解多功能性的概念，但在实践中很难将二者绝对地分开。尤其是对于“调节”和“支持”服务而言，他们通常也要用生态系统过程的指标来反映[23]。

2　森林生态系统服务多功能性构成指标

按照联合国千年评估关于森林生态系统服务的定义和分类，主要包括供给、调节、文化和支持 4 类[1]，每类由具体的指标来反映和度量。在 2016 年国家林业局发布的《全国森林经营规划（2016—2050 年）》中，进一步表述为林产品供给、生态保护调节、生态文化和生态系统支持 4 类。因此，森林多功能性的指标也是基于这 4 大类服务的指标。我国也发布了《森林生态系统服务功能评估规范》（GB/T 38582—2020），规定了包括保育土壤、林木养分固持、涵养水源、固碳释氧、净化大气环境、森林防护、生物多样性保护、林产品供给、森林康养等 9 项功能 18 类指标的评估指标体系。

为了给森林生态系统服务多功能性度量提供研究参照，便于在森林经营中应用，本文以 Nocentini[24] 对地中海森林生态系统服务综述中的指标为基础，对二级指标类进行了合并和修改（表 1），并补充了文献中其他区域研究提出的新指标。在森林多功能性的研究中，构成多功能性的服务个数和相对应指标并不相同，指标最多为 28 个[44]。

木材生产仍是供给服务的一个重要内容，实物量指标包括单位面积蓄积量、生长量和收获量，经济指标通常用净现值、土地期望值等表示；可持续性则常用采伐量和生长量之比表示。其他供给服务，如产水、饲料以及非木质林产品（如蘑菇、蓝莓、松籽等）的供给也受到关注。调节服务主要包括生物多样性、气候调节、水土保持、环境保护、病虫害控制等，指标差异较大，大部分指标如水土保持和碳等需要通过模型推算。文化服务主要包括景观游憩、动植物相关的文化、打猎和森林食物等，仍然是比较薄弱的环节。支持服务是多功能性的基础，包括生产力、更新过程、土壤过程等。土壤的多功能性也是为一个重要分支，主要表现在碳和气候调节、净化和调节水质、养分循环和病虫害控制等方面[45–46]。但也有学者认为，支持服务不应考虑，因为支持服务为其他服务提供了基础功能且间接得到反映，应当归为森林生态系统“功能”，是供给、调节和文化“服务”的基础[47]。

