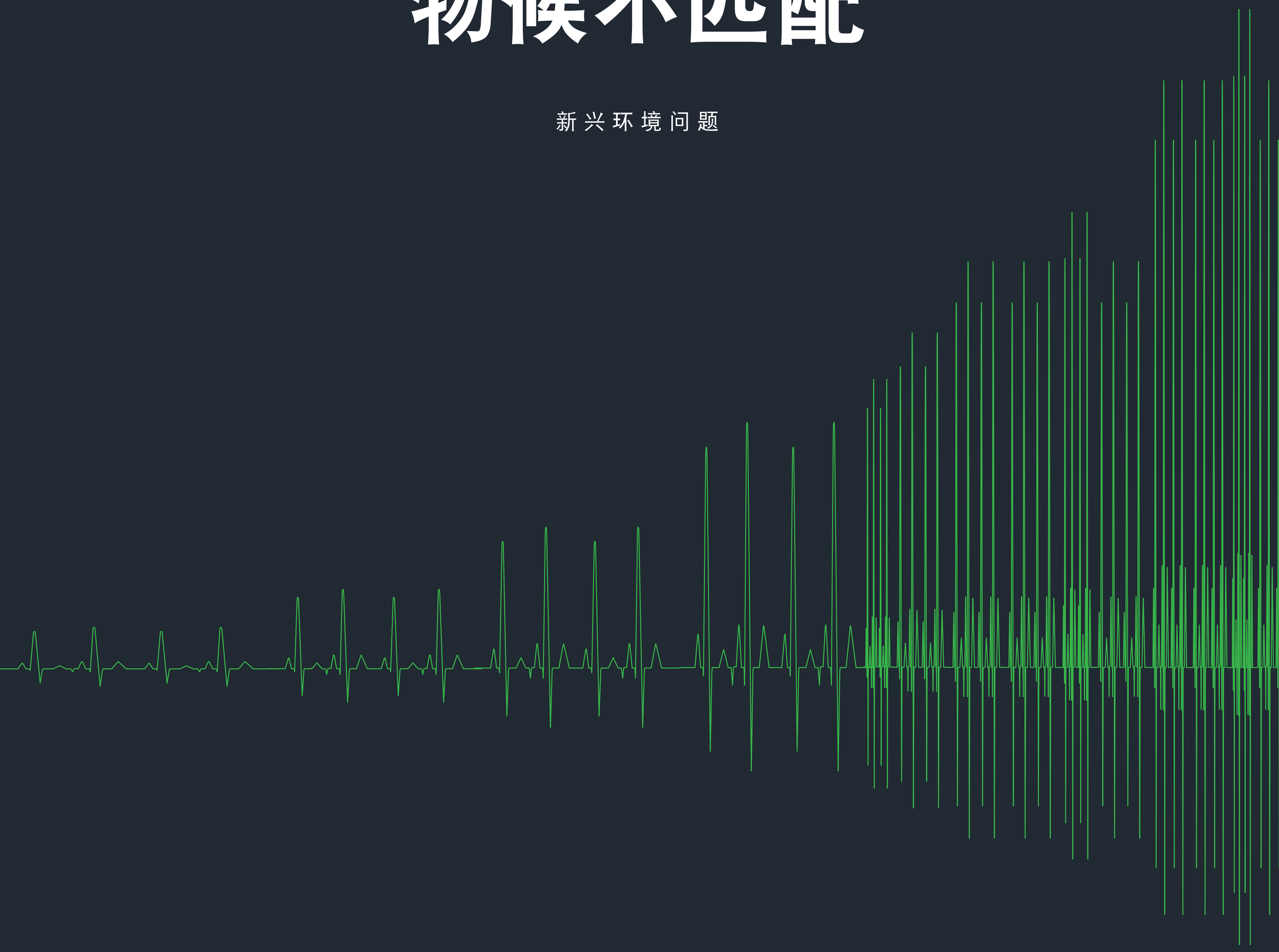
噪声、火灾和物候不匹配

新兴环境问题



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2022年前沿报告

2022年**前沿报告**

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2022年前沿报告

新兴环境问题

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本报告适合屏幕阅读。某些页面无法以清晰标准的字体用A4纸打印出来。

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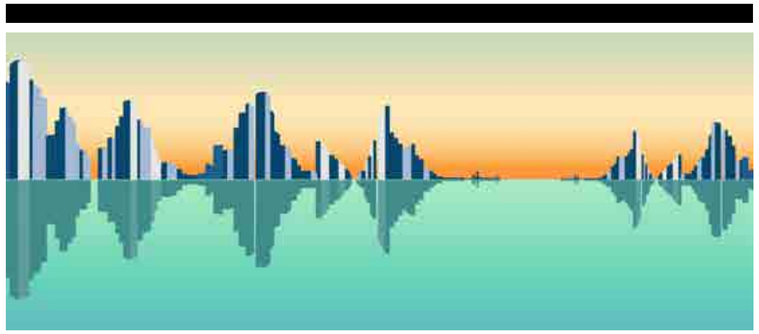
从噪声环境到积极声景



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序言

从气候变暖到陆地上和海洋中的未开发之地不断减少，人类以许多有害的方式改变了地球。但是在地球这样复杂的系统中，科学必须始终不断地寻找解决方案，既要解决已发现的问题，也要应对即将到来的新威胁。

为此，联合国环境规划署编制了《前沿报告》，确认并探讨存在新兴或持续环境问题的领域。《2022年前沿报告》深入探讨了三大问题：城市噪声污染、日益严重的野火威胁以及开花、迁徙和冬眠等季节活动的变化——对这一领域的研究被称为物候学。

随着城市的发展，噪声污染被认为是一大环境风险。高分贝噪声会扰乱睡眠，淹没生活在城市地区的许多动物物种间积极有益的声音交流，进而损害人类健康和福祉。不过，解决方法也触手可得，从电气化交通到绿地，这些都必须纳入城市规划，以减少噪声污染。

此外，近年来，澳大利亚、秘鲁等世界各地都发生了毁灭性的野火。由于大气温室气体浓度上升以及随之而来的野火风险因素升级，更加危险的火灾天气条件可能日趋恶化。未来十年对于建立更强的野火（包括野地-城区结合部的野火）抵御能力和适应能力至关重要。特别是，进一步的研究应涉及脆弱群体在极端野火发生前、中、后所面临的危害以及加大力度预防和防备野火所采取的行动。

尽管野火对气候变化有着显著影响，但物候变化也令人担忧。动植物往往以温度、降雨和日长为线索来判断进入季节周期的下一阶段。然而，气候变化速度太快，导致许多植物和动物物种无法适应，从而破坏生态系统的运作。恢复生境、建设野生生物走廊以加强生境的连通性、改变保护区边界以及保护生产性景观中的生物多样性，这些作为直接干预措施可以有所帮助。然而，如果不大力减少温室气体排放，这些保护措施只能延缓基本生态系统服务的崩溃。

本报告帮助我们了解向生态系统学习以及学习如何与生态系统和谐共处是我们所有人都需要设定的目标。没有健康的环境就没有健康的社会。我们需要良好的科学来为支持健康环境的负责任的政策提供依据，本报告便提供了此类依据。

