



•综述•

声景生态学研究进展和展望

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摘要: 声景生态学以景观中的声音为研究对象, 探讨其在不同时空维度上的分布和变化模式, 从而揭示自然环境、野生动物和人类活动的相互作用关系。本文通过系统检索声景生态学研究的相关文献, 回顾了该学科的研究框架和研究方法, 总结了目前常用的声学指标, 重点归纳了声景生态学的研究内容, 包括声景组成和各组分间的相互作用, 声景的时空格局, 以及声景生态学在生物多样性监测中的应用。目前, 声景监测中存在的问题主要包括监测的生态系统类型和物种类群有限、声学指标效力有待提高等。建议未来着重推进建立系统性的声景监测网络和数据管理平台, 开发和完善音频数据采集、分析方法和评估指标, 并重视声景数据的采集, 将声景视作一种资源进行研究和保护。

关键词: 声景监测; 声学指标; 声学生态位; 生物多样性监测; 自动录音技术

Progress and outlook for soundscape ecology

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Abstract: Soundscape ecology studies sound patterns across different spatial and temporal scales, which reflects coupled natural-human dynamics in a changing landscape. Here, we synthesized a list of peer-reviewed studies on soundscape ecology to summarize the conceptual framework of the field, the methodology used, and acoustic indices developed from these studies. Studies on soundscape ecology are currently focused on the following aspects: (1) acoustic composition of soundscape; (2) acoustic interactions between soundscape components; (3) temporal patterns and spatial variability in the soundscapes; (4) the development of acoustic indices for biodiversity monitoring. We suggest the following as focuses for future studies in soundscape ecology and biodiversity conservation: (1) establishing a systematic acoustic monitoring network and data management platform; (2) developing new methods for data collection and analysis (e.g., recording matrix and machine learning algorithm); and (3) treating soundscape ecology as an important resource for future research and conservation.

Key words: soundscape monitoring; acoustic indices; acoustic niche; biodiversity monitoring; automated acoustic recording

“声景”(soundscape)一词由Southworth (1967)提出, 指景观中全部声音信息的总和, 在城市规划

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(Southworth, 1967)、建筑设计(Thompson, 2004)、音乐作曲(Truax, 2008)等领域均有应用。20世纪60年代末, 加拿大作曲家Raymond Murray Schafer主持实施了首个声景研究项目“The World Soundscape Project”, 并创立了声学生态学(acoustic ecology), 呼吁人们关注环境中声音及其与人类活动的相互作用关系(Schafer, 1969, 1970)。1987年, 美国音乐学家和声景生态学家Bernie Krause (1987)提出了“声学栖息地理论”(acoustical-habitat theory), 认为每个生态系统有其独特的、反映其内部特征的生物声学谱(acoustic bio-spectrum)。2011年, 美国普渡大学的Bryan Pijanowski和意大利乌尔比诺大学的Almo Farina将声学生态学与景观生态学的理论框架结合, 主张研究声景的时空分布模式和生态过程(Pijanowski et al, 2011b), 并在此研究框架和研究内容的基础上提出了一个新的学科方向——声景生态学(soundscape ecology), 也有学者称其为“ecoacoustic”(Farina & Gage, 2017)。

Pijanowski等(2011b)沿用从声音来源角度描述声景构成的方法(Krause, 1987), 将声景分为3个组成部分: 生物声音(biophony), 物理环境声音(geophony, 如风声、雨声、流水声), 以及人造声音(anthropophony)。声景生态学研究声景在不同时空维度上的分布和变化模式, 及其与生物和非生物环境之间的关系, 以此揭示其所反映的人类活动与生态过程(Pijanowski et al, 2011b)。Pijanowski等(2011a)详细阐述了自然和人为因素改变声景格局的过程和机理: 大气动力学改变自然环境, 进而影响动物的生活史和栖息地, 以及生物多样性, 同时影响地形、光周期等地球物理特征。人类通过建筑环境和土地改造与大气过程共同影响声景特征, 具体体现在4个方面: (1)声学组成(指声景的频段和振幅大小); (2)声景的时间格局; (3)声景的空间变异性; (4)在自然和人为因素介导下, 生物声音、物理环境声音和人造声音间的交互作用。大气动力学和人为活动可以改变声景特性, 同时被改变的声景将反作用于生物和人类系统, 影响动物的种群和群落动态(Barber et al, 2010), 以及人类的健康和对环境的感知。

随着声景生态学概念的传播, 越来越多的研究者认识到声景在生态系统中具有重要的生态功能(Farina & Gage, 2017), 与声景相关的研究逐步深入开展。我们在Web of Science (www.webofknowledge.

com)上检索“soundscape ecology”或“ecoacoustic*”, 截至2019年12月, 共获得168篇声景生态学研究论文, 相关研究自2014年起快速增加, 2014年之后发表的相关论文占该领域论文总数的93.4%。

本文介绍了声景生态学的研究框架、研究方法和研究内容, 总结了目前常用的声景评估指标, 分析了已有研究的局限性, 并对未来声景生态学发展方向提出了建议, 以期为此领域研究的开展提供思路和参考。

1 声景生态学研究方法

1.1 数据采集方法

声景生态学主要利用自动录音机(automated acoustic recorders)采集音频数据。近年来, 可编程自动录音机的出现促进了声景生态学及其他与声学监测相关学科快速发展(Sugai et al, 2019)。自动录音机利用声学传感器(水听器hydrophone或麦克风microphone)采集环境中的声信号, 其中水听器适用于接收水中的声信号, 麦克风适用于接收陆地中的声信号。声学传感器将声波转化为电信号(Drafts, 2001), 再通过脉冲编码调制法(pulse code modulation, PCM)将电信号量化, 转换为数字信号储存在存储介质中。自动录音机可按照用户设定的日程, 在固定的时间自动进行声音采集。近年来电池寿命的延长、内存介质容量的增大等技术上的进步, 提高了录音设备的野外工作时长, 满足了声景生态学大尺度、长时期、自动化的声学监测需求。

