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森林木质残体对物种多样性的影响研究进展

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摘要:木质残体通过为多种生物提供栖息地、繁殖场所和养分支持,在维持物种多样性中起着关键作用。基于近 20 年国内外相关研究,系统梳理了木质残体对物种多样性的影响,涵盖了木质残体上栖息的动物、微生物和植物多样性。从木质残体的个体特征(如来源、体积大小、分解程度及树种类型)方面,系统分析其对物种多样性的作用机制;阐述了森林管理实践引起的木质残体数量、特征以及时空连续性的变化对生物多样性的影响。提出将木质残体纳入森林适应性管理的策略、气候变化背景下木质残体与物种多样性的关系评估、极端干扰事件对木栖物种群落组成的影响、木质残体树皮特性与生物群落构建的关系 4 个未来研究重点方向。旨在为森林木质残体的科学管理提供依据,亦为森林生态系统物种多样性保护提供新视角。

关键词:森林生态系统;倒木;木质残体;森林管理;物种多样性

Advances in the impact of forest woody debris on species diversity

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Abstract: Woody debris plays a critical role in maintaining species diversity, offering habitats, breeding grounds, and nutritional support to a variety of organisms. This review synthesizes the impact of woody debris on species diversity, drawing on studies spanning the last two decades and encompassing the diversity of animals, microorganisms, and plants within woody debris habitats. Mechanisms through which the individual attributes of woody debris are analysed, including origin, size, decomposition stage, and tree species—affect species diversity. For instance, larger woody debris provides stable microhabitats over extended periods, thereby supporting higher species richness, while specific tree species create unique ecological niches due to their distinct chemical and physical properties. The decomposition process, which occurs in distinct stages, drives dynamic changes in species composition, with each stage fostering specific ecological interactions. Additionally, the origin of woody debris—whether derived from natural events such as storms, fires, and insect outbreaks, or human activities like logging—plays a significant role in determining its quantity, quality, and habitat potential, thereby

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shaping biodiversity outcomes across different forest types. The review also discusses how changes in the quantity, characteristics, and spatial-temporal continuity of woody debris, resulting from forest management activities, affect biodiversity. Intensive forest management frequently reduces the volume and structural diversity of woody debris, negatively impacting specialized and rare species. In contrast, strategies that promote natural forest dynamics or adopt adaptive management approaches enhance habitat heterogeneity, thereby benefiting a wide array of organisms. Maintaining diverse types and decomposition stages of woody debris is crucial for supporting species across multiple trophic levels, including fungi, invertebrates, birds, and mammals. Furthermore, the spatial connectivity of woody debris is essential for low-dispersal species, underscoring the importance of landscape-scale planning to ensure habitat availability and ecological resilience. Building on existing knowledge, four key future research directions are identified: incorporating woody debris into adaptive forest management strategies, assessing the relationship between woody debris and species diversity under climate change, investigating the effects of extreme disturbance events on wood-dwelling species communities, and exploring the relationship between bark characteristics of woody debris and community structure. This review aims to provide scientific guidance for the management of forest woody debris and offer new perspectives for the conservation of species diversity in forest ecosystems.

Key Words: forest ecosystem; fallen log; woody debris; forest management; species diversity

物种多样性对于维持生态系统服务至关重要[1]。然而全球气候变化加剧了物种多样性的丧失,威胁着人类的福祉[2],如何充分认知、有效保护并持续维持全球物种多样性成为人类面临的巨大挑战。森林作为陆地上分布最广、结构最复杂的生态系统之一[3],集中了全球70%以上的物种[4]。森林物种多样性的研究和保护成为当前国际社会和各国政府普遍关注的热点问题。