表 1　森林生态系统服务多功能性主要构成指标

Tab. 1　Main index components of multifunctionality in forest ecosystem services

服务 Service	指标 Indicator
1 供给 Provisioning	
1.1 木材生产 Timber production	栓皮总产量、栓皮年生长量[24]；木材产量、木材收获量、年生长量[24−25]；木材生产净现值[26−28]；采伐量与生长量之比[29] Total cork supply, and annual increment cork mass[24]; wood production, timber yield, annual increment[24−25]; net present value of timber production[26−28]; harvest-to-growth ratio[29]
1.2 非木质林产品 Non-wood forest products	食用蘑菇产量[26,30]*；野生食用植物盖度[24,30]*；浆果、花、坚果、蜂蜜、松籽产量[24]；年饲料产量[24]；三文鱼的丰富度[31]；打猎的鹿的数量[31]；越橘产量[24,26,28,32−33]；越橘出现[33] Edible mushroom production[26,30]*; coverage of wild edible plants[24,30]*; production of berries, flowers, nuts, honey, and pine nuts[24]; annual fodder production[24]; salmon abundance[31]; hunting deers[31]; bilberry production[24,26,28,32−33]; presence of bilberry[33]
1.3 遗传资源 Genetic resources	遗传资源（种子传播面积）[24] Genetic resources (seed dispersal area)[24]
1.4水 Water	年产水量、基于硝酸盐含量的水质[24]；枯落物持水量[34] Annual water, water quality based on nitrate yield[24]; water-holding capacity of litter[34]
2 调节 Regulating	
2.1 生物多样性 Biodiversity*	树木微生境[24]；超过一定大小的生境树的数量[29]；死木量或出现的概率[27,33,35−36]；树种多样性[24,26]；下层植被多样性（丰富度）[24,36,45]；鲜果密度[24]；鸟类多样性[24]；鸟类生境质量[25]；脊椎动物[27]；林分结构多样性[24,25,37]；大树（胸径40 cm以上）的数量[26]；菌根多样性[30] Tree microhabitats[24]; number of habitat trees above a threshold[29]; amount of dead wood or the probability of occurrence[27,33,35−36]; tree species diversity[24,26]; understory vegetation diversity (richness)[24,45,36]; fresh fruit density[24]; bird diversity[24]; bird habitat quality[25]; vertebrates[27]; stand structural diversity[24,25,37]; number of large trees (diameter at breast height > 40 cm)[26]; mycorrhizal diversity[30]
2.2 虫害控制 Pest control	树皮甲壳虫控制[30,38]；天敌的生境[39]；杂草和开阔生境的植物的比例[40]Bark beetle control[30,38]; habitat for natural enemies[39]; proportion of ruderal and open habitat plant species on total plant cover[40]
2.3 调节气候 Climate regulation	调节温度[24,30]；生物量和碳贮量[24,25−28,38,41]；碳吸存[26]Temperature regulation[24,30]; biomass and carbon storage[24,25−28,38,41]; carbon sequestration[26]
2.4 环境保护 Environmental protection	河道周围25 m缓冲区护岸林的覆盖率[24] Riparian forest cover around watercourses considering a bufer zone of 25 m around[24]
2.5 土壤保持 Soil conservation	坡度30°以上区域的森林覆盖率、减少的土壤侵蚀量、沉积物滞留量、土壤有机碳量[24]Forest coverage in areas with a slope over 30°, reduced soil erosion, sediment retention, and amount of organic carbon in a soil[24]
2.6 水调节 Water regulation	林冠和土壤蓄水能力、森林巨苔藓蓄水量[24]；水质调节、枯落物蓄水量[34]；生物结皮的土壤比例（表土中的苔藓、蓝藻、地衣）[24] Canopy and soil water storage capacity, wter holding capacity by forest macrolichens[24]; water quality regulation, litter water storage capacity[34]; soil covered by biological crusts (mosses, cyanobacteria, and lichens in the topsoil)[24]
2.7 防风功能 Protection against wind damage	优势木高径比[24,41] Dominant tree height-to-diameter ratio[24,41]
2.8 防灾功能 Protection against hazards	林分密度指数、滑坡防控指数[29] Stand density index, landslide prevention index[29]
3. 文化 Cultural	
3.1 游憩 Recreation	每个城市农村旅游中的床位数量[24]；风景林面积；美景指数[26,28]；视觉吸引性[29]；景观美学[31]；旅游收入[29] Number of beds in rural tourism establishments per municipality[24]; scenic forest area; scenic beauty index[26,28]; visual attractiveness[29]; landscape aesthetics[31]; tourism revenue[29]
3.2 动植物文化 Animal and plant culture	乡土阔叶树的数量[24,35]；老龄林的指示性物种甲壳虫、表层苔藓和菌类[35]；文化相关的植物的盖度[38]；文化价值的植物（公众及植物学专家特别关注的植物）[30]；观鸟服务潜力[30,38] Number of native broadleaved tree species[24,35]; indicator species of old-growth forests, such as beetles, surface mosses, and fungi[35]; canopy cover of culturally related plants[38]; plants of cultural value (plants of particular interest to the public and botanists)[30]; bird-watching service potential[30,38]

表 1(续)

Tab.1 (continued)