根据人类听觉的频带范围, 声音信号可以划分为可听声频带(20 Hz–20 kHz)、超声频带(> 20 kHz)以及次声频带(< 20 Hz)。对于可听声频带的声音, 研究人员使用普通录音机录制即可。某些动物(例如蝙蝠、某些鲸豚类物种)具有特殊的超声回波定位能力, 会发出超声波, 对这些动物可以通过以较高采样频率(高达400 kHz)录制音频的方法, 探测并记录环境中它们发出的超声波(Fenton & Bell, 1979; Russ, 1999)。此外, 亚洲象(*Elephas maximus*)和非洲象(*Loxodonta africana*)会发出次声波进行远距离家族间的联络(Payne et al, 1986; Venter & Hanekom, 2010)。一般使用次声波探测器探测次声波, 主要应用于各类地质灾害监测中(吕君等, 2012), 在声景生态学研究中的应用较少。

目前常用的自动录音设备有用于监测陆生动

物的Song Meter (Wildlife Acoustics Inc., Maynard, MA, USA)、ARBIMON (ARBIMON/Sieve Analytics, Puerto Rico)和BATLOGGER (Elekon, Switzerland), 用于监测海洋哺乳动物的C-POD (Chelonia Limited, Cornwall, UK)等。部分设备结合了新一代传输技术可实时回传数据, 比如FrogPhone (Garrido et al, 2020)、Robust (Sethi et al, 2018)。近年来也出现了外形更小巧、价格更低廉的迷你自动录音设备, 如AudioMoth (Hill et al, 2018)、Solo (Whytock & Christie, 2017)、Song Meter Mini (Wildlife Acoustics Inc., Maynard, MA, USA)等。

自动录音设备通常被布设在野外调查点, 按照预先设定的启动时间和录音时长录制声音。当研究对象是明确的某个动物类群时, 需要有针对性地选择录音位点, 比如以森林鸟类为研究对象时, 可将录音设备布设在离地约1.5 m的树干上, 并回避环境声音(如湍急溪流声、录音设备周围树枝摇摆的声音)的干扰。建议在采集录音的同时记录调查日的天气状况, 可在后期数据处理时, 根据需要识别和去除带有较大环境背景噪声(如雨声、风声)的录音, 从源头上削弱噪声对后续音频数据分析处理的影响。

1.2 数据分析处理方法

声波在被声传感器转换为电信号之后, 通过模数转换(analog to digital, AD)芯片转换为数字信号, 一般以时间-幅值形式呈现(图1A), 其中横轴为时

间, 纵轴为幅值。通过短时快速傅里叶变换(short time fast fourier transform, STFT), 原始声音的时域信号被转换为具有随时间变化的不同频率、振幅和相位的正弦波信号的叠加, 构造时间、频率以及振幅这三种变量的三维图就可以得到声谱图(spectrogram)(图1B)。在声谱图中, 横坐标表示时间, 纵坐标表示频率, 不同颜色深度表示振幅大小。声谱图能够清晰地反映频率、振幅随时间的变化关系, 是声景分析中的重要手段。

针对动物类群, 研究者通常希望鉴定出录音数据中的发声物种。传统的方法需要手动扫描声谱图, 人为判读录音中的目标声音(Wimmer et al, 2013), 十分耗时。目前, Kaleidoscope, ARBIMON II, Raven等软件嵌入了基于机器学习算法的自动识别技术, 能够极大地减少扫描音频数据集时所用的时间, 快速地检测出发声物种(Brandes, 2008)。但目前, 自动识别结果的准确性仍存在假阳性和假阴性比例较高的问题(Swiston & Mennill, 2009; Towsey et al, 2012)。

与传统的录音数据处理方法不同, 声景生态学关注的重点通常不是录音里的物种, 而是用于录音数据的音频频域和时域的特征。这些特征可以使用声景指数(即声学指标)来描述, 比如多样性或复杂度等(Sueur et al, 2008, 2014)。声学指标可以分为两大类: (1) α 声学指标: 用于评估声景或动物群落的

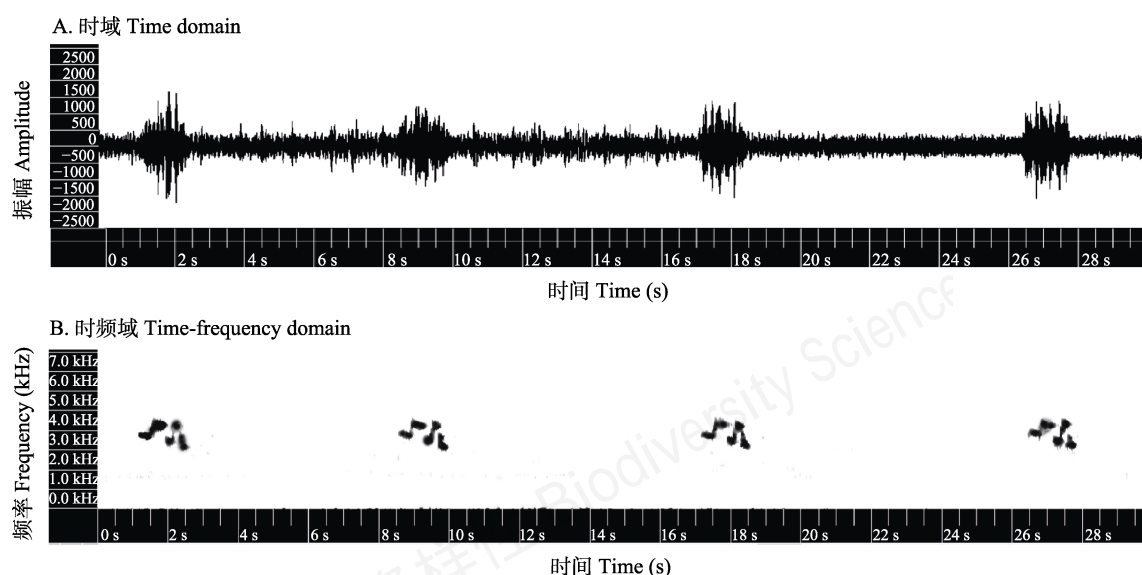


图1 在Kaleidoscope pro5软件中显示的褐顶雀鹛(*Alcippe brunnea*)鸣唱的波形图(A)和声谱图(B)

