



研究论文 ORIGINAL PAPERS

夜间路灯对东亚伏翼觅食行为的影响

何孟周冉¹, Tahir Abbas¹, 蒋春燕¹, 杨金瑞¹, 朱奕丞¹,
张焜榆¹, 刘汶沁², 杨 艳¹, 张 娟¹, 冯 江², 罗 波^{1,3*}

- (1. 西华师范大学西南野生动植物资源保护教育部重点实验室, 南充 637009;
2. 东北师范大学吉林省动物资源保护与利用重点实验室, 长春 130117;
3. 西华师范大学凉山山系珍稀野生动植物资源保护四川林业草原重点实验室, 南充 637009)

稿件运行过程

收稿日期: 2025-11-10
修回日期: 2025-12-18

摘 要

关键词: 光污染;

蝙蝠;

觅食行为;

回声定位声波;

环境风险假说

Keywords: Light pollution;

Bats;

Foraging behavior;

Echolocation call;

Environmental risk hypothesis

中图分类号: Q958.1

文献标志码: A

文章编号:

2310-1490(2026)-02-0216-09

DOI: 10.12375/ysdwx.202511013

路灯被广泛应用于道路夜间照明,然而目前针对路灯对夜行性动物觅食行为的影响研究仍较为匮乏。本研究以东亚伏翼(*Pipistrellus abramus*)为研究对象,探究夜间路灯对食虫蝙蝠觅食行为的影响。沿选定的公路布设10条东西走向样线,共设置50个监测样点(有路灯与无路灯样点各25个);于日落后录制东亚伏翼回声定位声波,量化其飞行通过次数和捕食蜂鸣数量,同步监测各样点光照强度、环境温度、昆虫丰度及微生物类型。克鲁斯卡尔-沃利斯检验显示,有路灯样点的平均光照强度(12.54 lx)显著高于无路灯样点(1.04 lx);有路灯样点的东亚伏翼通过次数和捕食蜂鸣数量均显著低于无路灯样点。广义线性混合模型分析表明,光照强度是影响两种觅食行为指标的关键因子;随样点光照强度升高,东亚伏翼的通过次数($P = 0.0032$)和捕食蜂鸣数量($P = 0.0380$)均呈显著下降趋势。本研究支持“环境风险假说”,表明夜间路灯产生的高强度光照会显著抑制东亚伏翼的正常觅食行为。建议在城市规划中统筹兼顾照明需求与蝙蝠保护,合理降低核心生境的路灯照度,以减缓光污染对蝙蝠种群的负面效应。

基金项目: 国家自然科学基金面上项目(32271561);国家级大学生创新创业训练计划项目(202510638029)

第一作者简介: 何孟周冉(2000—),女,硕士研究生;主要从事动物行为生态学研究。E-mail: 2724150591@qq.com

* 通信作者: 罗波, E-mail: luob041@nenu.edu.cn

Effects of Nighttime Streetlights on the Foraging Behavior of Japanese Pipistrelle

HE Mengzhou¹, TAHIR Abbas¹, JIANG Chunyan¹, YANG Jinrui¹, ZHU Yicheng¹, ZHANG Hanyu¹, LIU Wenqin², YANG Yan¹, ZHANG Juan¹, FENG Jiang², LUO Bo^{1,3*}

(1. Key Laboratory of Southwest China Wildlife Resources Conservation of Ministry of Education, China West Normal University, Nanchong 637009, China;

2. Jilin Provincial Key Laboratory of Animal Resource Conservation and Utilization, Northeast Normal University, Changchun 130117, China;

3. Sichuan Provincial Forestry and Grassland Key Laboratory of Rare Animal and Plant Resources Conservation in Liangshan Mountains, China West Normal University, Nanchong 637009, China)