服务 Service	指标 Indicator
3.3 打猎 Hunting	猎物生产潜力[24,36] Game production potential[24,36]
3.4 森林食物 Forest food	食用菌的数量、可食用植物的盖度[38] Number of edible mushrooms, cover of edible plants[38]
4. 支持 Supporting	
4.1 生产力 Productivity	净初级生产力[31] Net primary productivity[31]
4.2 更新过程 Regeneration process	天然更新幼苗种类和数量[35] Species and number of naturally regenerated seedlings[35]
4.3 土壤过程 Soil process	土壤速效 K、土壤速效 P、土壤全 N、土壤全 P[34,37−38,41−43] Soil available K and P, soil total N and P[34,37−38,41−43] 腐生真菌数量、菌根真菌数量、硝化作用潜势、菌根多样性、根的分解[30,38] Number of saprophytic fungi, number of mycorrhizal fungi, potential nitrification, mycorrhizal diversity, root decomposition[30,38]

注：*表示同时作为支持或文化服务指标。Note: * indicates that it also serves as an indicator for supporting or cultural services.

3 森林生态系统服务多功能性评价方法

王凯等[2]和徐炜等[10]对生态系统多功能性的度量方法进行了详细的总结和评述，主要包括单功能法、功能–物种替代法、平均值法、单阈值法、多阈值法、直系同源基因法和多元模型法等。其中，平均值法和多阈值法是应用最广泛的方法。平均值代表多功能性的平均水平，但存在可能与服务的数量无关、难以区分由相似水平的功能与部分较高水平和较低水平功能分别得到的多功能性指数差异、忽略了系统信息等问题；多阈值法则存在容易受主观选择阈值的影响、未考虑功能之间的相关性、相对比较繁琐问题[6,48−50]。二者也都未能反映不同功能之间的权衡和协同关系。此外，这些方法往往在局部（如样地）尺度上应用，不能进行跨尺度评价[51]，缺乏实现不同尺度多功能性分解转化的统计框架[52]。

为解决跨尺度生态系统多功能性度量问题，Hölting 等[51]提出了一种新的多尺度的多功能性度量方法。该方法借鉴生物多样性中 α 和 β 多样性的度量，通过丰富度（ecosystem service richness）、多度（ecosystem service abundance）和多样性（ecosystem service diversity）来测度生态系统服务。丰富度指一定面积森林提供的生态系统服务的数量；多度表示同时提供的多个生态系统服务的强度；多样性则是多度和丰富度的综合反映。由于不同生态系统服务的单位不同，需要先进行标准化。并用 α 和 β 多功能性来评价生态系统服务多功能性，前者用 Simpson 多样性指数来表示（式 1），后者用两个系统间生态服务的差异性 Bray-Curtis 指数来表示（式 2）。由于人们在不同尺度关注的生态系统服务有别，α 和 β 多功能性可全面反映多尺度的多功能性。α 多功能性主要用于局部，反映生态系统服务的多样性；β 多功能性主要用于景观尺度，反映不同区域或单元生态系统服务的独特性。这种跨尺度的多功能性评价有助于确定在大区域中独特的生态系统服务，该独特服务对实现大尺度的多功能性非常重要[51]。

$$D = 1 - \sum_{i=1}^{N} {p_i}^2 \tag{1}$$

$$\mathrm{BC}_{jk} = 1 - \frac{2C_{jk}}{S_j + S_k} \tag{2}$$

式中：D 为 Simpson 指数；N 为生态系统服务的个数；p_i 为第 i 个服务的比例；BC_{jk} 为 Bray-Curtis 指数，j、k 为两个林分或单元；S_j、S_k 分别为 j 和 k 两个单元的生态服务的和；C_{jk} 为两个单元共同的生态系统服务中较小值服务的和。