森林生态系统中,任何留在林地上的树木残骸都被称为木质残体,包括倒木、枯立木、大枯枝和树桩等[5]。根据直径大小分为粗木质残体(≥10cm, Coarse woody debris)和细木质残体(<10cm 且>2cm, Fine woody debris)。木质残体是一个以树木死亡输入及其分解输出的动态平衡过程[6—7],作为森林结构和功能的重要组成部分[8],在森林的多样性保育功能方面发挥着关键作用。它不仅促进森林更新[9],为新生树木提供养分、光照和生长空间[10],还充当植物与土壤间养分循环的桥梁,为土壤微生物提供能量[11]。木质残体作为一种特殊的生境,是多种生物的栖息地和营养来源[12—13],在维持生物多样性方面发挥着关键作用[14—15]。然而,目前对木质残体的生态功能及其对物种多样性的影响仍存在许多未知,亟需进一步研究。

传统的森林管理主要注重木材生产和采伐物的资源性利用[16],而木质残体被认为是潜在致命病原体的重要载体和森林地表可燃物,容易增加森林灾害的风险[17],导致木质残体往往被视为废弃物而被清除[18—21],进而对木质残体的数量、种类和分布产生直接影响[22]。这极大限制了我们对木质残体动态变化如何影响特定物种群落及其栖息地长期稳定性的认知。本文通过梳理近20年来木质残体对其栖居物种多样性影响的研究(图1),系统分析了木质残体的个体特征对物种多样性的影响,以及森林管理对木质残体及其物种多样性的影响,并对其未来研究领域予以展望,旨在为木质残体的合理管理提供科学依据,进而促进森林生态系统的健康和生物多样性的可持续保护。

1 木质残体上存在的物种多样性

许多研究从不同角度探究木质残体与物种多样性之间的作用关系或联系[22—23],涉及微生物、动物和植物等多个层面。据估计,仅与木质残体有关的物种多样性约占全球森林物种多样性的30%,在某些类群(如鞘翅目)中甚至达到50%[24]。近几十年来,关于木质残体物种多样性价值的研究显著增长[25—26]。

1.1 动物多样性

木质残体是动物在森林生态系统重要的栖息地之一,为动物提供了1/3—1/2的可利用资源,众多动物的种群数量与木质残体的生物量或贮量呈正相关关系[27—29]。无脊椎动物和脊椎动物使用木质碎片作为庇护

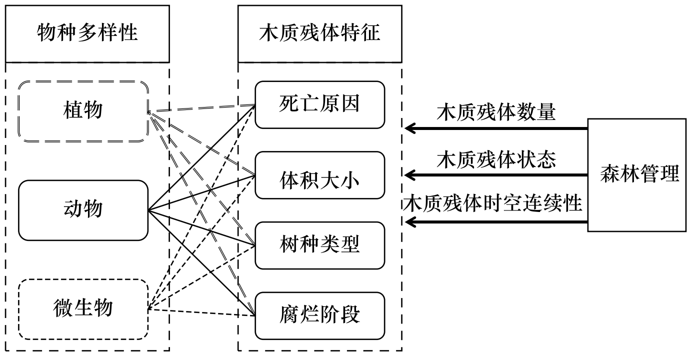

图 1　森林木质残体对物种多样性的影响

Fig.1　The impact of forest woody debris on species diversity

所、筑巢点或水分来源[30—31],对抵御极端温度起缓冲作用[32]。全球有 40—100 万种无脊椎动物栖息于森林的木质残体中[24,33]。其中,甲虫是无脊椎动物中被研究最多、且分类最明确的类群[34]。在欧洲北方森林中大约 20%——30%的昆虫属于木栖昆虫[26],其中,依赖木质残体的鞘翅目高达 4000 种[12]。在捷克共和国南摩拉维亚的阔叶林中发现了 14 种腐生蚂蚁和 389 种腐生甲虫[35]。类似的,法国拉马萨内古老森林中 37%的甲虫与木质残体密切相关[36]。这些昆虫不仅在森林物种丰富度中占有很大的比例,还对森林生态系统的分解和养分循环起着重要的作用[14,37]。有研究表明,无脊椎动物每年可导致木质残体 10%——20%的质量损失[38],特别是在热带和亚热带森林地区[39]。与此相比,哺乳动物对倒木的依赖性较弱,主要将其作为迁移廊道使用[40],例如美洲斑马鼬(*Martes americana*)利用倒木作为巢穴和通道[41—44]。如果将木质残体从森林中完全移除,将会导致森林生态系统 1/5 的动物区系丧失[45]。