Abstract: Streetlights are widely used for nighttime road illumination. However, research on the impacts of streetlights on the foraging behavior of wild animals is still lacking. In order to investigate the effects of nighttime streetlights on foraging behavior, Japanese pipistrelle (*Pipistrellus abramus*) was used as a model insectivorous bat. Ten east-west transects were established along a selected road and a total of 50 monitoring sites were set up (25 with streetlights and 25 without). Echolocation calls of Japanese pipistrelle were recorded after sunset to quantify the number of flight passes and feeding buzzes. Light intensity, ambient temperature, insect abundance, and microhabitat types were simultaneously monitored at each site. Kruskal-Wallis tests suggested that the average light intensity at sites with streetlights (12.54 lx) was significantly higher than that at sites without streetlights (1.04 lx). The number of passes and feeding buzzes of Japanese pipistrelle at streetlight sites was significantly lower than at without streetlights. Generalized linear mixed models revealed that light intensity was the key factor influencing both foraging indicators. With increasing light intensity, the number of passes ($P = 0.0032$) and feeding buzzes ($P = 0.0380$) of Japanese pipistrelle showed a significant decreasing trend. This study supports the “environmental risk hypothesis”, indicating that high-intensity light emitted by streetlights significantly inhibits the normal foraging behavior of Japanese pipistrelle. We recommend that urban planning balance lighting requirements with bat conservation, and appropriately reduce streetlight illuminance in core habitats to mitigate the adverse effects of light pollution on bat populations.

路灯被广泛应用于交通主干道和人行道的夜间照明,是最为普遍的光污染类型之一^[1-3]。路灯光照强度可达夜间月光强度的50倍^[1],可遮蔽夜间月光,扰乱昼夜光暗周期,在个体、种群和群落等多个层面对生物造成负面影响,被认为是加剧全球生物多样性丧失的关键因素^[4-7]。深入开展路灯对动物行为的影响研究,已经成为生态学和保护生物学的热点科学问题,有助于揭示野生动物对光污染的耐受性,为野生动物保护和管理提供直接的科学依据。

觅食行为是野生动物获取营养与能量的核心本能行为,直接影响种群繁衍、捕食者与猎物间相互作用及群落结构动态^[8-10]。当前,关于人工灯光对野生动物觅食行为的作用效应仍存在争议。环境风险假

说认为,灯光可提升环境照度,提高野生动物被更高营养级捕食者发现的概率,进而对其觅食行为造成负面影响^[11-14]。相反,觅食机遇假说认为,灯光会吸引趋光性猎物聚集于光源附近,提升局部猎物丰度,从而有利于增强野生动物的觅食活动^[15-17]。

食虫蝙蝠白天栖息于洞穴和建筑缝隙等黑暗生境,于日落后外出觅食,可作为光污染生态学研究的模式生物^[18-22]。食虫蝙蝠主要依靠回声定位完成空间定向与猎物探测,视觉在其觅食过程中也发挥重要作用^[23-25]。已有研究表明,人工灯光可吸引鳞翅目(Lepidoptera)和双翅目(Diptera)昆虫在光源附近聚集,为伏翼(*Pipistrellus* spp.)和棕蝠(*Eptesicus* spp.)提供潜在觅食机遇^[15,17,19,26]。然而,部分食虫

蝙蝠在觅食时会主动躲避人工光源^[19,21,27]。例如,泛光灯照射可促使夜棕蝠(*E. bottae*)和古氏伏翼(*Pipistrellus kuhlii*)提升飞行速度与飞行高度,进而降低觅食活动强度^[28]。Azam *et al.*^[29]通过野外实验探究食虫蝙蝠对灯光的敏感性,发现鼠耳蝠(*Myotis* sp.)和普通伏翼(*Pipistrellus pipistrellus*)对高压钠灯的光强敏感强度分别低于1 lx和5 lx。上述研究表明,不同食虫蝙蝠物种对人工灯光的耐受性存在显著种间差异。目前,路灯对多数食虫蝙蝠觅食行为的具体影响机制尚不明确,亟需在更多物种和更复杂生境中开展系统性验证。

东亚伏翼(*P. abramus*)隶属蝙蝠科(Vespertilionidae),是典型伴人型蝙蝠,广泛分布于我国南方和北方^[30]。该物种常栖息于人工建筑缝隙,于日落后20~30 min飞往觅食区域,主要捕食双翅目、鞘翅目(Coleoptera)及膜翅目(Hymenoptera)昆虫^[31]。由于其觅食时段与道路夜间照明时段高度重合,极易受路灯光污染的干扰^[32-34]。本团队前期在黑暗、弱光和强光环境下对3座桥梁的东亚伏翼觅食活动进行监测,发现强光环境下该物种的飞行通过次数显著降低^[34]。然而,该研究样点数量有限,仅涉及桥梁生境,未涵盖公路、河岸、农业用地及树林等更广泛的微生境类型,因此夜间路灯在不同生境背景下对东亚伏翼觅食行为的影响仍有待进一步验证。为此,本研究在四川省南充市师大路及其两侧区域,沿近5 km公路布设10条东西走向样线,共设置50个监测样点,涵盖公路、河岸、农业用地及树林4类微