实际上，在进行多功能性度量时，不仅要考虑跨尺度问题，多个服务间的相关性也需要考虑，避免信息冗余和重叠。既然物种多样性能描述其组成的生态系统物种的变化，多功能性也应能描述这些物种提供的服务。Byrnes 等[50]和 Chao 等[53]在这方面取得了新的重要进展，他们借用生物多样性中的 Hill 指数（Hill numbers）来量化多功能性。Hill 指数将物种丰富度及其均匀度同时考虑，通过 Hill 指数的 q 阶的取值来统一不同的多样性指数[54]。Chao 等[55−56]通过 Hill 指数将物种多样性、系统发育多样性、功能多样性以及相关的相似性和差别统一起来，称为 Hill-Chao 指数，该指数具有不同层次多样性的可分解特征。Byrnes 等[50]借用 Chao 等[57]关于物种多样性的统一框架，提出了一个新的多功能性指数，它考虑了组成多功能性的服务个数、均匀度、水平和相关性，最终的多功能性表达如式（3）所示。

$$^{q}M_{\mathrm{ef}} = A\left(\sum_{i=1}^{L} p_i \left(\sum_{j=1}^{L}\left[1 - \frac{d_{ij}(\tau)}{\tau}\right] p_j\right)^{q-1}\right)^{1/(1-q)} \tag{3}$$

式中：$^{q}M_{\mathrm{ef}}$为 q 阶有效多功能性，p_i为第 i 个服务的比例，L 为服务的个数，A 为 L 个服务的算术平均

值，τ为表征两个服务间差异性的阈值，d_{ij}为两个服务间的距离（差异）。

Chao 等[53]对上述指数进行了修正，提出了一个基于 Hill-Chao 指数的新的统计框架。该框架不仅可以将γ尺度的多功能性分解为 α 和 β 成分，而且可对各个生态系统功能进行加权，经过相关性校正后的多功能性为式 4。该指数与式(3)指数的理论区别在于：能满足当增加一种非常低水平的服务时，多功能性会随之增加，但式(3)不能满足[53]。

$$^{q}\mathrm{MF}^{*}(\tau)=\left(\sum_{i=1}^{H}w_i\frac{f_i^2}{a_i(\tau)}\left(\frac{a_i(\tau)}{\sum_{j=1}^{L}w_i f_i^2}\right)^{q}\right)^{\frac{1}{1-q}},\ q\geqslant 0,\ q\neq 1 \tag{4}$$

$$a_i(\tau)=f_i+\sum_{j\neq i}\left(1-\frac{d_{ij}(\tau)}{\tau}\right)f_j \tag{5}$$

式中：$^{q}\mathrm{MF}^{*}(\tau)$为 q 阶多功能性，f_i为第 i 个服务的水平，w_i为第 i 个服务的权重，H 为生态系统的子集个数，τ为表征两个服务间差异性的阈值，$a_i(\tau)$为考虑两个服务间的相关性后得到的第 i 个服务的新水平，d_{ij}为两个服务间的距离（差异）。

此外，虽然可持续经营希望最多的服务和最大的综合功能，但在局部尺度往往很难实现，原因是生态系统提供服务的能力不同及服务间存在权衡关系。如果在一个区域多种服务的供给不能在某个时间最大化，实现景观尺度的多功能性将是目标[51]。但景观尺度多功能的最大化不能牺牲局部的多功能性，因为局部的一些服务尤其是调节服务不可替代。景观尺度的多功能性与管理决策更为密切[22,58−60]，需要考虑不同尺度，将 α 和 β 多功能性综合考虑进行优化。

4　基于生长模型的森林多功能性模拟和优化

利用森林生长模型和优化方法来模拟不同经营措施（方案）对森林生态系统服务的影响，在林业上已有较长的历史，在森林经营规划中称为多目标优化（multi-objective optimization），如利用矩阵生长模型进行木材生产、碳贮量和结构多样性的模拟和经营优化[61−62]。近年来，结合生态服务多功能性的研究，在探索不同服务之间的权衡和协调关系方面也取得了一些进展。表 2 给出了森林生态系统服务多功能性经营生长模拟和优化模型、模拟方案、多功能组成和研究尺度。可以看出，木材生产、碳吸存、生物多样性仍是研究最多的生态系统服务，因为这些指标可以通过森林生长模型直接计算；其中单木水

表 2　森林生态系统服务多功能性经营模拟和优化模型

Tab. 2　Simulation and optimization models for forest management of ecosystem service multi-functionality