Fig. 1 Oscillogram (A) and spectrogram (B) of the song of *Alcippe brunnea* shown in Kaleidoscope pro5 (Wildlife Acoustics Inc., Maynard, MA, USA)

声音多样性或复杂性; (2) β 声学指标: 用于评估不同动物群落间或同一群落不同时段间的声音多样性的差异。Buxton等(2018b)分析了71篇与声学指标有关的文献, 统计了用于不同目的的60余种声学指标。这些指标大部分可在R语言环境中(比如软件包tuneR, seewave, soundecology)实现分析。Box 1列举了研究中较常使用的10个声学指标及其定义和相关研究。

声学指标评价生物多样性的效果受诸多因素

影响, 其中, 背景噪声, 如风声、雨声、人为制造的声音均是重要的影响因素。地震勘测活动可能掩盖声学熵指数(acoustic entropy index, H)与鲸鱼发声频率的线性关系(Parks et al, 2014); 昆虫鸣声、环境背景音、人为噪声数量的增加, 可能增加基于声学指标预测脊椎动物多样性水平的模型的残差(Buxton et al, 2018b)。后期实验室分析时, 通过噪声补偿(Parks et al, 2014)、使用合适滤波器(Farina & Pieretti, 2014)等信号处理方式, 可以达到降噪的目的。

Box 1 常见声学指标定义及其应用案例

声学指标 Acoustic indices	指标定义及其应用案例 Definition of indices and application cases
α声学指标 α acoustic index	
声音复杂度指数 Acoustic complexity index (ACI) (Pieretti et al, 2011)	音频中声强的变异性。Pieretti等(2011)的研究表明, 在飞行器噪声下, ACI与鸟类发声频次呈正相关关系。
生物声学指数 Bioacoustic index (BIO) (Boelman et al, 2007)	声谱图中超过分贝阈值部分的面积。该面积与动物鸣声的声强和占据的频段数有关。Boelman等(2007)用BIO声学指标评估夏威夷山地生态系统中植物入侵对鸟类多度和群落组成的影响。
时间熵指数 Temporal entropy index (H_t) (Sueur et al, 2008)	通过将音频切割为若干等时间间隔的声音片段, 计算每个时间片段内的振幅值 $A(t)$, 然后求振幅值 $A(t)$ 的Shannon均匀度(Shannon evenness): $H_t = -\sum_{t=1}^n A(t) \times \log_2 A(t) \times \log_2(n)^{-1}, H_t \in [0, 1]$
频谱熵指数 Spectral entropy index (H_f) (Sueur et al, 2008)	声信号平均频率谱 $S(f)$ 的Shannon均匀度指数(Shannon evenness), 指示声信号在频率分布上的丰富和均匀程度: $H_f = -\sum_{f=1}^N S(f) \times \log_2 S(f) \times \log_2(N)^{-1}, H_f \in [0, 1]$
声学熵指数 Acoustic entropy index (H) (Sueur et al, 2008)	时间熵指数(H_t)与频谱熵指数(H_f)的乘积, 体现声信号在时频域上的均匀度和复杂度。对于单调纯音, H 趋向于0; 对于随机噪声, H 趋向于1: $H = H_t \times H_f, H \in [0, 1]$ 。Sueur等(2008)的试验表明, 540个模拟声学群落中的 H 值与物种数呈对数相关。
声音丰富度指数 Acoustic richness index (AR) (Depraetere et al, 2012)	基于振幅指数(M)和时间熵指数(H_t)所得指标, 用于评估发声动物多样性与声学活动水平: $M = \text{median}(A(t)) \times 2^{(1-\text{depth})}, 0 \leq M \leq 1, \text{depth为信号数字化的深度}$ $AR = \frac{(\text{rank}(H_t) \times \text{rank}(M))}{n^2}, 0 \leq AR \leq 1, n \text{为音频文件数量}$ Depraetere等(2012)的研究表明, AR的计算结果与通过人工监听录音调查法国巴黎西南部3处温带林地的鸟类物种丰富度结果一致。
声音多样性指数 Acoustic diversity index (ADI) (Villanueva-Rivera et al, 2011)	提取每一频段中超过特定声压级阈值(默认为-50 dBFS)的声信号参数, 计算Shannon指数(Shannon's index), 指示声音多样性: $ADI = \sum_{i=1}^s p_i \ln p_i$, p_i 是声信号在第 i 个频段所占比例, s 是频段数量。Villanueva-Rivera等(2011)应用ADI比较了不同地点间以及一天中不同时段间的声景差异。
声音均匀度指数 Acoustic evenness index (AEI) (Villanueva-Rivera et al, 2011)	提取每一频段中超过特定声压级阈值(默认为-50 dBFS)的声信号参数, 计算吉尼指数(Gini index)来表示声信号强度在不同频段的不均等程度。Villanueva-Rivera等(2011)用AEI比较不同土地利用类型录制的音频信号在频谱上的差异性。
标准化声景差异指数 Normalised difference soundscape index (NDSI) (Kasten et al, 2012)	人类产生声音(anthrophony)与生物产生声音(biophony)声学成分间的比率, 评估人为干扰对声景的影响程度。Kasten等(2012)在建立远程声学评价实验室时, 利用NDSI筛选录音。
β声学指标 β acoustic index	
声学差异性指数 Acoustic dissimilarity index (D) (Sueur et al, 2008)	时域差异性指数(temporal dissimilarity index, D_t)和频域差异性指数(spectral dissimilarity index, D_f)的乘积, 评估群落间声信号在时域和频域上的差异性: $D_t = 0.5 \times \sum_{i=1}^N A_1(t) - A_2(t) $, $D_f = 0.5 \times \sum_{i=1}^N S_1(f) - S_2(f) , D = D_t \times D_f, D \in [0, 1]$ Sueur等(2008)用 D 比较坦桑尼亚干旱低地沿海破碎化森林和完整森林动物发声活动的差异。