生境,其中有路灯与无路灯样点各25个。通过超声波录制与环境因子同步监测,量化东亚伏翼的飞行通过次数和捕食蜂鸣数量,并分析光照强度、环境温度、昆虫丰度、微生境类型及月相对其觅食行为的影响。结合已有理论与前期发现,本研究提出如下假设和预测:(1)如果环境风险假说起主导作用,我们预测东亚伏翼的飞行通过次数和捕食蜂鸣数量会随光照强度升高而显著下降;(2)如果觅食机遇假说起主导作用,则预测其飞行通过次数和捕食蜂鸣数量随光照强度升高而显著增加。此外,也不排除二者的综合效应导致非线性响应的可能。

1 研究方法

1.1 研究样点

2025年3月末—7月初,于南充市顺庆区师大路及其两侧区域开展野外调查。师大路地处西河与西山之间,日落后常有东亚伏翼在该路段周边的各类微生境内觅食。该路段布设大量白色LED(light-emitting diode)路灯,日落后即开启照明。研究选取长约5 km的道路区段,以约500 m间隔布设10条东西走向的样线。每条样线按100~200 m间距设置5个监测样点,共50个样点,涵盖公路、河岸、农业用地和树林4类微生境,各样线均包含无路灯和有路灯两类样点。为平衡样本量,无路灯和有路灯样点各设25个(图1)。本研究为野外非损伤性调查,未涉及东亚伏翼的捕捉、饲养等操作,符合西华师范大学动物伦理审查委员会的伦理要求。



图1 野外样点分布

Figure 1 The distribution of field sites

1.2 野外监测

使用GPS定位仪(彩途K30S; 华辰北斗信息科技股份有限公司, 北京)记录并确定实验期间日落时刻。于日落后30 min在各样点布设1台超声波探测仪(Avisoft-UltraSound Gate 116H; Avisoft Bioacoustics, Berlin, Germany), 以10 min为一个监测周期, 录制东亚伏翼回声定位声波(图2)。录音采样频率设置为375 kHz, 采样精度16 bits。单个录音文件时长1 min, 数据存储于笔记本电脑(Inspiron 5580; 戴尔有限公司, 厦门)。麦克风(UltraSoundGate CM16; Avisoft Bioacoustics, Berlin, Germany)通过三脚架固定于距地面0.5 m高度处, 与地面呈45°角。采用红外夜视仪(SAGA; 神鹰光学有限公司, 苏州)观测夜间昆虫活动, 该设备经三脚架架设于距离地面1.5 m处, 与地面呈45°角。采用照度计(OPT4001DTS; 环球信士, 长沙)和温度传感器(SHT85; 环球信士, 长沙), 每隔1 min分别测定麦克风朝向的光照强度和环境温度, 以每10 min的均值用于后续数据分析。通过lunar程序包^[35], 根据监测日期和各样点经纬度提取对应当晚月相信息。每晚仅在单个样点开展60 min的声波录制和环境因子监测, 遇降雨天气暂停作业。每个样点共获得6个有效监测时段(每10 min为1个时段, 连续监测60 min), 因此总测量次数为300次(50个样点×6次), 其中有路灯与无路灯样点各150次(25个样点×6次)。

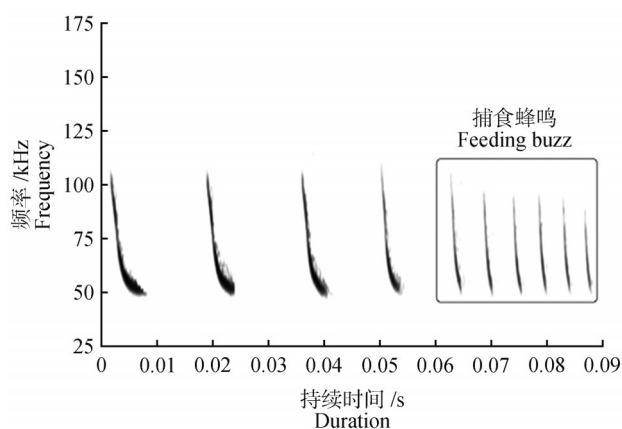


图2 东亚伏翼的回声定位声波和捕食蜂鸣声谱特征(采样频率: 375 kHz; 采样精度: 16 bits)