Inger Andersen
联合国环境规划署执行主任

致谢

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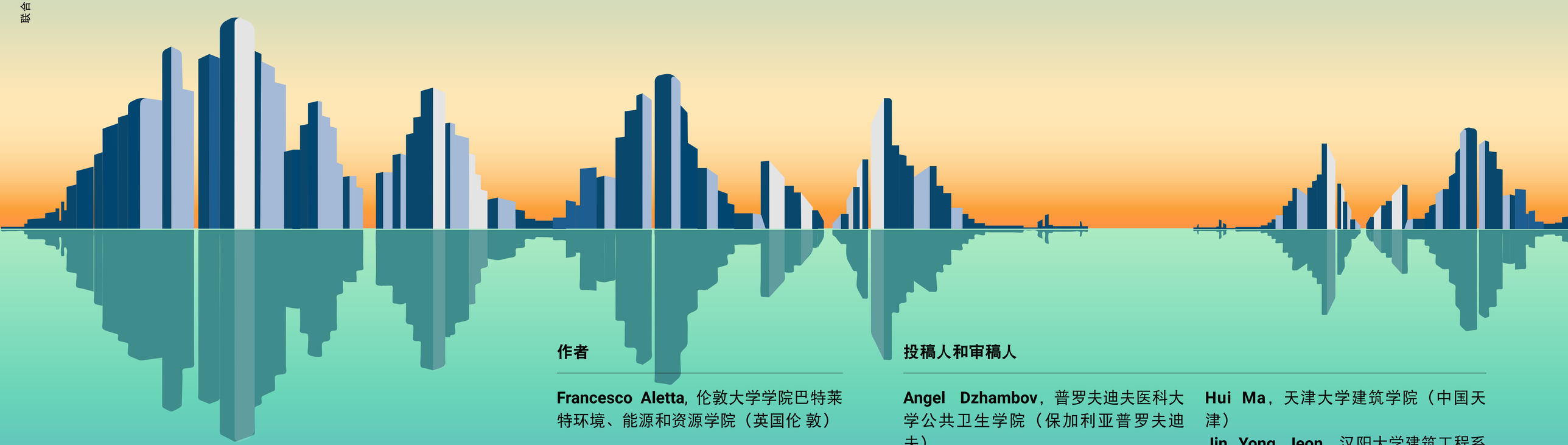
倾听城市 从噪声环境到积极声景



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向下滚动翻页

1. 周围声音：我们的声音环境

声音是一种复杂的物理现象，是以声波的形式将能量传播给介质的声源振动产生的。声音不断发生且无处不在：地球上并不存在“无声”这种状态。声音是一种物理现象，没有正面和负面之分。只有从听众的角度去考虑，它们才具有意义并产生影响。当声音不被需要时，它们就会变成噪声。当噪声太大且持续时间过长时，它们就会成为噪声污染。

今天，噪声污染是一大环境问题，不但被认为是对所有年龄和社会群体健康影响最大的环境风险，还加重了公共卫生负担。长期暴露于高分贝噪声环境中会损害人类健康和福祉，这是公众和决策者日益关切的一大问题。[1]目前，至少20%的欧盟公民暴露在被认为有害健康的道路交通噪声环境中，而这个估计值只是平均值，城市地区的这一比例要远高于此。[2]噪声污染来自公路、铁路、机场和工业等常规来源，而高分贝噪声可能来自家庭活动或休闲活动。交通及其他城市噪声不仅会影响人类健康，还会扰乱并危及对城市环境至关重要的物种的生存。[3]

分贝是表示声音强度或响度的测量单位，有助于预测开始让人感到烦躁或开始干扰睡眠的噪声阈值。虽然噪声响度很重要，但声音的频率（高音或低音）和出现时间模式也决定了声音对听者的身体和心理影响。[4]

就身体影响而言，接近非常响亮的突发声音，如超过140分贝的枪声，可能会使耳朵鼓膜破裂，导致立即丧失听力。每天使用耳机以最大音量（鼓膜处的音量在90到100分贝之间）仅听15分钟音乐就可能造成听力损伤。[5]每天暴露于超过85分贝的噪声环境中8小时或更长时间处可能会造成永久性听力损伤。长期暴露于噪声，即使是城市地区常见的相对较低的噪声也会损害身心健康。

然而，声音质量不能仅凭其物理特性加以判断。将噪声定义为不需要的声音，意味着这是一个心理学概念。[6]虽然有必要降低对人体有害的噪声水平，但这种评价可能稍显狭隘。声景有益于人们的身心健康，特别在城市环境中，研究声景越来越重要。[7]

然而，大多数人认为他们并不向往无声的世界，因为声音可以丰富我们的生活，让我们重新获得健康和幸福的感觉，并为我们的日常体验赋予意义。[8]它们有助于确定地方和文化的特征，并塑造生活质量。一些城市声音可能是某些社区独有的，并成为了其文化身份的一部分，甚至成为了历史声音地标。[9]例如，伦敦大本钟的声音或麦加禁寺的祈祷声都令人回味。从广义上来讲，声舒适不应仅仅被视为没有噪声，而应被视为环境声音为人们提供充足的机会去蓬勃发展，并为人们的身心健康保驾护航。

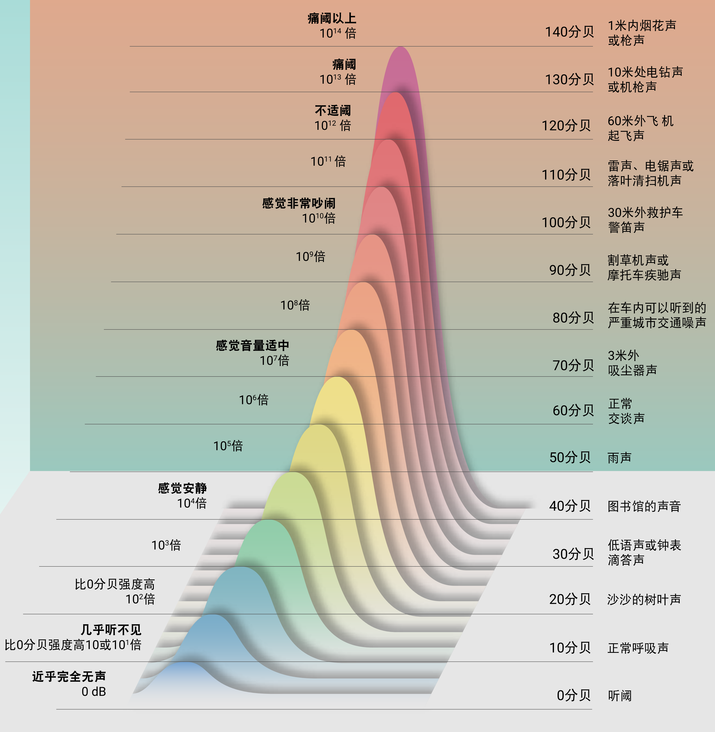
声景是什么？

国际标准化组织（ISO）将声景定义为“在给定场景中，个体或群体所感知或体验和/或理解的声环境”。[10]换句话说，声景包括人们在特定时间、特定场所感知、体验和回应各种声音的方式。[11]声景研究是一门新兴学科，试图从听者角度出发更全面地看待城市声环境问题。[12]声景方法往往关注场景、需要的声音而非不需要的声音，关注个人偏好而非不适感。[13]

噪声测量

声音压力或强度通常以分贝或dB表示。由于人耳能察觉到的声压范围很大，所以分贝采用以10为底的对数标度。

至于分贝标度，人们能听到的近乎完全无声的最低声音是0分贝。声压比0分贝大101倍的声音是10分贝。但是10分贝的增量通常是人耳能听到的声音响度的两倍。比0分贝强度高100（102 ）倍的声音是20分贝，依此类推。也就是说，每增加10分贝就相当于声压增加了10倍。



完整参考见第39页。

2. 声音影响

噪声对公众健康的不良影响是多方面的，并且是全球日益关切的问题。从轻度和暂时的痛苦到严重和慢性的身体损伤，噪声造成的后果多种多样。夜间噪声会扰乱睡眠并影响第二天的身体状态。据估计，欧洲分别有2,200万和650万人长期饱受噪声和睡眠障碍困扰。[2]老年人、孕妇和轮班工作者均面临因噪声引起的睡眠障碍风险。[2,14]

被噪声吵醒会引发一系列生理和心理压力反应，因为睡眠对激素调节和心血管的正常运转而言是必要的。[14,15]越来越多的证据表明，暴露于交通噪声是血压升高、动脉高血压、冠心病和糖尿病等心血管和代谢疾病的致病风险因素。[16]据保守估计，欧洲每年因长期暴露于环境噪声中导致的缺血性心脏病病例有48,000例，过早死亡人数达12,000人。[2]

针对加拿大多伦多的长期居民开展的为期15年的两项研究发现，暴露于道路交通噪声会增加急性心肌梗塞和充血性心力衰竭的风险，糖尿病的发病率增加8%，高血压的发病率增加2%。[17,18]这些研究已经考虑了与交通相关的空气污染（与相同的研究结果相关）的混杂影响。对韩国国家健康和噪声数据的分析估计，白天暴露于的噪声每增加1分贝，心脑血管疾病病例就会增加0.17%-0.66%。[19]