的。如果无法去除录音中的噪声,可以通过统计学手段屏蔽噪声的影响,比如将信噪比(signal-noise ratio, SNR)设为控制变量进行偏相关分析(Desjonqueres et al, 2015)。此外,声学指标的效果还受到目标鸣声的类型、鸣声间的重叠程度、发声强度、发声频次以及傅里叶变换长度(FFT size)大小的影响(Gasc et al, 2015; Zhao et al, 2019)。如Zhao等(2019)通过模拟实验发现,声学群落中发声频率的下降,会使得声音多样性指数(ADI)、声音均匀度指数(AEI)、声学熵指数(H)等指标的标准差增大。Harris等(2016)用声学指标评估温带珊瑚礁鱼类多样性时,发现傅里叶变换长度从512上升至1,024后,声学熵指数(H)数值显著增加。

2 声景生态学的主要研究内容

声景生态学早期研究集中于描述陆地生态系统中的声景在时间尺度上的动态变化以及在环境梯度上的空间异质性(Krause et al, 2011),并开发了一系列声学指标(Sueur et al, 2008; Villanueva-Rivera et al, 2011)及音频数据分析平台(Kasten et al, 2012)用于野生动物研究(Lillis et al, 2014; Buxton et al, 2016)、栖息地环境质量评价(Gomez et al, 2018)、生物多样性评估(Pieretti et al, 2011; Gasc et al, 2013a)、保护成效评估(Bobryk et al, 2016)以及气候变化和人类开发建设活动对生物多样性影响的调查(Krause & Farina, 2016; Deichmann et al, 2017; Burivalova et al, 2018; Gasc et al, 2018)等领域。随后,声景生态学研究范围从陆地生态系统扩展到淡水和海洋生态系统(Harris et al, 2016; Putland et al, 2017),研究的动物类群从鸟类扩展到鱼类(Parsons et al, 2016)、珊瑚虫(Lillis et al, 2014, 2016)、鸣虫(Roca & Proulx, 2016)等,研究的对象也从单一的物种类群扩展到多物种类群(Ferreira et al, 2018)。

2.1 声景的组成及有效传播

同域生活的动物发出的声音具有多样化的频段范围和特征(图2)。在同一时间、同一地点,不同频率和振幅的声音共同构成了声景,即声景的声学组成(acoustic composition) (Pijanowski et al, 2011a)。研究者提出了相关假说试图解释动物声音多样性的成因,如声学生态位假说(acoustic niche hypothesis, Krause, 1993)和声学适应假说(acoustic adaptation hypothesis, Morton, 1975)。

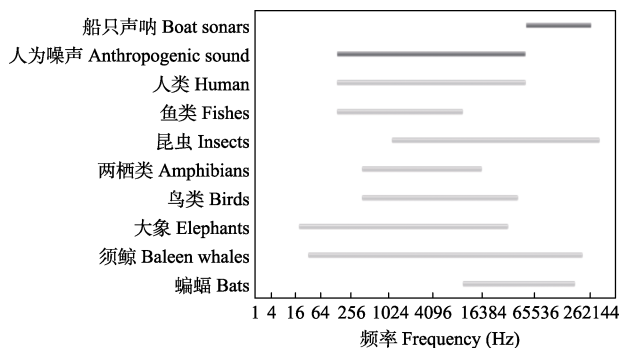


图2 常见人为噪声源与动物发声的频率范围

Fig. 2 The frequency range of common anthropogenic noise and animal vocalization

声学生态位假说认为,物种间的竞争排斥作用会促进不同物种发出的声音在时间和频率上出现分化,以减少种间声信号的重叠,实现对声学空间的高效利用(Krause, 1993)。已有研究发现,鱼类(Ruppé et al, 2015)、两栖类(Villanueva-Rivera, 2014)、鸟类(Halfwerk & Slabbekoorn, 2009)等动物发出的声音存在种间频率分化。比如,在南非东南部海域索德瓦纳湾中,日间和夜间发声的鱼类类群在组成上有所差异,声音在时间上存在分化(Ruppé et al, 2015)。在波多黎各高地中,卵齿蟾属(*Eleutherodactylus*)的不同物种发出的声音占据不同频段(Villanueva-Rivera, 2014)。

声学适应假说认为,环境倾向于筛选和保留传播距离远且保真度损失小的声信号,因此动物发出的声音会根据其所处环境做出适应性改变,以提高声信号传输的效率(Morton, 1975)。Velásquez等(2018)在南美洲8个不同地点收集了南美细趾蟾(*Pleurodema thaul*)的叫声,并在这8个地点分别做声信号传播试验,结果显示叫声在原发地的传播效率最高。声学适应性假说在鸟类和哺乳动物的研究中也得到过验证(Ey & Fischer, 2009)。除此之外,环境过滤作用可能去除部分声信号,也会导致不同栖息地的声景呈现出相异的声学特征。