模型 Model	国家 Country	模拟方案 Modeling scenario	多功能组成 Multi-functionality composition	应用尺度 Application scale	文献 Reference
SwissStandSim	瑞士 Switzerland	栽植密度、间伐强度和择伐强度＋气候变化 Planting density, thinning intensity, selection cutting intensity, and climate change	木材生产、碳和生物多样性、游憩、防护 Wood production, carbon and biodiversity, recreation, and protection	林分 Stand	[65]
Samsara2	法国 France	异龄林经营 Uneven-aged forest management	木材收获、生物多样性、防护 Timber harvest, biodiversity and protection	林分 Stand	[66]
ForSAFE	瑞典 Sweden	常规经营、增加间伐次数、缩短轮伐期 Business as usual, increased thinning frequency, and shortened rotation period	生产力、碳贮量、木材生产、水量和水质 Productivity, carbon storage, wood production, water quantity and water quality	林分 Stand	[67]
单个模型 Single model	芬兰 Finland	同龄林经营、异龄林经营 Even-aged forest management and uneven-aged forest management	木材生产、碳和蓝莓 Wood production, carbon and blueberry	林分 Stand	[68]
矩阵生长模型 Matrix growth model	中国 China	择伐强度和周期的组合 Combination of selective cutting intensity and cycle	木材生产、碳贮量、林分结构多样性 Wood production, carbon storage, and stand structural diversity	林分 Stand	[62]
MASSIMO	瑞士 Switzerland	常规经营和不同强度采伐 Business as usual and different intensity harvest	木材生产、碳和生物多样性 Wood production, carbon and biodiversity	样地 Sample plot	[69]
SORTIE-ND	加拿大 Canada	生物能源、增碳、降低脆弱性策略和常规经营＋气候变化 Biomass energy, carbon enhancement, strategies to reduce vulnerability, business as usual, and climate change	木材生产、碳、蘑菇产量、供水、土壤保持和生物多样性生境 Wood production, carbon, mushroom yield, water supply, soil conservation and biodiversity habitats	样地 Sample plot	[70]
经验生长模型 Empirical growth model	中国 China	优化 Optimization	木材生产和碳贮量 Wood production and carbon storage	森林经营单位 Forest management unit	[71−72]

表 2(续)

Tab.2 (continued)