Figure 2 The spectral characteristics of echolocation calls and feeding buzz of Japanese pipistrelle (sampling frequency: 375 kHz; sampling precision: 16 bits)

1.3 数据分析

利用超声波分析软件(Avisoft-SASLab Pro; Avisoft Bioacoustics, Berlin, Germany)对东亚伏翼回声定

位声波进行可视化处理, 统计各样点内东亚伏翼的飞行通过次数和捕食蜂鸣数量。参考已有研究^[34,36-37], 将东亚伏翼的一串连续回声定位声波序列定义为一次通过, 将其在觅食终止阶段发出的回声定位声波序列定义为捕食蜂鸣(图2)。应用视频播放软件(PotPlayer; Kakao Corp, South Korea)回放由红外夜视仪录制的昆虫视频, 每隔1 min统计视频中的昆虫个体数量, 以此量化各样点昆虫丰度。利用dunn.test程序包进行克鲁斯卡尔-沃利斯检验(Kruskal-Wallis test)^[38], 比较无路灯和有路灯样点在光照强度、东亚伏翼通过次数及捕食蜂鸣数量上的差异。分别以东亚伏翼通过次数和捕食蜂鸣数量为因变量, 以光照强度、环境温度、月相、昆虫丰度及微生境类型为预测变量, 以调查日期为随机变量, 利用lme4程序包^[39]构建服从负二项分布的广义线性混合模型(generalized linear mixed model, GLMM), 解析光照强度和其他环境因子对东亚伏翼觅食活动的影响。模型拟合前对全部预测变量进行标准化处理, 以消除量纲差异。经似然比检验, 各预测变量间无显著交互作用。利用MuMIn程序包^[40], 基于修正样本量的赤池信息准则(Akaike's information criterion corrected for sample size, AICc), 筛选最优负二项广义线性混合模型^[20,37]。本研究数据采用均值±标准误表示。所有数据分析均在R 4.5.0中完成, 样点地图在图新地球4.5.3中绘制。

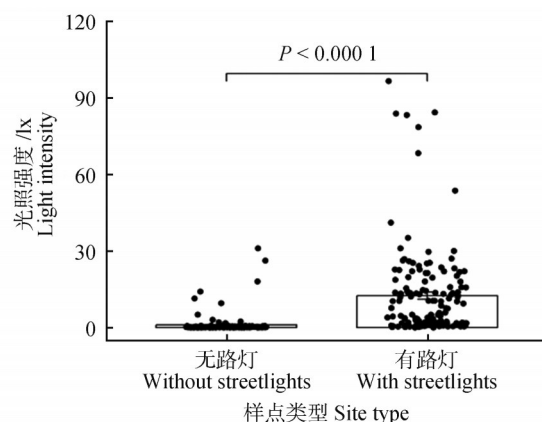


图3 有无路灯样点光照强度的差异(Kruskal-Wallis 检验)

Figure 3 Differences in light intensity between sites with and without streetlights (Kruskal-Wallis test)

2 结果

2.1 路灯对样点光照强度的影响

野外监测结果发现, 50个样点整体平均光照强

度为 $(6.79 \pm 0.80)lx$ ($n = 300$), 其中无路灯样点平均光照强度为 $(1.04 \pm 0.32)lx$ ($n = 150$), 有路灯样点平均光照强度为 $(12.54 \pm 1.43)lx$ ($n = 150$)。克鲁斯卡尔-沃利斯检验结果表明, 有路灯样点光照强度显著高于无路灯样点 ($\chi^2 = 158.36, df = 1, P < 0.0001$; 图3)。

2.2 路灯对东亚伏翼觅食行为的影响

东亚伏翼在所有50个样点的平均通过次数为 (5.20 ± 0.76) 次 ($n = 300$), 平均捕食蜂鸣数量为 (0.92 ± 0.19) 个 ($n = 300$)。其中, 无路灯样点平均