气候变化正在改变声景的组成。气候变化影响声信号在介质中传递的衰减速率,进而引起生物发声行为的改变。例如,当气温升高时,高频超声波信号的衰减速率增加,在蝙蝠捕食过程中的使用频率有降低的趋势(Luo et al, 2014)。空气湿度上升会造成大气对声音吸收的增加(Snell-Rood, 2012),因此,在高湿环境中,北美的林莺科鸟类物种会降低

叫声的频率带宽和鸣叫持续时长。在海洋环境中,海水酸化减少了海水对低频声信号的吸收,海洋动物因此改变发声频率、持续时长和声强,以避免自己发出的声信号被低频噪声掩盖(Brewer & Hester, 2009)。

2.2 声景组成成分间的相互作用

声景的3个组分(生物声音、物理环境声音和人造声音)间存在相互作用(Pijanowski et al, 2011a)。生物的发声行为会受到物理环境声音的影响。例如,动物通常在刮风或下大雨时停止发声(Feng & Schul, 2007),或者倾向于在一天中风速最低时(例如黎明和黄昏)发出和鸣(Cuthill & Macdonald, 1990; Hutchinson, 2002; Berg et al, 2006; Hardouin et al, 2008)。为了实现有效通讯,动物发出声音的频率往往高于背景风声的频率(Greenfield, 1994);如帝企鹅(*Atenodytes patagonicus*)在强风噪声下,通过提高呼叫频率和单次呼叫的音节数来保持通讯效率(Lengagne et al, 1999)。

近年来,人造声音如何影响生物的发声成为声景生态学的研究热点之一。人造声音来源众多,包括工业、交通、人类的生活娱乐等诸多方面。一些人造声音与动物发出的声信号在频率上重叠(图2),可能干扰两栖类、鸟类和哺乳动物的种内通讯,进而危害动物繁殖(Smott et al, 2018)、栖息地选择(Lecchini et al, 2018)、捕食者识别(Ferrari et al, 2018)等重要行为。有研究表明即使人为噪声与水鼠耳蝠(*Myotis daubentonii*)的发声在频率上不重叠,也会显著降低其觅食效率(Luo et al, 2015b)。噪声环境中生活的动物在发声上会做出适应性改变(如调整发声时长、频率或振幅),以提高声信号的传输效率,即“隆巴德效应(Lombard effect)”(Lombard, 1911)。例如,长期在嘈杂环境中生活的鸟类通过提前和鸣时间、增加鸣唱时长(Sierro et al, 2017)、提高鸣唱频率(Slabbekoorn & Peet, 2003)、增大鸣唱振幅(Cynx et al, 1998; Brumm, 2004)等途径,提高个体间的通讯效率。蝙蝠用增大发声振幅和频率、延长发声时长、增加信号冗余、降低发声复杂程度等方式,来应对噪声对蝙蝠个体之间通讯的干扰(Hage et al, 2013; Luo et al, 2015a; Jiang et al, 2019)。

2.3 声景的时空格局

声景具有典型的时间格局,在温带森林(Depraetere et al, 2012)、热带雨林(Rodriguez et al,

2014)、城市(Botteldooren et al, 2006)、河流(Martin & Popper, 2016)、湖泊(Gage & Axel, 2014)、海洋(Staaterman et al, 2014)等生态系统中,均存在日、月或季节性的变化规律。声景的时间模式与生物的活动节律和生命周期有着密不可分的联系,又被称为“自然的节奏”(rhythms of nature)。例如,鸟类的晨昏和鸣行为使得晨间和傍晚的声学丰富度指数(AR)显著高于一天中的其他时段(Depraetere et al, 2012; Gage & Axel, 2014; Rodriguez et al, 2014)。在特定季节里,昆虫和两栖类动物常会出现夜间发声活跃的现象(Rodriguez et al, 2014)。在海洋中,海胆(Putland et al, 2017)、虾类(Lillis & Mooney, 2018)、鱼类(Rice et al, 2017)、鲸豚类(Au et al, 2000; Guan et al, 2016)均有和鸣现象,并存在昼夜、季节性的规律,同时受到天体运动和环境的影响(Lillis & Mooney, 2018)。例如,珊瑚礁声景存在月节律,在新月时增强,满月时减弱(Staaterman et al, 2014);温带沿海声景的夏季声强高于冬季(Radford et al, 2008);在开阔海域中,大型海洋哺乳动物影响季节性声音强度,例如座头鲸(*Megaptera novaeangliae*)在冬春之交繁殖季节发出的声音,会增加海洋声景中100–2,000 Hz频率段的声强(Bittencourt et al, 2016);而在城市和农村生态系统中,声景的时间变化模式主要受人类活动驱动(Liu et al, 2013)。

受自然因素(纬度、海拔、植被类型、植被垂直结构等)和人为因素(土地利用类型、人为噪声等)的影响,声景呈现出空间异质性。由于声景与发声动物的分布紧密相关,因而在较大的空间尺度上,可能呈现出沿纬度梯度和海拔梯度的分布格局。比如,在赤道地区较高的生物多样性环境里,声景的多样性和复杂性也可能更高(Pijanowski et al, 2011a)。与低海拔的常绿阔叶林相比,高海拔针叶林中声音多样性指数(ADI)较低,但季节性变化更为明显(Lin et al, 2017)。声景在不同的植被类型和植被垂直结构中存在差异。蔡学林等(2010)依据声学特征的差异,建立了不同类型的森林声景资源信息库(包括阔叶林声景、针叶林声景、毛竹林声景、灌木林声景、小溪声景、河流声景、瀑布声景7种类型);Rodriguez等(2014)发现法属圭亚那热带森林中林冠层声音的振幅高于林下层;Lin等(2017)的研究结果显示常绿阔叶林中的生物声音多样性要高于针叶林。