世界卫生组织（世卫组织)欧洲区域办事处开展了系统性审查，以评估噪声与健康结果之间的关联，从而为保护人类健康免受各种来源的环境噪声的影响而制定指导方针并提出建议。[1]健康结果包括烦恼、心血管和代谢影响、认知障碍、对睡眠的影响、听力障碍和耳鸣、不良分娩结果、生活质量，以及身心健康。审查中考虑到的噪声源包括道路交通、铁路、飞机、风力涡轮机以及参加体育活动或音乐会活动、使用个人设备听音乐和其他娱乐消遣等休闲活动。

基于这些审查，世卫组织提出了一些暴露阈值建议，以避免对健康造成不良影响。这些阈值是根据日间、傍晚和夜间的综合噪声水平以及夜间噪声水平报告的。这些阈值是相关时段内各个时间的平均噪声指标，以分贝为单位表示，并在暴露程度最大的建筑物一侧的接收端监测。建议夜间时段的噪声限值要始终低于24小时的平均值，因为特定噪声源和事件在活动较少的时段更易察觉，进而导致睡眠障碍和易醒。[1,20]世卫组织审查中使用的科学证据来自代表各大洲众多区域的研究，为推荐暴露于的噪声阈值提供了依据。这种全面的覆盖有助于噪声阈值的采用，为向世界各地的噪声控制政策提供依据。

相比之下，某些声音有益于身体健康，尤其是大自然的声音。大量系统性审查记录了有关健康对声环境反应的临床生理和主观心理研究的实证研究。[21,22]这些审查报告了大自然的声音和寂静对身心健康的积极影响。大自然的声音对整体健康的重要性也可能与进化优势有关。大自然的声音可能代表安全的环境，有助于减少焦虑并恢复精神，而缺乏大自然的声音会让人更加警觉、警惕，对脆弱群体而言尤其如此。[23,24]

欧洲每年因长期暴露于环境噪声中导致过早死亡人数达

12,000人，

缺血性心脏病病例有

48,000例。

缺血性心脏病病例有

22 万

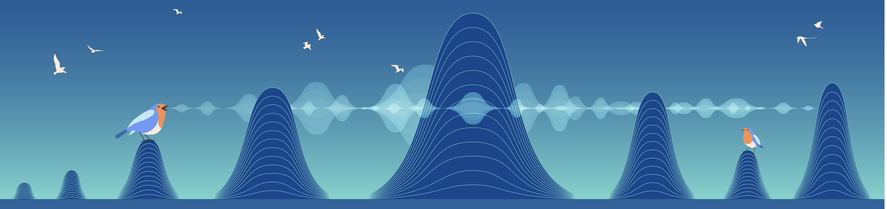
欧洲人长期饱受噪声困扰。

世卫组织对噪声水平的建议

暴露于的噪声应保持在下列水平以下，以避免 对健康有害的影响。[1]

噪声源	最大日间-傍晚-夜间暴露于的噪声水平 L_{den}	最大夜间暴露 于的噪声水平（L夜间）
道路交通	53分贝	45分贝
铁路	54分贝	44分贝
飞机	45分贝	40分贝
风力涡轮机	45分贝	（证据不足，无法建议限值）

被噪声淹没：城市中的生物



声音交流对许多动物物种至关重要。声音信号用于各种交流场景，包括领土防御、危险示警、定位或吸引配偶以及抚育后代。虽然动物可 能把不可预测的突然响声视为威胁，但交通噪声等长期声音干扰会扰 乱许多物种的声音交流并改变它们的行为。[1,25-27]

放弃嘈杂的居住地看似是最直接的反应，但有些动物选择适应嘈杂的环境，它们会改变鸣叫时间或模式来避免它们的信号被掩盖。在许多欧洲城市，知更鸟多在夜间鸣叫，以避免白天的高声干扰；而在哥伦比亚波哥大的一些城市公园，红领带鹟在日间交通繁忙的地方一大早 就开始鸣叫。[28,29]一些青蛙间歇性地发出叫声，因为它们是根据噪声的中断来确定发出叫声的时间。[30]

其他物种通过改变鸣叫频率、音高和振幅来改变信号，以盖过低频交通噪声。城市中许多天生发出低频鸣叫的鸟类在城市嘈杂区会发出更高频的鸣叫。[31-33]在欧洲大陆、日本和英国的30个城市-森林组合区域开展的研究发现，城市中的大山雀比森林中的大山雀的鸣叫声更高。[34-36]斑胸草雀和白冠麻雀在城市噪声中拉长鸣叫声。[37,38]在青蛙和生活在嘈杂的公路附近的蚱蜢等昆虫中也观察到了这类鸣叫变化。[39-42]

这些变化当然有助于动物的声音在嘈杂的环境中被听到，但有时改变 后的鸣叫模式对潜在配偶缺乏吸引力，因此会影响繁殖成功率。[3,30]此外，如果物种在发出或接收信号方面不知变通，则无法交流，这可能会让它们面临灭绝，甚至会对生态造成重大影响。[3,27]

声音测试：
城市有多嘈杂？

该图显示了在特定日间时段测量得到的不同城市的交通相关噪声水平（dB，LAeq）。这些数据来自各种已发表的研究，而这些研究使用了不同的方法。根据1999年世卫组织社区噪声指南，建议住宅区室外的噪声限值为55dB LAeq，而交通和商业区的噪声限值为70dB LAeq。[19] 最新的2018年世卫组织指南根据Lden指标（是日间、傍晚和夜间的平均噪声水平，不同于Laeq指标）建议，为保护健康将道路交通噪声水平定为53分贝。

纽约

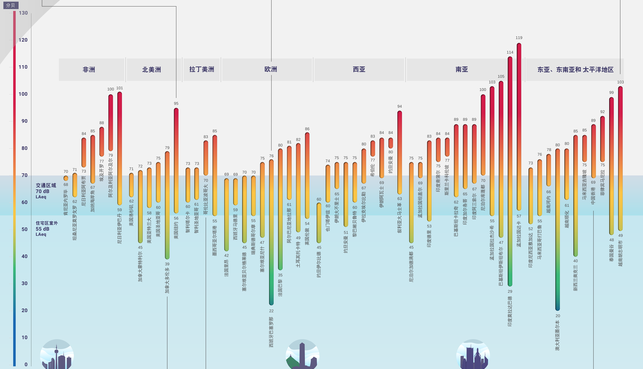
纽约大都市区有超过200万人乘坐公共交通工具通勤。在纽约市，10个公共交通用户中有9个暴露在超过建议限值70分贝的噪声环境中，并可能面临无法逆转的听力损失风险。

巴塞罗那

超过72%的城市居民暴露在超过55分贝的噪声环境中。欧洲大城市中超过一半的居民生活在噪声水平可能影响健康和福祉的地区。

胡志明市

一项针对在该市内骑行超过1,000公里的骑行者的研究表明，骑行者暴露在超过78分贝的噪声环境中，可能会导致听力损伤。



多伦多

针对多伦多的长期展民开展的为期15年的两项研究发现，暴露于道路交通噪声会增加急性心肌梗塞和充血性心力衰竭的风险，糖尿病和高血压的发病率分别增加8%和2%。

波哥大

针对生活在波哥大市公园的红领帽朴黎清晨鸣叫的一项研究发现，这些鸟儿针对早高峰时段改变了鸣叫行为，在日间交通繁忙的地方一大早就开始鸣叫。

香港

每5名香港居民中就有2名暴露于超过容许限值的道路交通噪声中。城市形态和建筑设计在噪声分布方面起着关键作用。与富裕的居民相比，收入低且住房条件差的居民更易受到交通噪声的影响。

完整参考见第19页。

声景管理：
从噪声缓解到理想声景

有充分的证据表明，暴露于道路交通、空中交通、铁路、机械、工业和娱乐活动等环境噪声源会对身心健康造成负面影响。降噪是一大公共健康问题，城市规划者必须创造并保护越来越多的安静空间，打造令人愉悦的城市声景。