通过次数为 (8.80 ± 1.40) 次 ($n = 150$), 有路灯样点的平均通过次数为 (1.59 ± 0.39) 次 ($n = 150$); 无路灯样点平均捕食蜂鸣数量为 (1.61 ± 0.36) 个 ($n = 150$), 有路灯样点的平均捕食蜂鸣数量为 (0.23 ± 0.08) 个 ($n = 150$)。克鲁斯卡尔-沃利斯检验结果显示, 相较于无路灯样点, 有路灯样点东亚伏翼的通过次数 ($\chi^2 = 20.50, df = 1, P < 0.0001$; 图4A) 和捕食蜂鸣数量均显著降低 ($\chi^2 = 20.72, df = 1, P < 0.0001$; 图4B)。

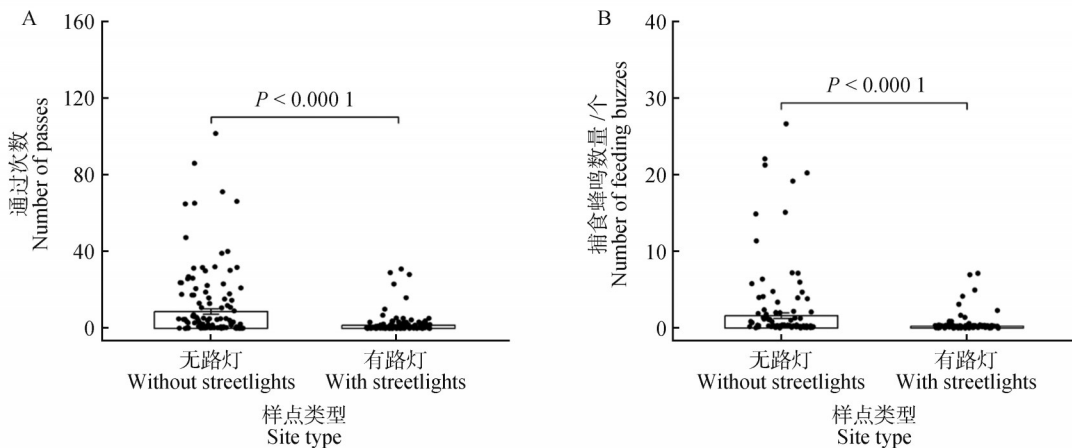


图4 路灯对东亚伏翼通过次数与捕食蜂鸣数量的影响

Figure 4 Effects of streetlights on the number of passes and feeding buzzes of Japanese pipistrelle

2.3 东亚伏翼觅食行为的预测因子

根据修正样本量的赤池信息准则, 光照强度和环境温度是影响东亚伏翼通过次数和捕食蜂鸣数量的关键预测变量, 其余环境因子(微生境类型、月相和昆虫丰度)未纳入最优负二项分布广义线性混合模型(表1)。最优模型结果表明, 光照强度对东亚伏翼的通过次数有极显著的负向影响 (GLMM: Estimate =

$-1.07, z = -2.95, P = 0.0032$; 图5A), 对其捕食蜂鸣数量有显著的负向影响 (GLMM: Estimate = $-5.04, z = -2.07, P = 0.0380$; 图5B)。环境温度显著负向影响东亚伏翼的通过次数 (GLMM: Estimate = $-0.92, z = -3.35, P = 0.0008$), 但对其捕食蜂鸣数量的影响未达到统计学显著水平 (GLMM: Estimate = $-0.90, z = -1.90, P = 0.0580$)。