近年来,气候变化正在改变物种分布格局和物候特征,进而改变声景的时空格局。Parmesan (2006)综述了过去几十年来全球变暖引起的物候变化,发现许多生物(特别是两栖动物)的物候受到了温度升高的明显影响。例如,相比于1900年,纽约伊萨卡蛙类繁殖和鸣的时间提前了10–13天(Gibbs & Breisch, 2001);北美繁殖鸟类灰胸丛鸦(*Aphelocoma ultramarina*)的繁殖期提前(Brown et al, 1999)。在北美,由于气候变暖,外来种红嘴相思鸟(*Leiothrix lutea*)的分布范围逐步扩大,与同域分布的黑顶林莺(*Sylvia atricapilla*)和其他鸣禽对声学空间的竞争更为激烈(Farina et al, 2013)。

相比生物声音,人造声音的频率一般较低,但强度较高、持续时间长(Dooley & Brown, 2019)。人造声音可以直接塑造声景格局,进而影响声景环境中的野生动物。研究发现城市化过程中,声景中人造声音的比例增加,生物声音的比例减少(Kuehne et al, 2013)。在海洋环境中,珊瑚礁鱼类在幼年阶段通过感知声环境选择合适栖息地,船只噪声会掩蔽声环境,干扰鱼类在适宜生境定居(Holles et al, 2013)。同时,人类活动也可以通过改变物种及其栖息地的空间分布格局,间接地改变声景的空间格局。例如,被人类开发利用后的森林(如开垦种植棕榈林后)里,声景在晨昏时段的饱和度下降(Burivalova et al, 2018),在空间上的同质性增加(Burivalova et al, 2019)。森林破碎化会改变森林斑块大小和联通性,进而改变生物声音和人造声音的功率水平(Tucker et al, 2014)。声景的声学特征与土地利用类型和距交通密集区的距离紧密相关,在城市到乡村的梯度下,生物声音的功率谱密度(power spectral density)上升,人造声音的功率谱密度下降(Joo et al, 2011)。因此,一些能反映人类活动干扰强度的声学指标可用于评估生态系统质量(Fuller et al, 2015)。

2.4 声景生态学在生物多样性监测中的应用

生物多样性评估作为保护生物学的基础和核心内容(马克平, 2011),常用于评估特定地区的生物多样性、比较不同地区多样性组成的差异和监测生物多样性的动态变化。传统的生物多样性评估方法,如快速生物多样性评估和物种编目调查等,受环境条件、人力、物力的限制,通常存在数据收集耗时

长、数据量匮乏、数据采集标准与数据质量参差不齐等问题(Heywood & Watson, 1995; David, 2005)。

基于“较高的物种丰富度可转化为较高的声学复杂性”假设,声景生态学研究开发了一系列声学指标提取音频中的信息指示生物多样性(Boelman et al, 2007; Sueur et al, 2008; Pieretti et al, 2011; Depraetere et al, 2012)。一方面, α 声学指标(测量声学熵指数,如 H , ACI , ADI , AEI 等)可以评估某一特定群落中的声音多样性。通过建立声学指标与实地调查获得的物种信息,或与从录音提取的声音类型(比如将声音片段按频谱图相似性划分的若干类型, Desjonqueres et al, 2015)信息间的关系,采用声学指标评估发声群落的物种多样性。在陆地环境中,声学指标已被用于评估昆虫群落物种丰富度(Roca & Proulx, 2016)和鸟类群落物种丰富度、多度与组成(Pieretti et al, 2011; Depraetere et al, 2012; Borker et al, 2014; Towsey et al, 2014),如Gasc等(2013a)尝试建立了声学指标与鸟类功能多样性、系统发育多样性间的关系。另一方面, β 声学指标可以度量不同群落间声音多样性的差异。如,声学差异性指数(D)与频域差异性指数(D_f)均能探测到不同群落间物种组成的区别(Sueur et al, 2008; Gasc et al, 2013b)。除了用声学指标指示多样性外,蒋锦刚等(2016)将遥感领域常用的面向对象图像分割技术用于分割语谱图,试图用斑块统计分析方法提取音频中鸟类的多样性信息。

Buxton等(2018b)对声学指标的荟萃分析结果表明,声学指标在大多数情况下(74%, $n = 151$)与生物发声活动水平或生物多样性(如物种丰富度)显著相关;但同时还有部分指标(如 β 声学指标,在50%的情况下)并不能如实反映生物信息。本文作者统计了12篇在陆地环境中研究声学指标与生物多样性水平相关性的文献,结果显示相关性系数绝对值在0.01–0.97之间(图3)。在湖泊环境中,声音丰富度指数(AR)与湖泊中声音类型的丰富度($r = 0.2$)和多度($r = 0.19$)呈显著正相关(Desjonqueres et al, 2015)。在海洋环境中, Parks等(2014)建立了鲸类鸣声频率与噪声补偿后的熵指数(noise-compensated entropy index, H_N)的线性回归模型($R^2 = 0.225$),用于评价海洋中的生物多样性和生境健康状况; Harris等(2016)发现,声音复杂度指数(ACI)是评估温带珊瑚礁鱼类多样性的有效指标, ACI 与鱼类香农指数(H')的相