声景

声景包括人们在特定时间、特定场所感知、体验和应对有声音的方式。声景规划旨在打造令人赏心悦目的声环境。声景设计考虑了场所的环境特征、包括感知的声音参数、物理特征、自然因素、目的、用途和用户社区。

景观和声音

景观和声音都会影响人类对周围环境的感知。景观影响声音，反之亦然。视觉环境是声景规划和设计的一大考量因素。

绿色解决方案

城市环境中的植被可以吸收声能、分散噪声并降低街道扩音。树带、灌木、绿墙和绿色屋顶不仅通过吸引城市野生生物来增加大自然的声音，还具有积极的视觉效果。

树带

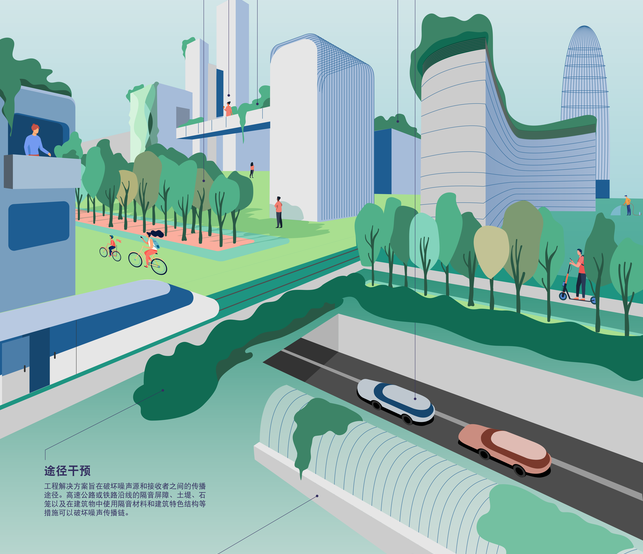
路边树带达到足够高的生物量密度后，可以屏蔽噪声。正确选择树种、树干尺寸、树带的长度和宽度、与噪声源的距离和种植方案均有助于降噪。

绿色屋顶

种植植被的屋顶通过吸收从街道到安静侧屋顶传播来的声音实现降噪。

电动汽车

即便是电动汽车，如果以超过50千米/时的速度行驶，轮胎与路面接触也会发出噪声。多孔沥青路面等解决方案可以减少高速行驶中排放的噪声。



途径干预

工程解决方案旨在破坏噪声源和接收者之间的传播途径。高速公路或铁路沿线的隔音屏障、土堤、石笼以及在建筑物中使用隔音材料和建筑特色结构等措施可以破坏噪声传播线。

源头减轻措施

减噪措施的效果各有不同。从源头上减少排放是最有效的，包括限制交通流量或隧道、低音车辆发动机和低噪声路面。

隔音屏障

设置在源头或接收者附近的屏障可以显著降低噪声。由塑料和汽车轮胎等回收材料制成的传统和创新材料均已证明可有效降低噪声。丹麦报废的风力涡轮机叶片制成的玻璃纤维已显示出隔音屏障的效果，可将交通噪声水平降低6-7分贝。

植被隔音屏障

植被可增强对声音的吸收、减弱声音传播。在传统高速公路隔音屏障后面回地制发栽种多排树木或在坚硬的隔音墙上的种植多层植被最多可将噪声水平降低12分贝。

生态系统服务

大自然的声音有助于心理健康。一般宁静的环境被认为是大自然提供的心理上的生态系统服务。聆听大自然的声音有助于放松心情、从压力中恢复过来和恢复心理健康。

绿地

城市绿地和植被产生积极的心理效应。公共公园、花园和其他小型绿地带来大自然悦耳的声音，比如沙沙作响的树叶、随风摇曳的树枝和叽叽喳喳的鸟儿。大自然的声音有助于从压力中恢复过来和恢复注意力。

安静的空间

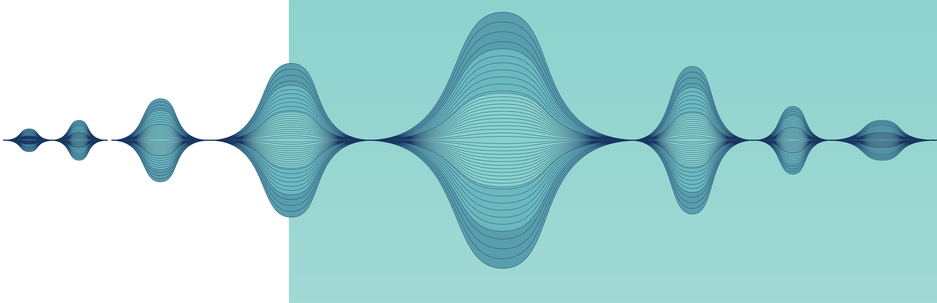
安静的城市地区能城市居民免受嘈杂的周围环境的影响，这是恢复精神并获得幸福的先决条件。城市公园、花园和其他绿地中的大自然声音有助于营造宁静环和的声景。

场所创造

某个场所极具识别度的日常声音有助于打造该场所的识别特征。当这些声音是独一无二的并传达出独特的地方感，它们就会具有超越当地社区的意义，成为声音地标。

完整参考见第21页。

3.
降低音量



“如果全域普遍降噪难以实现时，则必须保证能让人们在公共场所局部享受安静。”

噪声和大多数污染源一样，是必须治理的一大问题。许多国家制定了监管框架和法律要求，而且有时会开展多边协调，比如欧盟各国就是这样。[43,44]常用的措施通常针对噪声源，因为这些措施最具成本效益且可直接执行。源头干预措施包括控制公路、铁路和空中交通流量、使用低噪路面和铁轨、改进飞机的空气动力学性能和零部件，以及从内燃机转向低音推进系统。[2]

公共机构、行业和研究主要关注这些类型的技术发展。安装隔音屏障等其他面向接收者的措施通常不太具有成本效益，只能解决局部问题，而且潜在的负面景观影响也是一个缺点。

也可以通过间接方法来实现城市降噪。埃及政府已在整治噪声并减少噪声源的国家计划中纳入了具有环境协同效益的措施。其中包括鼓励使用自行车。以及实行建筑能源标准来减少空调系统的噪声排放。[43,45]在德国柏林，在宽阔的道路上新建自行车道是间接的降噪策略，旨在减少机动车的可用行驶空间。超过500,000万名居民最初暴露于50分贝以上的夜间噪声，因此许多单向双车道且日车流量达20,000辆次的城市道路被收窄为单车道道路，为自行车和行人腾出空间。这样，声音发出源就移动到道路中间，远离了住宅区域。总之，这为50,000多名居民创造了夜间低噪环境。[2]

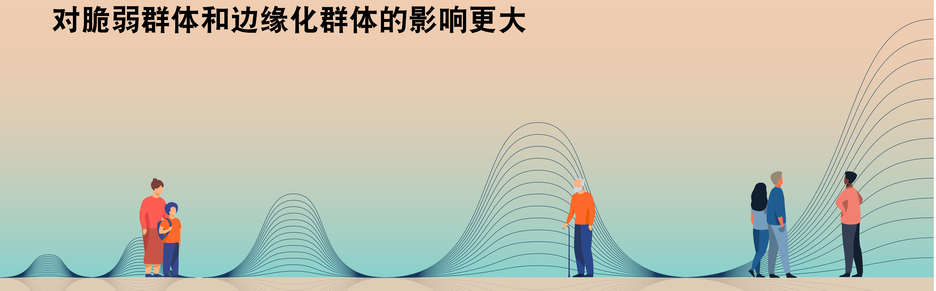
2019年4月，伦敦市中心划定了超低排放区，并于2021年底扩大了范围，惠及380万人口。[46,47]虽然该计划的主要驱动力是希望改善空气质量，但鼓励使用电动汽车和混合动力汽车对于降噪有好处，因为这些车辆远比内燃机车辆安静，尤其是在低速行驶的情况下。[48]然而，低噪车辆的可察觉性可能给行人带来安全隐患，因此也是一项新挑战。[49,50]