1.2　微生物多样性

木质残体上存在丰富的微生物群落,主要包括真菌、细菌、黏菌和古菌等,其中真菌和细菌是最为重要的类群,承担了木质残体分解的主要功能[46]。木腐真菌被视为森林生态系统中木质残体的先锋物种,其初始化生态演替过程维持着森林生物多样性[47]。由于真菌能够迅速定殖木质残体并分解纤维素和木质素,其多样性的增加对木质残体的有机物循环具有积极影响[48—50]。在全世界估计的 150 万种真菌物种中,仅木栖物种就占了 20%—40%左右[12]。例如,在澳大利亚南部塔斯马尼亚的原生桉树林中,已发现多达 295 种大型真菌附生于木质残体上[51]。Yang 等[52]在 10 个常见的欧洲树种的倒木上共记录到了 4644 个真菌子实体。木质残体作为木腐真菌的主要栖息地,已成为欧洲生态与保护生物学研究的重要研究方向之一[47,53]。

相比真菌,尽管细菌在分解木材以及在植物组织中定殖的能力有限[54],但它们仍然对木质残体的物理结构和化学组成具有重要影响。细菌的作用主要体现在改变木材的渗透性、破坏木材结构、充当其他细菌的“拮抗剂”并通过与其他微生物群体的相互作用来维持微生物群落的平衡[55]。杨立宾等[56]在探究大兴安岭寒温带兴安落叶松倒木分解过程中共发现细菌 637 种,其中变形菌门(*Proteobacteria*)和放线菌门(*Actinobacteria*)为各分解等级倒木细菌的主要共有优势菌。Hoppe 等[57]比较了两种常见温带树种(落叶树欧洲山毛榉(*Fagus sylvatica*)和针叶树欧洲云杉(*Picea abies*))在不同腐烂阶段和不同森林管理下的木质残体中的细菌群落,结果显示细菌的定殖与木质残体的树种和腐烂阶段密切相关。

1.3　植物多样性

木质残体为植物的生长提供了重要基质,特别对森林中的地衣、苔藓和维管植物多样性具有重要意义[58—59]。已有研究表明,大约有 200 种地衣、70 种苔藓将木质残体作为它们的主要生长基质[60]。Dittrich 等[61]在木质残体上发现了 70 种植物,包括苔藓植物(47%,其中苔类占 24%,藓类占 23%)、地衣(37%)和维管植物(16%)。Rajandu 等[62]在对爱沙尼亚松树林内木质残体的研究中记录了 73 种附生在木质残体上的苔藓植物。木质残体作为一种微环境调节器,有助于苔藓植物的生长[63],但苔藓植物仅利用其作为自养生活方

式的平台,并不直接参与木质残体的分解[12]。

随着木质残体的逐渐腐烂,附生的苔藓植物群落在覆盖率、厚度以及物种组成方面发生显著变化[64]。此外,苔藓植物的多样性也与木质残体直径呈正相关[65]。木质残体的 pH 值是影响苔藓植物群落发育的重要因素之一,它影响着苔藓植物的多项生物学特性,如孢子萌发[66—67]。例如,Fukasawa 等[68]的研究显示,异叶齿萼苔(*Lophocolea heterophylla*)和矮锦藓(*Sematophyllum subhumile*)偏好于低 pH 值的褐腐木质残体。因此,木质残体被认为是决定森林苔藓植物多样性的关键因素[69]。

2 木质残体基础特征对物种多样性的影响

木质残体不是一个单一的栖息地,而是一系列复杂的不同微生境,栖息着数千种不同的物种,这些微生境会随着时间的推移而变化。木质残体存在的形式(站立、倒下或由树桩组成)、不同的死亡原因、体积大小、腐烂程度、树种类型以及周围环境条件等都可能影响木质残体的质量及其与森林生物的关联性[24,70];这些特征不仅决定了木质残体的生态功能,也直接影响了木栖生物的栖息偏好和物种多样性[12]。