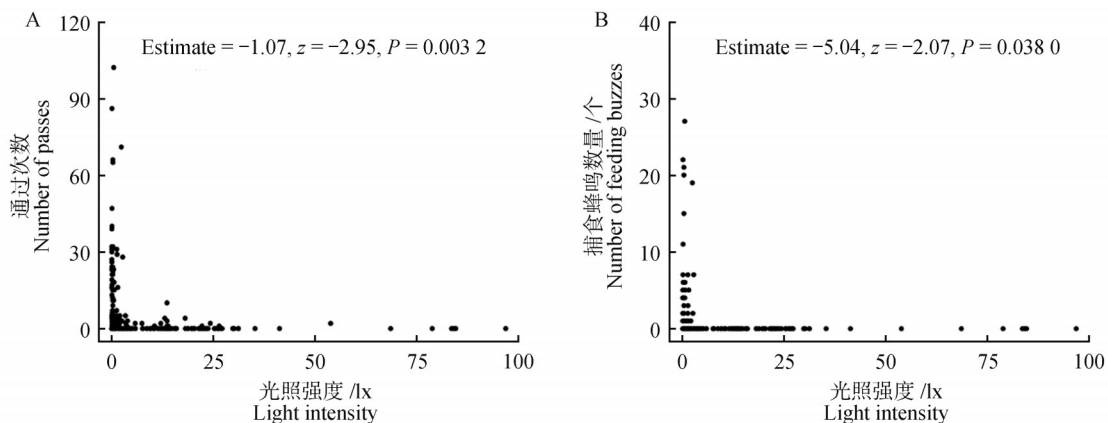


图5 光照强度与东亚伏翼通过次数、捕食蜂鸣数量的关系(负二项分布广义线性混合模型结果)

Figure 5 Relationships between light intensity and the number of passes and feeding buzzes of Japanese pipistrelle (results from negative binomial generalized linear mixed models)

表1 影响东亚伏翼觅食行为的前5个备择负二项分布广义线性混合模型

Table 1 The top five alternative generalized linear mixed models with a negative binomial distribution for influencing foraging behavior of Japanese pipistrelle

因变量 Dependent variable	预测变量 Predictor variable	基于修正样本量的赤池信息准则 AICc
通过次数 Number of passes	光照强度 + 环境温度 Light intensity + Ambient temperature	1 074. 33
	光照强度 + 环境温度 + 微生境类型 Light intensity + Ambient temperature + Microhabitat type	1 075. 67
	光照强度 + 环境温度 + 月相 Light intensity + Ambient temperature + Moon phase	1 076. 39
	光照强度 + 环境温度 + 昆虫丰度 Light intensity + Ambient temperature + Insect abundance	1 076. 41
	光照强度 + 环境温度 + 微生境类型 + 月相 Light intensity + Ambient temperature + Microhabitat type + Moon phase	1 077. 54
捕食蜂鸣数量 Number of feeding buzzes	光照强度 + 环境温度 Light intensity + Ambient temperature	438. 45
	光照强度 + 环境温度 + 昆虫丰度 Light intensity + Ambient temperature + Insect abundance	438. 75
	光照强度 + 环境温度 + 微生境类型 Light intensity + Ambient temperature + Microhabitat type	439. 60
	光照强度 + 环境温度 + 昆虫丰度 + 微生境类型 Light intensity + Ambient temperature + Insect abundance + Microhabitat type	440. 33
	光照强度 + 环境温度 + 月相 Light intensity + Ambient temperature + Moon phase	440. 35

3 讨论与结论

3.1 夜间路灯对东亚伏翼觅食行为的抑制作用

本研究通过超声波监测与环境因子同步分析证实,光照强度是影响东亚伏翼飞行通过次数和捕食蜂鸣数量的关键预测变量;随光照强度升高,东亚伏翼的觅食行为显著下降。该研究结果与已有相关研究结果一致。例如,蒋昀珂等^[34]对桥梁生境中东亚伏翼的夜间觅食行为开展监测,发现光照强度大于10 lx的白色LED灯会显著抑制其觅食行为;Stone *et al.* ^[41]通过野外灯光操控实验发现,当白色LED光照强度超过3.6 lx时,欧洲小菊头蝠(*Rhinolophus hipposideros*)和鼠耳蝠(*Myotis sp.*)的夜间通勤行为显著减少;Azam *et al.* ^[29]的野外声学监测证实,普通伏翼在1~5 lx弱光条件下通过次数较多,在光照强度

超过5 lx后其通过次数反而减少;Seewagen *et al.* ^[42]进一步证实,白色LED灯75 m范围内的弱光环境仍会对莹鼠耳蝠(*M. lucifugus*)的觅食行为造成负面影响。综合本研究与已有研究结果可见,相较于菊头蝠和鼠耳蝠,伏翼这类伴人型蝙蝠对人工灯光具有更强的耐受性,但高强度灯光污染仍然会显著干扰其正常觅食行为。

值得注意的是,本研究中东亚伏翼的飞行通过次数和捕食蜂鸣数量在有路灯样点均发生显著下降。由于捕食蜂鸣是衡量蝙蝠成功捕获猎物的直接声学证据,其数量的锐减强有力地说明,东亚伏翼在有路灯环境中不仅减少活动频次,且捕食成功率也降低。这为夜间路灯对东亚伏翼觅食行为的抑制作用提供了比单纯通过次数减少更直接、更有力的证据。