纵观呈现复杂的纵向发展和具有拥挤的道路网络的城市，香港就是极具挑战性的一个鲜明例子，在那里，土地利用和城市形态是影响人工建成的环境中噪声源空间分布的关键因素。[51,52]超过100万居民暴露于超出70分贝限值的道路交通噪声，香港当局采取了以基础设施设计和土地利用规划为中心的相对激进的政策，但收效甚微。[53-55]世卫组织噪声指南还强调，政策不应仅仅关注高分贝噪声区域，还应关注已有或可以打造积极声景的区域。[1,56,57]许多环境噪声政策和地方当局的行动认为，如果全域普遍降噪难以实现，则必须保证能让人们在公共场所局部享受安静。[57]因此，大多数城市化环境应注重发现并保护安静区域，以及恢复融入城市肌理中的环境资产。[45]安静的城市公园、改建的运河纤道和铁路支线以及公寓楼、庭院、花园和其他休闲区内的小型绿地和碧水都是人们可以逃离城市噪声的去处。有机会进入附近的安静区域有助于当地社区的健康和福祉。[58]

“安静区域一般指的是有悦耳声景或基本没有不需要的声音的场所。”

虽然噪声水平是一个重要方面，但声景质量也与环境有关，受到非声音因素的影响，其中包括可能值得女性和家长关心的安全感。[23,58,60]安静区域一般指的是有悦耳声景或基本没有不需要的声音的场所，且通常搭配绿植和水景等积极的景观元素。[59-61]提供或保护这类空间虽然是被动的，但其仍不失为整治城市地区噪声的有效方法。

对脆弱群体和边缘化群体的影响更大



噪声对健康的影响因个体或人群而异。特定的个体差异会让个人变得更加脆弱。个人对噪声的敏感度被认为是相对稳定的部分遗传特征，与暴露于的噪声水平无关。[62]噪声敏感度表现为对声音的高度警觉和生理反应。对噪声高度敏感会加重应激反应，并且可能与个人的健康状况欠佳有关。[63]

年龄似乎也会影响我们对声音的反应，幼儿和老年人受到特定噪声影响的风险更高。[64-66]在易受噪声影响方面存在性别差异的证据各种各样，其中有证据表明差异可能在于男性和女性感知和应对压力源的普遍方式。[67,68]

就人口规模而言，一些社会群体比其他群体更容易受到影响。[69]贫困人 口的住房选择较少，他们往往被迫住在垃圾场、工业区和交通繁忙路段等环境压力源附近。[70,71]

此后长期暴露于此类环境压力源可能会加剧居住在这些社区的个人的潜 在健康问题。[72]许多主要城市的研究表明，边缘化社区更容易暴露于高分贝的环境噪声，有迹象表明，在某些多种族社会中，各种族暴露于的噪声水平也不平等。[73-79]

有机会进入公共绿地和当地的安静场所可以提高声景质量并减缓负面噪声影响。有证据表明，绿地和社区绿化对健康的积极影响在社会经济最 贫困群体的社区中表现的最为强烈。[80]然而，与富裕的社区相比，边缘化社区进入高质量公共绿地的机会有限。[80-84]

4. 有关积极声景的有益决定

“应根据综合政策，在环境挑战的广义范围内考虑噪声污染，特别是针对噪声和空气污染叠加的情况。”

在过去的几十年里，虽然决策者在治理噪声污染这一环境和公共健康问题方面取得了一定进展，但也存在两大不足之处。一是主要关注事后降噪时所采用的被动方法存在固有的局限性；二是仅考虑消除交通和工业噪声等令人不适的声音，而不是去研究如何促进发出悦耳的声音。建设宜居城市的当务之急是解决这两个问题，并且在此过程中，为有研究依据的干预措施提供支持至关重要。

为克服第一个不足之处，在任何城市发展战略中，都应在规划和设计的最早阶段就考虑到环境声音，避免事后才想到——这可能牵涉巨大成本。欧洲各国的数据表明，超过50%的行动旨在管理集中在源头的噪声，这种做法通常是有效的，但不一定保证声景质量。[2]只有非常有限的环境噪声治理措施诉诸土地利用或城市规划，而越来越多的研究证据表明，这种方法才是最可持续的发展道路。[85,86]因此，环境声音和城市声景专家必须参与城市发展过程并与当地利益攸关方沟通。[87]

此外，应根据综合政策，在环境挑战的广义范围内考虑噪声污染，特别是针对噪声和空气污染叠加的情况。欧洲环境署调查的许多国家报告了带来协同效益的成功政策，包括交通稳静化措施、绿色环保车辆、节能建筑、种植树木和灌木以建设并连通绿色走廊，以及将降级回收材料纳入工程噪声控制方案中。[2]

为克服第二个不足之处，需要扩大政策制定的范围，从仅当环境声音造成噪声污染时对其加以整治转变为将环境声音视为促进为所有年龄、性别和社会群体创造健康生活环境的机会。威尔士政府希望保留或营造积极的声景，并将声景定义为“流水声、鸟鸣声、风吹树木的声音和人类的谈话声等大自然的声音高于交通噪声的地方”。[57]

为促进积极的声景发展，同时将噪声污染控制在可接受的范围内，新方法需要考虑人们的感觉，而不仅仅是暴露于的噪声水平；这是对声音措施的补充和加强，以突出声景。尽管无声或安静对于城市公园或住宅区等一些场所是可取的，但它并不是评估所有城市空间质量的标准。我们需要一个具有声音多样性和包容性的城市，支持多种声音用途，而这单靠无声是无法实现的。

“我们需要一个具有声音多样性和包容性的城市，支持多种声音用途，而这单靠无声是无法实现的。”

在经历2019新型冠状病毒肺炎（COVID-19)大流行后，更多人认识到在自然环境中度过的时间与总体幸福感之间的关系。[97]COVID-19导致的封锁让人们对各种城市绿地产生了新的认识。[98,99]城市规划者希望在大流行后通过增加更多绿地来“重建得更好”，而且有些人对经常被忽视的贫困社区和住房边缘化群体享受这些绿地及其益处表示特别关切。[100,101]参与创建更宜居城市的决策者、城市规划者、社区成员和其他利益攸关方需要时刻考虑新建和重建场所的声音。

封锁下的声景

2019年底SARS-CoV-2病毒肆虐，世界各国政府采取了措施来遏制感染率。[88]大多数非必要的商业和社会活动暂停，当地通勤停摆，其他出行活动停止，这些都有助于减轻噪声等污染。[89]

许多研究小组和政府机构报告称噪声水平有所下降，特别是在城市地区。[90]在2020年3月17日巴黎首次封城后，通过监测发现整个道路交通网络噪声平均降低了7.6分贝。[91]戴高乐机场区域的空中交通噪声也显著下降，降幅达20.4分贝。

在马德里，由于车流量减少且街上没有行人，噪声降低了4-6分贝。[92]在针对伦敦11处场开展的一项研究中，通过比较当地封锁措施高峰期的数据，得出噪声平均降低5.4分贝。[93]在旧金山，人类噪声突然降低意味着人们可以听到更多大自然的声音，如鸟鸣。[94]在孟买，2020年COVID-19相关城市限制措施下举行象神节庆祝活动期间，对不同地点的噪声水平进行了监测。与2018年和2019年的测量值相比，噪声水平降幅介于27.5到28.5分贝。[95]这种与大流行相关的普遍安静状态可以通过地震学调查在全球范围内检测到，这些调查报告称封锁期间噪声 大幅降低。[96]

COVID-19危机对环境的长期影响尚不清楚，当前的全球研究应提供进一步洞见。人类声源的突然沉寂在学术界和公众之间引发了一场关于现代城市如何发声以及我们是否足够努力地打造积极声景的辩论。

尽管人们一致认为封锁措施施加的限制使许多城市的噪声水平有所降低，但观测到的交通噪声的最大降幅通常仍在6到10分贝之间。虽然在大多数情况下人们可以明显感受到交通噪声的降低，但降幅还不足以将噪声污染减轻到世卫组织建议的安全水平。为了改善城市的声景质量，不同的规划策略和基础设施的改变将创造更健康的声环境。