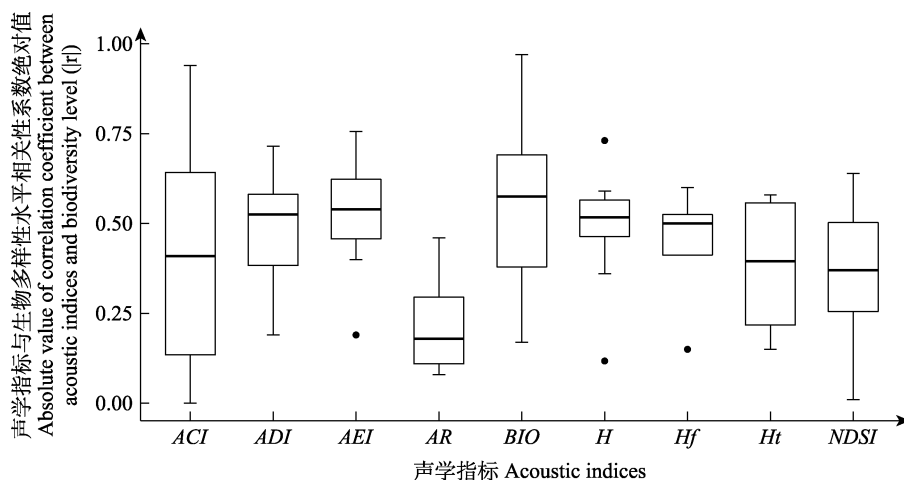


图3 声学指标与生物多样性水平相关性分析结果统计, $|r|$ 为12篇陆生环境中研究声学指标与生物多样性耦合关系的相关性系数绝对值。ACI: 声音复杂度指数; ADI: 声音多样性指数; AEI: 声音均匀度指数; AR: 声音丰富度指数; BIO: 生物声学指数; H: 声学熵指数; H_f : 频谱熵指数; H_t : 时间熵指数; NDSI: 标准化声景差异指数。

Fig. 3 Correlation between acoustic indices and biodiversity level, $|r|$ is the absolute value of the correlation coefficient. ACI, Acoustic complexity index; ADI, Acoustic diversity index; AEI, Acoustic evenness index; AR, Acoustic richness index; BIO, Bioacoustic index; H, Acoustic entropy index; H_f , Spectral entropy index; H_t , Temporal entropy index; NDSI, Normalised difference soundscape index.

关性系数达到0.81。整体而言, 声学指标与动物群落多样性和发声活动水平之间关系的显著性, 在不同研究区域、不同生态系统中并不相同, 目前仍然缺少能用于比较大尺度(比如中国跨生态区)生物多样性差异的指标。

此外, 也有部分研究通过鸣声识别途径开展野生动物个体、种群、群落水平的研究。例如, Chen等(2020)利用深度学习算法开发了Waveman软件程序, 可自动识别东南亚36种蝙蝠的叫声; Xia等(2012)根据鸣唱的特征差异来区分北方中杜鹃(*Cuculus optatus*)和喜马拉雅中杜鹃(*C. saturates*)。对于个体间鸣声差异较大的物种, 可以基于鸣声的声学特征识别个体, 并估算种群数量。Gilbert等(2002)通过鸣声识别大麻鵂(*Botaurus stellaris*)个体, 评估了英国境内大麻鵂繁殖种群大小及存活状况。也有研究在自动识别物种鸣声的基础上计算声学指数来估算种群大小。例如, Perez-Granados等(2019)利用Song Scope 4.1.5 (Wildlife Acoustics 2011)自动辨识黄喉蜂虎(*Merops apiaster*)和杜氏百灵(*Chersophilus duponti*), 并用发声活动频率指数(vocal activity rate index)估算了两物种的种群大小。物种识别途径仅被用于有限物种的研究, 当录音内容涉及大量物种时, 识别出每个物种的难度和时间成本大大增加, 监测整个群落的物种多样性

较为困难。

目前, 国内外已建立起若干区域性的声景监测网络。如日本建立的Cyberforest森林声景监测网络, 该网络曾配合社交媒体开展森林鸟类普查(Saito et al, 2015); 中国台湾林业研究所及资讯科技创新研究中心建立的亚洲声景监测网络(Asian Soundscape Monitoring Network); 美国为量化海洋声景基线水平和评估动态变化趋势建立的国家公园管理局海洋噪声参考站网络(National Park Service Ocean Noise Reference Station Network); 普渡大学为保护自然声学遗址(natural soundscape heritage)建立的声景生态学研究项目(Soundscape Ecology Research Project, <http://centerforglobalsoundscapes.org/pumilio-sites>); 中国科学院植物研究所自2014年起在钱江源国家公园建立的声景监测平台。这些动态化的监测平台为生物多样性和保护研究提供了有力数据支撑。

3 展望

经过近十年的发展, 声景生态学研究已涉及陆地、淡水和海洋生态系统中声景的时空格局、各组分间的相互作用以及人类活动对声景的影响等多个方面。自动录音技术的进步和声学指标的开发促进了该学科的发展。同时, 声景生态学的理论和方

法也已在调查生物多样性(Sueur et al, 2008)、评估生态系统健康状况(Tucker et al, 2014)和保护地管理成效(Borker et al, 2014)等方面得到初步应用。根据该学科的发展态势,我们提出以下几个今后应该重点关注的方向。

3.1 建设声学监测网络

推进建立具有生态系统代表性的声学监测网络,收集长时期、大尺度的音频数据,推动声景和生物多样性、生态系统结构和功能的相互关系的研究。声学监测网络的搭建需要开发低成本的录音设备来满足用户大尺度研究的需求;同时需要搭建数据存储和管理平台,管理数据量庞大的录音文件。也可以基于GIS技术开发声景信息系统(soundscape information systems, SIS),便于研究人员在线查询、分析和监听音频文件。由于网络平台日常维护成本较高,存储空间需求较大,目前已建立的部分平台难以长期运营,如,普渡大学开发的Pumilio (<http://pumilio.sourceforge.net>)和密歇根州立大学开发的REAL (<http://real.msu.edu>)。