模型 Model	国家 Country	模拟方案 Modeling scenario	多功能组成 Multi-functionality composition	应用尺度 Application scale	文献 Reference
经验生长模型 Empirical growth model	中国 China	轻度、中度、重度择伐及无采伐 Light, moderate and heavy selective cutting, and no harvesting	木材生产、碳 Wood production and carbon	森林经营单位 Forest management unit	[73]
经验生长模型 Empirical growth model	中国 China	优化 Optimization	木材生产、碳 Wood production and carbon	森林经营单位 Forest management unit	[74]
ETCAP	土耳其 Turkey	低、中、高不同经营强度 Low, medium, and high management intensities	生物多样性、木材生产、碳、文化价值、供水和土壤保护 Biodiversity, wood production, carbon, cultural values, water supply, and soil conservation	区域 Region	[64]
SIMO-forest simulator	芬兰 Finland	轮伐经营、恒续林经营、对照 Clear cutting, continuous cover forest management, control	木材生产、碳贮量和吸存、非木质林产品(越桔、蘑菇、视觉)、生物多样性等 Wood production, carbon storage and sequestration, non-timber forest products (such as blueberries, mushrooms, and visual aesthetics), and biodiversity，etc	景观 Landscape	[26,28,75]
FORRUS-S	俄罗斯 Russia	间伐、造林 Thinning and reforestation	林分结构、游憩 Stand structure and recreation	景观 Landscape	[76]
Heureka，Kupolis，Sibyla，Growfor + Remsoft，StandSim + SADfLOR, InVEST，EFISCEN-space		多种方案 Multiple scenarios	生物多样性、碳吸存、木材生产、水土保持、游憩 Biodiversity, carbon sequestration, wood production, soil and water conservation, and recreation	景观 Landscape	[63]
Woodstock	加拿大 Canada	常规、对照 Business as usual, control	碳、防风、水质、生物多样性 Carbon, wind protection, water quality, and biodiversity	景观 Landscape	[77]
Monsu	芬兰 Finland	轮伐经营、恒续林经营、其他经营 Rotation management, continuous cover forest management, and other management practices	木材生产、碳贮量、碳平衡、生物多样性 Wood production, carbon storage, carbon balance, and biodiversity	景观 Landscape	[78]
SILVA	德国 Germany	木材生产、多功能经营、对照 Wood production, multi-functional management, and control	生产力、碳吸存和地下水补给 Productivity, carbon sequestration, and groundwater recharge	景观 Landscape	[79]
LanClim	瑞典 Sweden	同龄林经营、异龄林经营 Even-aged forest management and uneven-aged forest management	木材生产、生物量、树种和林分结构多样性 Wood production, biomass, tree species and stand structural diversity	景观 Landscape	[80−81]
PICUS	奥地利 Austria	常规经营和对照 + 气候变化 Business as usual, and control under climate change	木材生产、碳吸存、生物多样性、山体滑坡防护 Wood production, carbon sequestration, biodiversity, and landslide protection	景观 Landscape	[82−83]
LPJ-GUESS	瑞典 Sweden	对照、同龄林经营、异龄林经营经营 Control, even-aged and uneven-aged forest management	收获生物量、收入、抗灾、碳贮量、文化等 Harvested biomass, income, predisposition to storm damage, carbon storage, and culture，etc	景观 Landscape	[84]
YAFO	德国 Germany	对照、常规经营、轻度和中度间伐 + 气候变化 Control, business as usual, light and moderate thinning under climate change	防止雪崩和落石、土壤侵蚀、调节气候、蓄积量等 Avalanche and rockfall prevention, soil erosion, climate regulation, and stock volume, etc	景观 Landscape	[85]
ForClim	瑞士 Switzerland	对照、常规经营、替代经营 Control, business as usual, and alternative management	木材生产、碳、生物多样性、减灾 Wood production, carbon, biodiversity, and disaster mitigation	区域 Region	[86]
SiTree	挪威 Norway	完全保护、常规经营、集约经营、粗放经营、恒续林经营、考虑应对气候变化的经营 Complete protection, business as usual, intensive management, extensive management, continuous cover forest management, management considering climate change adaptation	生物多样性保护、生物能源、调节气候、木材、水和游憩 Biodiversity conservation, bioenergy, climate regulation, wood, water, and recreation	区域 Region	[87]

平的经验模型如 PICUS、SILVA、MASSIMO 等，过程模型如 Samsara2、LPJ-GUESS；林分水平的经验模型如 SwissStandSim。用于规划的优化决策平台如 ETCAP、Woodstock、YAFO、SIMO 等。林分或样地是最常用的尺度，景观尺度的研究逐渐得到重视。模拟方案涵盖常规（business as usual）、同龄林经营、异龄林经营、不同采伐强度、国家或区域宏观战略等，这些经营方案和气候变化情景相结合，成为一种新的趋势，它可以为应对气候变化的适应性多功能森林经营提供依据。Biber 等[63]以欧洲 9 个国家 10 个森林景观案例为对象，模拟了不同经营策略下森林生态系统服务 100 年后的变化。对于每个案例研究，都使用了相应的森林生长和规划模拟器。通过分析，探讨了木材生产、碳吸存和生物多样性两两之间的权衡和协调关系，但并未发现确定的相关关系。在研究中，还采用了两个模型相结合的方法。此外，一些服务如产水量、土壤流失量等，采用包含林分断面积的经验模型来估计[64]。

5　问题与趋势

森林生态系统的多功能性成为共识，但在实际操作层面仍面临诸多困难。如何将生态学领域关于森林生态服务多功能性的理论研究结果和不同层次的森林经营规划相结合，是将来的主要研究方向。