参考文献

1. World Health Organization (2018). Environmental Noise Guidelines for the European Region. *Copenhagen: WHO Regional Office for Europe*. https://www.euro.who.int/en/health-topics/environment-and-health/noise/environmental-noise-guidelines-for-the-european-region

2. European Environment Agency (2020). Environmental noise in Europe — 2020. *Luxembourg: Publications Office of the European Union*. https://doi.org/10.2800/686249

3. Francis, C.D. and Barber, J.R. (2013). A framework for understanding noise impacts on wildlife: an urgent conservation priority. Frontiers in Ecology and the Environment 11(6). https://doi.org/10.1890/120183

4. Basner, M., Brink, M., Bristow, A., de Kluizenaar, Y., Finegold, L., Hong, J. *et al.* (2015). ICBEN review of research on the biological effects of noise 2011-2014 17(75), 57-82. https://doi.org/10.4103/1463-1741.153373

5. World Health Organization (2015). Hearing loss due to recreational exposure to loud sounds: A review. *Geneva: World Health Organization*. https://www.who.int/pbd/deafness/Hearing_loss_due_to_recreational_exposure_to_loud_sounds.pdf

6. Kjellberg, A. (1990). Subjective, behavioral and psychophysiological effects of noise. *Scandinavian Journal of Work, Environment and Health* 16(suppl 1), 29-38. https://doi.org/10.5271/sjweh.1825

7. Kang, J., Aletta, F., Gjestland, T.T., Brown, L.A., Botteldooren, D., Schulte-Fortkamp, B. *et al*. (2016). Ten questions on the soundscapes of the built environment. *Building and Environment* 108, 284-294. https://doi.org/10.1016/j.buildenv.2016.08.011

8. Brown, A.L. (2010). Soundscapes and environmental noise management. *Noise Control Engineering Journal* 58(5), 493-500. https://doi.org/10.3397/1.3484178

9. Yelmi, P. (2016). Protecting contemporary cultural soundscapes as intangible cultural heritage: sounds of Istanbul. *International Journal of Heritage Studies* 22(4), 302-311. http://dx.doi.org/10.1080/13527258.2016.1138237

10. International Organization for Standardization (2014). ISO 12913-1:2014 Acoustics — Soundscape — Part 1: Definition and conceptual framework. *Geneva: ISO*.

11. Sztubecka, M., Skiba, M., Mrówczý, M. and Mathias, M. (2020). Noise as a Factor of Green Areas Soundscape Creation. *Sustainability* 12(3), 999. https://doi.org/10.3390/su12030999

12. Kang, J., and Schulte-Fortkamp, B. (eds.). (2015). Soundscape and the Built Environment. *Boca Raton: CRC Press*.

13. Brown, A.L. (2012). A Review of Progress in Soundscapes and an Approach to Soundscape Planning. *International Journal of Acoustics and Vibration,* 17(2), 73-81. http://doi.org/10.20855/ijav.2012.17.2302

14. Halperin, D. (2014). Environmental noise and sleep disturbances: A threat to health? *Sleep Science*, 7(4), 209-212. http://doi.org/10.1016/j.slsci.2014.11.003

15. Münzel, T., Gori, T., Babisch, W. and Basner, M. (2014). Cardiovascular effects of environmental noise exposure. *European Heart Journal* 35(13), 829–836. https://doi.org/10.1093/eurheartj/ehu030

16. Münzel, R., Schmidt, F.P., Steven, S., Herzog, J., Daiber, A. and Sørensen, M. (2018). Environmental Noise and the Cardiovascular System. *Journal of the American College of Cardiology*, 71(6), 688-697. https://doi.org/10.1016/j.jacc.2017.12.015

17. Bai, L., Shin, S., Oiamo, T.H., Burnett, R.T., Weichenthal, S., Jerrett, M. *et al*. (2020). Exposure to Road Traffic Noise and Incidence of Acute Myocardial Infarction and Congestive Heart Failure: A Population-Based Cohort Study in Toronto, Canada. *Environmental Health Perspectives* 128(8). https://doi.org/10.1289/EHP5809

18. Shin, S., Bai, L., Oiamo, T.H., Burnett, R.T., Weichenthal, S., Jerrett, M. *et al*. (2020). Association Between Road Traffic Noise and Incidence of Diabetes Mellitus and Hypertension in Toronto, Canada: A Population-Based Cohort Study. *Journal of the American Heart Association*, 9(6). https://doi.org/10.1161/JAHA.119.013021

19. Oh, M., Shin, K., Kim, K. and Shin, J. (2019). Influence of noise exposure on cardiocerebrovascular disease in Korea. *Science of The Total Environment*, 651, Part 2, 1867-1876. https://doi.org/10.1016/j.scitotenv.2018.10.081

20. World Health Organization (1999). Guidelines for Community Noise. *Geneva: World Health Organization*.

21. Erfanian, M., Mitchell, A.J., Kang, J. and Aletta, F. (2019). The Psychophysiological Implications of Soundscape: A Systematic Review of Empirical Literature and a Research Agenda. *International Journal of Environmental Research and Public Health*, 16(19), 3533. https://doi.org/10.3390/ijerph16193533

22. Aletta, F., Oberman, T. and Kang, J. (2018). Associations between Positive Health-Related Effects and Soundscapes Perceptual Constructs: A Systematic Review. *International Journal of Environmental Research and Public Health* 15(11), 2392. https://doi.org/10.3390/ijerph15112392

23. Andringa, T.C., and Lanser, J.J.L. (2013). How pleasant sounds promote and annoying sounds impede health: A cognitive approach. *International Journal of Environmental Research and Public Health*, 10(4), 1439-1461. https://doi.org/10.3390/ijerph10041439

24. Buxton, R.T., Pearson, A.L., Allou, C., Fristrup, K. and Wittemyer, G. (2021). A synthesis of health benefits of natural sounds and their distribution in national parks. *Proceedings of the National Academy of Sciences*, 118(14). https://doi.org/10.1073/pnas.2013097118

25. Francis, C.D., Ortega, C.P. and Cruz, A. (2011). Noise Pollution Filters Bird Communities Based on Vocal Frequency. *PLoS ONE* 6(11): e27052. https://doi.org/10.1371/journal.pone.0027052

26. Halfwerk, W., Lohr, B. and Slabbekoorn, H. (2018). Impact of Man-Made Sound on Birds and Their Songs. In *Effects of Anthropogenic Noise on Animals*. Slabbekoorn, H., Dooling, R., Popper, A., Fay, R. (eds). *Springer Handbook of Auditory Research*, 66. Springer, New York, NY. https://doi.org/10.1007/978-1-4939-8574-6_8

27. Kunc, H.P. and Schmidt, R. (2019). The effects of anthropogenic noise on animals: a meta-analysis. *Biology Letters*, 15(11). http://doi.org/10.1098/rsbl.2019.0649

28. Fuller, R.A., Warren, P.H. and Gaston, K.J. (2007). Daytime noise predicts nocturnal singing in urban robins. *Biology Letters* 3(4), 368-370. http://doi.org/10.1098/rsbl.2007.0134

29. Dorado-Correa, A.M., Rodríguez-Rocha, M. and Brumm, H. (2016). Anthropogenic noise, but not artificial light levels predicts song behaviour in an equatorial bird. *Royal Society Open Science*, 3(7). http://doi.org/10.1098/rsos.160231

30. Potvin, D.A. (2017). Coping with a changing soundscape: avoidance, adjustments and adaptations. *Animal Cognition* 20(1), 9-18. https://doi.org/10.1007/s10071-016-0999-9

31. Brumm, H. and Zollinger, S.A. (2013). Chapter 7, 187-227: Avian Vocal Production in Noise. In *Animal communication and noise*. Brumm, H. (ed.). Berlin: Springer-Verlag. https://doi.org/10.1007/978-3-642-41494-7

32. Francis, C.D., Ortega, C.P. and Cruz, A. (2011). Noise Pollution Filters Bird Communities Based on Vocal Frequency. *PLoS ONE* 6(11), 305-313. https://doi.org/10.1371/journal.pone.0027052

33. Slabbekoorn, H. and den Boer-Visser, A. (2006). Cities change the songs of birds. *Current Biology* 16(23), 2326-2331. http://doi.org/10.1016/j.cub.2006.10.008