2.1 木质残体来源

森林生态系统中木质残体来源主要分为自然因素和人为干扰两大类。自然因素包括林木在生长过程中的自然死亡、竞争排斥以及受到火灾、风暴、洪水和森林病虫害等灾难性干扰事件的影响[71—72];人为干扰则主要指砍伐活动[73—74]。不同森林类型中,木质残体的来源及其对物种多样性的影响存在明显差异。例如,火灾不仅会增加木质残体的数量,还会通过改变木质残体的物理和化学特性,创造新的栖息环境,进而影响物种的组成和生态位[75]。研究表明,火灾后,一些红色名录物种和稀有物种的数量增加,尤其是某些甲虫类群[76—77],但在某些情况下,火灾频发可能导致木质残体碳化严重,抑制一些物种(如象虫科的 *Araucarius*、*Hylurgonotus* 和 *Sinophloeu* 等食木树皮甲虫)的存续[78]。此外,自然灾害如台风和人为干扰如森林砍伐,也会显著改变木质残体的质量和分布,进而影响生物多样性。例如,台风或砍伐后,白腐菌和褐腐菌的丰度和种类发生了显著变化[79],特别是褐腐真菌的相对优势地位提升[80],这与开放的森林环境中更高的温度和干燥条件有关[81]。总体来看,不同来源的木质残体对森林物种的组成、丰富度和多样性具有深远影响,这种影响取决于干扰的类型、强度以及干扰后环境条件的变化。

2.2 体积大小

木质残体的体积大小对物种多样性有着显著影响,不同物种对木质残体直径的偏好程度各异[82]。较大的木质残体更容易吸引受威胁或濒危物种,而常见物种则对木材体积大小的偏好较弱[83]。例如,Pouska 等[84]对高山云杉林木质残体的研究发现,受威胁和特化物种的数量会随着木质残体平均直径的增加而增加。当木质残体直径超过 70 cm 时,对所有腐殖甲虫都有明显的积极影响[83],能容纳更多的濒危和常见的木栖物种[85]。在瑞典,超过 50%的木栖物种集中在直径大于 20 cm 的倒木上,而约 15%的物种仅限于直径大于 40 cm 的倒木[86]。这可能是由于较大体积的木质残体存留时间更长,且具有更丰富的结构多样性,能够为更多具有不同生态需求的物种提供栖息地,从而促进物种共存和群落演替[24]。较大体积的木质残体还与某些鸟类(如啄木鸟科)有密切关系,它们更倾向于利用这些大倒木、树桩或枯立木作为筑巢和栖息场所[87—88]。此外,这些较大木质残体还为腐殖甲虫和蝙蝠提供了重要的微生境[58]。相比之下,细木质残体和极细木质残体在生态研究中较少被关注,因为它们不会像大树干那样提供长期稳定的栖息地[89—91]。然而,研究表明,细木质残体对某些真菌(如羊肚菌和盘菌)以及昆虫的多样性也具有重要意义[92—93]。尽管它们较快分解,但仍然是木腐真菌和苔藓植物的重要基质[94]。

2.3 分解程度

木质残体的分解过程是维持森林生态系统生物多样性的重要机制,这一过程通常由微生物、无脊椎动物和脊椎动物等分解者主导,历经数百年完成。分解过程通常分为三个阶段:定殖阶段、分解阶段和腐殖化阶段[95]。在不同的分解阶段,不同物种会根据其生长策略和生态位逐步取代先前物种,导致物种组成的动态变

化[54]。在定殖阶段,树木死亡后,木食性昆虫如甲虫类会首先侵入,通过在树皮和木材中挖掘隧道为真菌提供通道[96]。这些昆虫,尤其是小蠹虫(*Bark beetles*)和长小蠹亚科(*Platypodinae*)的成虫,具有特殊的解剖结构,有助于真菌孢子的传播,从而促进木材的初始分解[24]。随后的分解阶段,随着树皮脱落和真菌活性的增强[97],更多的无脊椎动物参与进来(如膜翅目(*Hymenoptera*)、树蜂科(*Siricidae*)以及长颈蜂科(*Xiphydriidae*)的物种)。它们的幼虫以木质部为食,而蚁类则在树干中筑巢,加速木质残体的进一步分解[98]。在腐殖化阶段,木材几乎完全被分解,伴随着初级无脊椎动物和其捕食者数量的增加[99]。该阶段最常见的生物类群主要有:跳虫、甲虫、双翅目、等足目、蜈蚣目、环节动物、线虫、螨类、伪蝎目和腹足类[100]。这些生物共同作用,加速了木材的腐烂与有机物质的腐殖化过程[24]。