5.1　多功能性指标的选择

反映不同服务的指标差异较大，尤其是文化服务仍然是薄弱环节。因缺乏统一的分类方法，使得森林生态系统系统服务比较和研究变得困难。表 1 虽然给出了文献中主要的生态系统服务指标，但很难完全覆盖。从表 1 可以看出，一些指标，如越橘产量既是供给服务，也是文化服务；乡土阔叶树的数量既是支持服务，也是文化服务。大部分将生物多样性归为支持服务，但也有归为调节服务。一些指标在林分（样地）层次，一些在森林经营单位或景观层次。一些指标通过调查或测定获得，但并不是所有的生态服务通过测定获得，一些主要通过模型得到。虽然对指标的选择需要考虑诸多因素，比如随时间的变化、可测等，但重要的是要考虑选择该指标的原因以及它对多功能性的贡献和解释[23]，尤其是如何定量反映森林经营目标。此外，随着社会经济的发展，人们对从森林中获得精神享受的需求越来越强烈，总的来看，景观和游憩价值最常用[88]，需要进一步开展森林文化服务的度量指标研究。

5.2　多功能性度量方法

森林生态系统服务多功能性是一个宽泛的概念，不同的研究人员选择的指标和方法各异，至今没有一个统一或最佳的方法来进行评估。传统的森林经营规划通常用加权的目标函数或效用函数来表示多目标，生态学领域则采用平均值法和阈值法构造综合指数。但这些都是一种综合指数的方法，均未体现不同目标或服务功能间的权衡和协调关系。如何考虑不同生态服务指标间的权衡和协调关系、实现林分、森林经营单位等跨尺度的森林生态服务多功能性评价和比较，并和森林经营相联系，是将来需要进一步研究的问题。Siwicka 等[89]引入了一种多元网络分析方法，利用网络理论来评估多功能性、树种功能性状、环境特征和功能之间的关系，该方法具有节点间关系清晰和透明、可以揭示格局和共同出现等优点，适用对森林生态系统服务多功能性的复杂性的理解。Chao 等[53]最新提出的基于 Hill 指数的多功能性统计框架，具有跨尺度、可分解、统一化等特点，但过于复杂的指标和评价方法反而会限制其在森林多功能经营实践中的应用。

5.3　经营模拟和优化模型

将森林生态系统服务多功能性纳入森林经营规划是森林可持续经营的必然要求，因此预测和模拟森林生态系统服务的动态非常重要[90−91]。尽管森林生态系统服务多功能性构成要素很多，但其基础始终是以森林的生长为基础。除了木材生产外，其他生态系统服务的预测同样非常重要，这需要采用过程生长模型，或者利用一些容易测量的变量进行预测。由于森林经营规划有不同的层次，其规划的时间和空间尺度及信息也不相同，核心是森林经营单位层次的优化和林分层次的生长预测与模拟[92]。在林分层次，主要通过林分生长模型，模拟和优化最优的能实现多功能性森林经营策略；在森林经营单位（景观）层次，主要优化得到满足景观层多功能性的不同森林经营策略的比例。这就要求在森林经营单位编制经营方案时，采用多目标空间优化技术[93]，考虑多种生态服务的权衡和协同，实现多功能性最大即整体最优。从现有研究的模拟结果来看，不同服务间的权衡和协调关系存在较大的变异性。尤其是国内尚缺乏自主研发的森林生态系统服务多功能性预测和经营优化工具，需要在此领域持续研究，开发软件平台，实现林分和森林经营单位等不同尺度的生态系统服务预测。生态服务指标的多样性增加了模型模拟的复杂性，因为不同的生态服务目标组合常常会导致不同的经营策略组合[84]。需要考虑更多的生态服务，尤其是调节和文化服务。未来的研究重点包括：通过模拟和优化模型来寻找能最有效的减少生态系统服务的冲突、增加协调（即增加多功能性）的经营策略；回答森林经营和气候变化如何影响

不同生态系统服务间的权衡和协调关系，以及这些权衡和协调关系随时空如何变化等理论和实际问题。

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