34. Hamao, S., Watanabe, M. and Mori, Y. (2011). Urban noise and male density affect songs in the great tit *Parus major*. *Ethology Ecology & Evolution*, 23(2), 111-119. http://doi.org/10.1080/03949370.2011.554881

35. Mockford, E.J. and Marshall, R.C. (2009). Effects of urban noise on song and response behaviour in great tits. *Proceedings of the Royal Society B: Biological Sciences* 276(1669), 2979-2985. http://doi.org/10.1098/rspb.2009.0586

36. Zollinger, S.A., Slater, P.J.B., Nemeth, E. and Brumm, H. (2017). Higher songs of city birds may not be an individual response to noise. *Proceedings of the Royal Society B: Biological Sciences*, 284(1860), 20170602. http://dx.doi.org/10.1098/rspb.2017.0602

37. Potvin, D.A., Curcio, M.T., Swaddle, J.P. and MacDougall-Shackleton, S.A. (2016). Experimental exposure to urban and pink noise affects brain development and song learning in zebra finches (*Taenopygia guttata*). *PeerJ – Life and Environment,* 4. https://doi.org/10.7717/peerj.2287

38. Moseley, D.L., Derryberry, G.E., Phillips, J.N., Danner, J.E., Danner, R.M., Luther, D.A. *et al*. (2018). Acoustic adaptation to city noise through vocal learning by a songbird. *Proceedings of the Royal Society B: Biological Sciences* 285(1888). http://doi.org/10.1098/rspb.2018.1356

39. Caorsi, V.Z., Both, C., Cechin, S., Antunes, R. and Borges-Martins, M. (2017). Effects of traffic noise on the calling behavior of two Neotropical hylid frogs. *PLoS one,* 12(8). https://doi.org/10.1371/journal.pone.0183342

40. Higham, V., Deal, N.D.S., Chan, Y.K., Chanin, C., Davine, E., Gibbings, G. *et al*. (2021). Traffic noise drives an immediate increase in call pitch in an urban frog. *Journal of Zoology* 313(4). https://doi.org/10.1111/jzo.12866

41. Lampe, U., Reinhold, K. and Schmoll, T. (2014). How grasshoppers respond to road noise: developmental plasticity and population differentiation in acoustic signalling. *Functional Ecology*, 28(3), 660–668. https://doi.org/10.1111/1365-2435.12215

42. Parris, K.M., Velik-Lord, M. and North, J.M.A. (2009). Frogs call at a higher pitch in traffic noise. *Ecology and Society* 14(1), 25. http://www.ecologyandsociety.org/vol14/iss1/art25/

43. Schwela, D. (2021). Environmental noise challenges and policies in low- and middle-income countries. *South Florida Journal of Health*, 2(1). https://doi.org/10.46981/sfjhv2n1-003

44. European Parliament and Council (2002). Directive 2002/49/EC relating to the assessment and management of environmental noise. *Brussels: Publications Office of the European Union.*

45. Egypt, Ministry of Environment (2021). The National Plan to Combat Noise and Reduce its Sources. *Egyptian Environmental Affairs Agency*. https://www.eeaa.gov.eg/ar-eg/موضوعاتبيئية/الهواء/الضوضاء/خطةمكافحةالضوضاء.aspx (in Arabic). Accessed 21 September 2021.

46. Greater London Authority (2019). Central London Ultra Low Emission Zone – Four month report. *London: Greater London Authority.*

47. Transport for London (2021). Guide to ULEZ expansion. *Transport for London*. https://tfl.gov.uk/modes/driving/ultra-low-emission-zone/ulez-expansion. Accessed 21 September 2021.

48. Campello-Vicente, H., Peral-Orts, R., Campillo-Davo, N. and Velasco-Sanchez, E. (2017). The effect of electric vehicles on urban noise maps. *Applied Acoustics,* 116, 59-64. https://doi.org/10.1016/j.apacoust.2016.09.018

49. Misdariis, N. and Pardo, L.F. (2017). The sound of silence of electric vehicles – Issues and answers. *The 46th International Congress and Exposition on Noise Control Engineering (InterNoise)*. Hong-Kong, China, 27-30 August 2017. https://hal.archives-ouvertes.fr/hal-01708883

50. Neurauter, L., Roan, M., Song, M., Miller, M., Glenn, E. and Walters, J. (2020). Quiet car detectability: Impact of artificial noise on ability of pedestrians to safely detect approaching electric vehicles. *Virginia Tech*. http://hdl.handle.net/10919/97586

51. Brown, A.L., Lam, K.C. and van Kamp, I. (2015). Quantification of the exposure and effects of road traffic noise in a dense Asian city: a comparison with western cities. *Environmental Health*, 14(22). http://doi.org/10.1186/s12940-015-0009-8

52. Lam, K.C., Ma, W., Chan, P.K., Hui, W.C., Chung, K.L., Chung, Y.T. *et al*. (2013). Relationship between road traffic noisescape and urban form in Hong Kong. *Environmental Monitoring and Assessment* 185, 9683-9695. https:/doi.org/10.1007/s10661-013-3282-4

53. Cai, C., Mak, C.M. and He, X. (2019). Analysis of Urban Road Traffic Noise Exposure of Residential Buildings in Hong Kong Over the Past Decade. *Noise & Health* 21(101), 142-154. https://pubmed.ncbi.nlm.nih.gov/32719301/

54. Cheung, K.M.C., Wong, H.Y.C., Hung, W.C.T., Lau, K.K., Yim, Y.C.S. and Lee, Y.C.R. (2019). Development and application of specially designed windows and balconies for noise mitigation in Hong Kong. *Inter-Noise and Noise-Con Congress and Conference Proceedings, InterNoise19*. Madrid, Spain, September 2019. http://www.sea-acustica.es/fileadmin/INTERNOISE_2019/Fchrs/Proceedings/2101.pdf

55. China-Hong Kong, Environmental Protection Department (2020). *Environmental Noise*. https://www.epd.gov.hk/epd/noise_education/web/ENG_EPD_HTML/index/index.html Accessed 21 September 2021.

56. UN-Habitat (2020). City-wide Public Space Assessment Toolkit - A guide to community-led digital inventory and assessment of public spaces. *Nairobi: United Nations Human Settlements Programme*.

57. Wales, Ministry of Environment (2018). Noise and Soundscape Action Plan 2018-2023. *Cardiff: Ministry of Environment*. https://gov.wales/sites/default/files/publications/2019-04/noise-and-soundscape-action-plan.pdf

58. Payne, S.R. and Bruce, N. (2019). Exploring the Relationship between Urban Quiet Areas and Perceived Restorative Benefits. *International Journal of Environmental Research and Public Health,* 16(9), 1611. https://doi.org/10.3390/ijerph16091611

59. Cerwén, G. (2019). Listening to Japanese Gardens: An Autoethnographic Study on the Soundscape Action Design Tool. *International Journal of Environmental Research and Public Health* 16(23), 4648. https://doi.org/10.3390/ijerph16234648

60. European Environment Agency (2014). Good practice guide on quiet areas. *Luxembourg: Publications Office of the European Union.* https://doi.org/10.2800/12611

61. European Environment Agency (2016). Quiet Areas in Europe - The environment unaffected by noise pollution. *Luxembourg: Publications Office of the European Union*. https://doi.org/10.2800/7586

62. Kliuchko, M., Heinonen-Guzejev, M., Vuust, P., Tervaniemi, M. and Brattico, E. (2016). A window into the brain mechanisms associated with noise sensitivity. *Scientific Reports*, 6, 39236. https://doi.org/10.1038/srep39236

63. Baliatsas, C., van Kamp, I., Swart, W., Hooiveld, M. and Yzermans, J. (2016). Noise sensitivity: symptoms, health status, illness behavior and co-occurring environmental sensitivities. *Environmental Research*, 150, 8-13. https://doi.org/10.1016/j.envres.2016.05.029

64. Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S. *et al*. (2014). Auditory and non-auditory effects of noise on health. *The Lancet*, 383(9925), 1325-1332. https://doi.org/10.1016/s0140-6736(13)61613-x