2.4　树种类型

不同树种的木质残体因其独特的物理和化学特性,支持不同的物种组成和群落丰富度,为特定腐殖群落提供了多样化的生存条件。大多数木栖物种偏好落叶乔木,特别是白桦、橡树和杨树,这些树种通常拥有较高的物种丰富度[86]。尽管落叶树种的周转率比针叶树种更快[6],但其树皮,特别是桦树,能够在较长时间内保持完整,进而为依赖树皮的木栖物种提供了长期的栖息环境[101]。无脊椎动物在木质残体分解的早期阶段,物种组成受到特定树种类型的限制[102],主要也是受树皮特征的影响[103]。由于定殖初期分解阶段的无脊椎动物主要摄食韧皮部,树皮的特性(树皮覆盖的木材表面、树皮厚度和松散度)成为分解早期动物物种组成的重要因素之一[14,24]。虽然无脊椎动物表现出对特定寄主树种的偏好,但这种偏好通常是针对一个科而不是一个具体树种[104]。这种现象与密切相关的树种共享相似的特征的观点一致[105],因此近亲树种的无脊椎动物群落组成通常更相似。此外,树种类型同样被认为是影响真菌群落组成和物种丰富度的关键因素[106—107]。例如,落叶阔叶树的木质残体通常支持更多的真菌物种,而针叶树的真菌群落相对较少[108],这可能与针叶树木材中的低 pH 值和低氮含量有关,这些因素不仅减缓了木材的分解速度,还限制了栖息物种的多样性[109]。

3　森林管理对木质残体及其物种多样性的影响

木质残体作为一种局部动态和瞬态的森林基质[58,110],其对物种多样性的影响不仅限于个体尺度上,森林管理通过调节木质残体的产生、分布及分解动态,进而从更广泛的群落尺度上影响生物多样性[108]。不同的管理策略(如砍伐、残体移除或保留)对木质残体的数量、质量和时空分布产生直接影响,塑造了栖息在其上的多样化生物群落[111—112]。因此,关注森林管理与未管理下的木质残体的状态,对于全面理解木质残体对物种多样性的作用机制至关重要。

3.1　森林管理引起的木质残体数量变化对物种多样性的影响

木质残体数量是影响物种丰富度的重要因素之一,它为生态系统提供了独特的异质性小斑块,构成“养分岛”,支持多样化的生物群落[113—115]。木质残体的数量和质量为研究过去的自然和人为干扰提供了线索,并预示了未来木质残体积累的可能性[116]。木质残体的减少可能会导致扩散受限或生境需求狭窄的物种灭绝,并对物种丰富度产生级联效应[58,110]。

许多研究证明,管理森林中木质残体的数量通常低于天然林[19—21],这主要是由于集约化管理中木材和木材生物质的提取[117—118]。在北方天然林中,木质残体的储量通常超过 100 m^3/hm^2,而在集约管理的森林中,木质残体的数量仅占天然林的 2%到 30%[119—121]。例如,在北欧北部的管理森林中,由于森林采伐和轮伐期的缩短,木质残体的数量下降至原始森林中的 10%——15%[36,58]。相比之下,采用“接近自然”原则管理或无管理措施的森林中,木质残体的数量明显更多[117,122]。例如,古老的山毛榉林木质残体平均储量为 136 m^3/hm^2[123],未受干扰的美国西北部成熟林木质残体储量为 55.35 m^3/hm^2[124]。平均而言,未经管理的森林中的木质残体数量比管理森林中的数量高出三分之一[125]。尽管管理森林中的木质残体数量通常较少,但某些研究提出,在特定情况下,停止管理后的森林中木质残体数量可能增加[126],但这一变化通常需要较长时间才能显现,例如欧洲山毛榉(*Fagus sylvatica*)的木质残体数量需经历 200—230 年才能显著增长[122]。