3.2 开发新方法和新指标

鉴于许多现有声学指标的使用效果并不好(Buxton et al, 2018b),开发新方法和新指标,从海量的音频数据中提取有生态学意义的信息,将是未来声景生态学研究的一项关键内容。目前,声景生态学研究中调查的生态系统类型和动物类群仍有限,需要开展更多的野外研究,以检验不同生境和物种组合下声学指标评估生物多样性的效果及其影响因素,探讨不同声学指标的适用范围和局限,寻求更为普适的方法和指标,用于大尺度生物多样性的研究和监测。同时,在此过程中需建立声景标准信息库,收集声景各个组分(生物的、物理环境的、人造的声音)的音频资料信息,提升单个项目对声音信息的识别能力。

建立新的数据收集方法和分析方法,从音频数据中获取物种、个体层面更为精细的数据信息,可以深度挖掘声景数据的信息。比如,使用多台录音机建立麦克风阵列,定位、追踪声源具体位置,研究野生动物个体的行为(Payne et al, 2003)、个体间的交互作用(Mennill & Vehrencamp, 2008)、种群的密度、对栖息地的利用等(Kirschel et al, 2011);在自动录音数据的基础上,通过机器学习算法,自动识别录音中包含的鸟类(Aide et al, 2013; Stowell et al,

2019)、两栖爬行类(Ospina et al, 2013)、蝙蝠(Walters et al, 2012)、鲸类(Mellinger et al, 2007)、昆虫(Chesmore & Ohya, 2004)等不同类群的物种,甚至分辨目标物种的不同个体(Terry et al, 2005),获取其性别、年龄(Thompson et al, 2010)等信息。当这些新的或者正在被开发的方法应用到声景生态学研究时,可以拓宽和加深我们对音频数据的解读,更为准确地验证声学指标对生物多样性的指示作用,促进更为有效的声学指标的开发。有必要强调的是,作为一个跨学科的研究方向,声景生态学需要生态学和声学、计算机科学等不同领域研究者的合作,仅生态学家开展此领域的研究会时时感到技术上的困难。

声景监测获得的数据可与传统监测手段和其他监测技术(比如,红外相机技术)所得数据相结合(Bustamante et al, 2016; Campos-Cerqueira & Aide, 2016),用来评估多类群、多物种的空间分布格局,以及识别保护优先区和制定土地利用规划(Rich et al, 2019);研究动物行为和种间关系,识别生物多样性对人为干扰或气候变化的响应(Buxton et al, 2018a)。由于从录音中提取的物种数据与红外相机调查收集的物种数据类似,均为物种在调查点的分布数据(presence数据),在针对物种的研究中可借鉴红外相机技术的数据分析方法,比如,采用占域模型(occupancy model)估算物种栖息地占有率(MacKenzie et al, 2002),随机相遇模型(random encounter model, REM)估算种群密度(Lucas et al, 2015),贝叶斯层次模型(Bayesian hierarchical modeling)评估物种丰富度(Tobler et al, 2015)等。

3.3 记录和保存声景资源

人类活动引起生态环境的改变和生物多样性的丧失正在改变声景的组成。建议采集和保存不同景观(尤其是原生自然景观)中的声景,服务于未来的保护管理、成效评估和科学比较研究。人类社会城镇化、人口增长、交通运输业和制造业的发展,使原本丰富的自然声音逐渐被单调的人造声音所取代。在此背景下,应在有代表性的生态系统内开展系统的声学监测,收集声学基线数据,并通过长期监测记录声景的变化。这样的长期声景监测数据,可以记录下不断变迁的环境里自然、生物和人类活动的信息,今日录制的音频可能成为来日的“声学化石”(Pijanowski et al, 2011a)。尽管目前对音频数

据的分析处理能力有限, 我们仍然可以收集和存储录音数据, 构建典型群落的“声学博物馆”, 如麦考利博物馆(<https://www.macaulaylibrary.org/>)、Borror生物声学实验室(<https://blb.osu.edu/>)、British Library Sounds (<https://sounds.bl.uk/Environment/Soundscapes>)等。同时鼓励公众使用身边的移动录音设备采集声景数据, 并做出描述与标注, 上传至数据库中共享。随着分析技术的进步, 这些数据将在未来的研究和自然教育中发挥作用。如Schafer (1994)所言, 我们应积极倾听自然中的声音, 认识其价值(Murray, 1977), 从而进一步制定和实施有效的声景保护政策。

同时, 声景通过诸多途径为人类和野生动物带来裨益和提供服务, 具有内禀价值, 应将其视作一种资源进行保护和管理(Dumyahn & Pijanowski, 2011), 通过保护自然环境的途径保护承载生物多样性信息、文化价值和对人类健康有益的声景。人类借由与声景的交互作用, 认知和理解周遭环境, 建构起“场所感(sense of place)”。研究表明, 场所内的声景有助于提升个人对视觉景观的体验感(Southworth, 1967)。健康的声环境对人类的生活和野生动物的生存至关重要。噪声有损人体的精神和身体健康(Staples, 1996; Passchier-Vermeer & Passchier, 2000), 影响野生动物对猎物的定位, 对捕食者的趋避和种间的交流(Barber et al, 2010), 导致野生动物的适合度下降(Reijnen et al, 1997; Stone, 2000)。因此, 建议将栖息地声景的质量作为野生动物栖息地保护与管理的一项内容, 保护自然原生景观中的声环境, 促进声音信息在其中的有效传递。此外, 声景具有文化和历史价值, 社会的加速发展正在快速改变文化和历史遗迹中的声景(O'Connor, 2008)。在日本, 声景被视为国家历史文化遗产的一部分, 并被系统采集和记载(比如: 100 Soundscape of Japan: Preserving Our Heritage, Torigoe, 2003)。应将自然中的健康声环境和对人类而言有历史文化意义的声景视作一种资源进行保护, 避免其遭受人为开发和建设活动的破坏。

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