3.2 夜间路灯影响东亚伏翼觅食行为的生态机制

目前,关于人工灯光影响食虫蝙蝠觅食行为的生态机制尚存在学术争议。一方面,觅食机遇假说认为,灯光会吸引夜间昆虫聚集于光源周边,提升局部昆虫的可利用性,从而为食虫蝙蝠创造有利的觅食条件^[15-16,43]。该假说预测光照强度升高会使东亚伏翼的通过次数和捕食蜂鸣数量增加。另一方面,环境风险假说认为,灯光提升环境照度,增强昼行性和夜行性猛禽对食虫蝙蝠的视觉识别能力,使食虫蝙蝠感知到更高的捕食风险,进而主动远离路灯区域觅食^[19-21,28,34,44]。该假说预测有路灯样点东亚伏翼的通过次数和捕食蜂鸣数量更低,且光照强度与上述觅食指标呈显著负相关。整体而言,本研究发现光照强度与东亚伏翼的通过次数及捕食蜂鸣数量均呈显著负相关,与环境风险假说的预测结果相符。然而,东亚伏翼在强光下觅食行为减少,也可能源于其他非捕食风险因素,例如强光可能对其视觉系统造成直接生理胁迫或干扰,或是其出于本能对光亮环境存在主动回避行为。尽管存在多种可能机制,但本研究表明,夜间路灯产生的高光照强度会显著抑制东亚伏翼的觅食行为,为“人工光照对野生动物存在负面效应”这一主流观点提供了新的野外实验证据。

3.3 降低路灯光照强度是缓解光污染的有效途径

东亚伏翼及其他食虫蝙蝠在夜间农林害虫防控、生态系统能量流动过程中发挥着不可替代的作用^[7,45-46]。如何有效控制路灯对食虫蝙蝠觅食行为的不利影响是维持其生态系统服务功能的关键。从光照衰减规律来看,路灯的光照强度随距光源距离的增加而逐步衰减^[47]。因此,降低食虫蝙蝠觅食生境周边的路灯光照强度,可有效减小灯光辐射范围,进而减弱路灯光污染对其觅食行为的负面作用^[29,34]。结合本团队近年研究成果和国内外相关研究结论^[20,22,29,47-48],本研究提出以下保护建议:市政部门在规划路灯建设时,应统筹兼顾人类夜间照明需求与食虫蝙蝠保护。建议在食虫蝙蝠核心生境适度拆除冗余路灯,或更换为低光照强度、对蝙蝠影响较小的光源类型(如红色光源),使夜间灯光强度接近当地食虫蝙蝠的耐受阈值。例如,本研究发现,东亚伏翼在光照强度大于5 lx时觅食活动显著下降(图5),且有路灯样点(平均光照强度12.54 lx)的通过次数仅为无路灯样点(平均光照强度1.04 lx)的

18%。因此,建议将东亚伏翼核心生境的路灯光照强度控制在5 lx以下,以减少对其觅食行为的干扰。总之,科学合理地优化路灯布局与照明参数,既可满足居民夜间的基本照明需求,又能够保障食虫蝙蝠正常觅食,有利于实现人与食虫蝙蝠和谐共生。

综上所述,本研究在一段公路及其两侧生境中,比较了无路灯和有路灯样点东亚伏翼的觅食行为响应。研究发现,东亚伏翼的飞行通过次数和捕食蜂鸣数量在有路灯样点显著减少。即便整合环境温度、昆虫丰度、微生物类型及月相这些因素,光照强度仍然是预测东亚伏翼通过次数和捕食蜂鸣数量的关键因子。这些结果表明,夜间路灯会显著干扰东亚伏翼的正常觅食行为。本研究拓展了路灯对食虫蝙蝠觅食行为影响的研究内容,为环境风险假说提供了新的野外实验证据,也为光污染背景下蝙蝠保护和暗夜环境的时空规划提供了科学依据。由于路灯会对大部分食虫蝙蝠的觅食行为产生负面影响^[19,21],本团队建议把夜间路灯光照强度纳入食虫蝙蝠的生境质量评估与管理体系中。后续研究将从更长时间尺度揭示夜间路灯对食虫蝙蝠觅食行为的影响机制,并探索减缓光污染对食虫蝙蝠负面作用的工程技术与管理策略。

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