为保护物种多样性,维持一定数量的木质残体至关重要[108]。随着木质残体数量的增加,物种丰富度和群落结构的复杂性也相应提升,尤其是对腐殖昆虫和木腐真菌等依赖木质残体的生物群体[119,127]。研究表明,每公顷倒木体积的增加可以显著提高腐殖甲虫和木腐真菌的物种丰富度[128—130]。当木质残体的体积达到 20 至 60 m^3/hm^2时,林分中腐殖甲虫的物种多样性显著增加[22,131]。而木腐真菌通常需要很大的木质残体体积,其最佳体积可能超过 100 m^3/hm^2,并且从 20 m^3/hm^2开始才出现第一种濒危物种[132]。此外,大量的木质残体能够调节微气候并维持土壤湿度,为植物种子萌发和幼苗生长提供了关键的养分,为植物的定殖创造理想的环境条件,从而有效促进森林更新[133—134]。这不仅助于维持植物多样性,同时也为其他依赖这些植物及其生态系统的生物提供了多样化的栖息地,从而进一步提升了整体物种多样性。因此,在间伐作业中制造并保留木质残体是维持森林生物多样性的重要管理手段[58]。

3.2 森林管理引起的木质残体特征差异对物种多样性的影响

不同状态的木质残体为木栖生物提供了多样的栖息环境[135—136]。例如,与天然林相比,管理林中的木质残体多样性较低,通常缺乏天然林中常见的大型粗木质残体和枯立木[108,120]。在北方森林中,松树等树种死亡后可长期保持站立状态,枯立木占木质残体总量的比例可高达 50%[14,137]。相较之下,由于管理林中的树木常在衰老或自然干扰前被砍伐[58],因此其木质残体多由小树枝、树桩组成,且大倒木的比例较低[94]。此外,管理林中高度腐烂的倒木容易受到干扰而破碎或被移除[138],影响了相关生物群落,尤其是专门分解特定木质基质的真菌类群[115,139]。

鉴于木质残体的差异特征对于维持物种多样性至关重要,因此,在森林管理中应保留不同类型的木质残体,模拟未经人为干预和老龄森林的特征[140]。第一,木质残体的树种多样性应得到保持,尤其是不同谱系的树种(如被子植物与裸子植物)[141—142]。第二,除了保留粗木质残体外,也应该适当保存一些细木质残体。大型倒木由于较低的表面积/体积比,能够更好地维持温度与湿度的稳定性,从而为腐殖生物提供更加稳定的微生境[143]。并且,倒木直径的增加与腐殖甲虫和木腐真菌的多样性密切相关[19,129]。但仅保留粗木质残体会严重低估物种多样性[144]。与等体积的粗木质残体相比,细木质残体支持更高的真菌多样性[93—94],倘若忽略了细木质残体将使木腐真菌的物种丰富度被低估 10%左右[90]。第三,管理林中应保留一定比例的枯立木,其数量应占木质残体体积的 50%左右,以提供空巢鸟类、腐生甲虫等物种所需的栖息地[145—146]。最后,还应该注意留下不同腐烂阶段的倒木,以供不同物种进行定殖生存。例如,大多数无脊椎动物在腐烂的初期阶段出现,而草本植物和其他维管植物则更偏好腐烂晚期的倒木[59,86,102,147]。

3.3 森林管理形成的木质残体时空连续性对物种多样性的影响

木质残体在森林生态系统中形成了动态的生境,除木质残体的数量、质量与类型外,其时空连续性对于支持依赖这些残骸的生物群落也至关重要,均匀而连续分布的木质残体比孤立的森林碎片更有利于低扩散能力物种的定殖[148]。在森林经营管理规划过程中,需考虑时间因素,以增加木栖物种在不同时期的生存潜力[149]。随时间演变,依赖木质残体微生境的物种一旦失去其特定的栖息环境,可能面临局部灭绝的风险[150—151]。因此管理策略应通过保留不同类型和分解阶段的木质残体,提供多样化的微生境,以满足不同物种的生存需求[82]。例如,欧洲山毛榉(*Fagus sylvatica*)、欧洲云杉(*Picea abies*)、银杉(*Abies alba*)与橡树(*Quercus palustris Münchh.*)的木材平均分解时间为 20—60 年、50—100 年、70—110 年与 90 年以上[152—155]。根据这些差异,森林管理可通过多次富集不同树种的木质残体,确保微生境的持续供给。例如,在欧洲山毛榉轮伐期内需要进行至少 3 次富集,挪威云杉需进行 2 次,而橡树平均仅需 1 次足以满足需求[156]。

除时间连续性外,景观水平上的空间连续性同样不可忽视。木质残体的分布应与物种的扩散能力相匹配,以避免物种定殖的局限[157—158]。低扩散能力的生物,如真菌、地衣和某些甲虫,依赖于木质残体的空间连通性来实现有效传播和资源获取[159—160]。因此,林分中木质残体的空间连续性对木栖生物的多样性和种群稳定性的作用比单独存在的木质残体更为重要[128]。在连通性高的区域中,腐殖昆虫的物种丰富度更高,并且对物种组成和特定物种的反应有影响[150]。为了维持森林生态系统的健康和物种多样性,森林管理应注重

合理的疏伐、保留自然木质残体以及促进自然更新等策略，并在采伐作业中尽量避免破坏现有木质残体。

4 研究展望

世界自然基金会指出，木质残体是评估森林健康和生物多样性的重要指标[36]。合理管理木质残体不仅有助于促进森林生态系统的可持续发展，还能为腐殖物种及其他生物提供支持[161]，然而，目前对木质残体的科学认识和管理实践仍存在差距，尤其是如何平衡木质残体的生态功能与森林管理目标。为应对这些挑战，未来研究应关注以下几个关键方向：

（1）木质残体纳入森林适应性管理的策略

尽管木质残体在森林生态系统中扮演着至关重要的角色，但其潜在的火灾风险[162]、病虫害吸引[163]以及造林障碍[164]等问题，导致其常常被不恰当地移除。因此，未来研究应关注如何在森林适应性管理中合理纳入木质残体，探究如何在不同的森林管理情境下，平衡木质残体的生态功能和潜在风险，从而形成一套可操作的管理策略[165]。同时，现有研究多集中在局部区域或单一尺度[166]，未来应进一步探讨木质残体在景观及更大尺度上的分布特征及其对物种多样性的影响。

（2）气候变化背景下木质残体与物种多样性关系评估

现有的木质残体空间分布模型尚未充分考虑气候变化的影响，特别是全球变暖导致的干旱、气候极端事件频发对木质残体及其物种多样性的影响[168—171]。未来的研究应进一步探讨气候变化对木质残体的分解速率、形成模式和空间分布的影响，以及不同的生物群落（如腐生真菌、木栖无脊椎动物等）在气候变化的驱动下对木质残体动态变化的响应，并构建气候响应评估模型，量化气候变化对木质残体及其物种多样性的长期影响。

（3）极端干扰事件对木栖物种群落组成的影响

目前的研究多集中在火灾影响，其他干扰类型对木质残体的输入和生物多样性的长远影响仍然缺乏深入探讨。极端气候事件（如风暴、洪涝、干旱等）对木质残体的产生及其生物多样性影响仍有待进一步研究。因此，未来的研究应涵盖多种干扰类型，尤其是不同分类群和功能群如何响应极端干扰事件，并评估这些干扰对稀有和濒危物种的影响。

（4）木质残体树皮特性与生物群落构建的关系

目前，树种的树皮类型和特征差异对群落构建的影响仍存在许多未知[103,167]。因此，生物群落对树种和树皮特性的响应需要进一步研究。未来应更深入地探究树皮的物理和化学特性及其变化如何影响木质残体的分解过程及其对依赖木质残体的生物群落（包括微生物、无脊椎动物等）形成和演替的影响。

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