65. Stansfeld, S. and Clark, C. (2015). Health Effects of Noise Exposure in Children. *Current Environmental Health Report*, 2, 171-178. https://doi.org/10.1007/S40572-015-0044-1

66. Van Kamp, I. and Davies, H. (2013). Noise and health in vulnerable groups: A review. *Noise & Health*, 15(64), 153-159. https://doi.org/10.4103/1463-1741.112361

67. Eriksson, C., Bluhm, G., Hilding, A., Östenson, C.G. and Pershagen, G. (2010). Aircraft noise and incidence of hypertension – Gender specific effects. *Environmental research*, 110(8), 764-772. https://doi.org/10.1016/j.envres.2010.09.001

68. Orban, E., McDonald, K., Sutcliffe, R., Hoffmann, B., Fuks, K.B., Dragano, N. *et al*. (2016). Residential road traffic noise and high depressive symptoms after five years of follow-up: Results from the Heinz Nixdorf recall study. *Environmental health perspectives*, 124(5), 578-585. https://doi.org/10.1289/ehp.1409400

69. Dreger, S., Schüle, S.A., Hilz, L.K. and Bolte, G. (2019). Social inequalities in environmental noise exposure: A review of evidence in the WHO European Region. *International Journal of Environmental Research and Public Health*, 16(6), 1011. https://doi.org/10.3390/ijerph16061011

70. Dale, L.M., Goudreau, S., Perron, S., Ragettli, M.S., Hatzopoulou, M. and Smargiassi, A. (2015). Socioeconomic status and environmental noise exposure in Montreal, Canada. *BMC Public Health*, 15(1), 1-8. https://doi.org/10.1186/s12889-015-1571-2

71. Taylor, D.E. (2014). Toxic Communities: Environmental Racism, Industrial Pollution, and Residential Mobility. *NYU Press*. https://www.jstor.org/stable/24889758

72. Hajat, A., Hsia, C. and O'Neill, M.S. (2015). Socioeconomic disparities and air pollution exposure: a global review. *Current Environmental Health Reports*, 2(4), 440-450. https://doi.org/10.1007/s40572-015-0069-5

73. Casey, J.A., Morello-Frosch, R., Mennitt, D.J., Fristrup, K., Ogburn, E.L. and James, P. (2017). Race/ethnicity, socioeconomic status, residential segregation, and spatial variation in noise exposure in the contiguous United States. *Environmental Health Perspectives*, 125(7), 077017. https://doi.org/10.1289/EHP898

74. Choi, E., Bhandari, T.R. and Shrestha, N. (2020). Social inequality, noise pollution, and quality of life of slum dwellers in Pokhara, Nepal. *Archives of Environmental & Occupational Health*, 1-12. https://doi.org/10.1080/19338244.2020.1860880

75. Hoffimann, E., Barros, H. and Ribeiro, A.I. (2017). Socioeconomic inequalities in green space quality and accessibility – Evidence from a Southern European city. *International Journal of Environmental Research and Public Health*, 14(8), 916. https://doi.org/10.3390/ijerph14080916

76. Kohlhuber, M., Mielck, A., Weiland, S.K. and Bolte, G. (2006). Social inequality in perceived environmental exposures in relation to housing conditions in Germany. *Environmental Research*, 101(2), 246-255. https://doi.org/10.1016/j.envres.2005.09.008

77. Lam, K.C. and Chan, P.K. (2008). Socio-economic status and inequalities in exposure to transportation noise in Hong Kong. *Open Environmental Sciences Journal*, 2(1), 107-113. http://doi.org/10.2174/1876325100802010107

78. Nega, T.H., Chihara, L., Smith, K. and Jayaraman, M. (2013). Traffic noise and inequality in the twin cities, Minnesota. *Human and Ecological Risk Assessment: An International Journal*, 19(3), 601-619. https://doi.org/10.1080/10807039.2012.691409

79. Verbeek, T. (2019). Unequal residential exposure to air pollution and noise: A geospatial environmental justice analysis for Ghent, Belgium. *SSM-Population Health*, 7, 100340. https://doi.org/10.1016/j.ssmph.2018.100340

80. World Health Organization (2016). Urban green spaces and health. *Copenhagen: WHO Regional Office for Europe*. https://www.euro.who.int/en/health-topics/environment-and-health/urban-health/publications/2016/urban-green-spaces-and-health-a-review-of-evidence-2016

81. Casey, J.A, James, P., Cushing, L., Jesdale, B.M. and Morello-Frosch, R. (2017). Race, Ethnicity, Income Concentration and 10-Year Change in Urban Greenness in the United States. *International Journal of Environmental Research and Public Health* 14(12), 1546. https://doi.org/10.3390/ijerph14121546

82. De Vries, S., Buijs, A.E. and Snep, R.P. (2020). Environmental Justice in The Netherlands: Presence and Quality of Greenspace Differ by Socioeconomic Status of Neighbourhoods. *Sustainability* 12(15), 5889. https://doi.org/10.3390/su12155889

83. Mitchell, R.J., Richardson, E.A., Shortt, N.K. and Pearce, J.R. (2015). Neighborhood Environments and Socioeconomic Inequalities in Mental Well-Being. *American Journal of Preventive Medicine* 49(1), 80-84. https://doi.org/10.1016/j.amepre.2015.01.017

84. Wolch, J.R., Byrne, J. and Newell, J.P. (2014). Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. *Landscape and Urban Planning,* 125, 234-244. https://doi.org/10.1016/j.landurbplan.2014.01.017

85. Bild, E., Coler, M., Pfeffer, K., and Bertolini, L. (2016). Considering sound in planning and designing public spaces: A review of theory and applications and a proposed framework for integrating research and practice. *Journal of Planning Literature,* 31(4), 419-439. http://doi.org/10.1177/0885412216662001

86. Lam, K.C., Ma, W., Chan, P.K., Hui, W.C., Chung, K.L., Chung, Y.T. *et al*. (2013). Relationship between road traffic noisescape and urban form in Hong Kong. *Environmental Monitoring and Assessment,* 185(12), 9683-9695. https://doi.org/10.1007/s10661-013-3282-4

87. Van Renterghem, T., Dekoninck, L. and Botteldooren, D. (2020). Multi-stage sound planning methodology for urban redevelopment. *Sustainable Cities and Society,* 62, 102362. https://doi.org/10.1016/j.scs.2020.102362

88. Brown, A.L. and Horton, R. (2020). A planetary health perspective on COVID-19: a call for papers. *The Lancet,* 395(10230). http://doi.org/10.1016/S0140-6736(20)30742-X

89. Dutheil, F., Baker, J.S. and Navel, V. (2020). COVID-19 as a factor influencing air pollution? *Environmental pollution*, 263. http://doi.org/10.1016/j.envpol.2020.114466

90. Asensio, C., Aumond, P., Can, A., Gascó, L., Lercher, P., Wunderli, J.M. *et al*. (2020). A Taxonomy Proposal for the Assessment of the Changes in Soundscape Resulting from the COVID-19 Lockdown. *International Journal of Environmental Research and Public Health,* 17(12), 4205. https://doi.org/10.3390/ijerph17124205

91. Bruitparif (2020). *Les effets du confinement sur l'environnement sonore au sein de la zone dense francilienne*. 11 mai 2020. https://www.bruitparif.fr/bruitparif/

92. Asensio, C., Pavón, I. and de Arcas, G. (2020). Changes in noise levels in the city of Madrid during COVID-19 lockdown in 2020. *Journal of the Acoustical Society of America,* 148(3), 1748-1755. https://doi.org/10.1121/10.0002008

93. Aletta, F., Oberman, T., Mitchell, A., Tong, H., and Kang, J. (2020). Assessing the changing urban sound environment during the COVID-19 lockdown period using short-term acoustic measurements. *Noise Mapping* 7(1), 123-134. https://doi.org/10.1515/noise-2020-0011

94. Derryberry, E.P., Phillips, J.N., Derryberry, G.E., Blum, M.J., and Luther, D. (2020). Singing in a silent spring: Birds respond to a half-century soundscape reversion during the COVID-19 shutdown. *Science,* 370(6516), 575-579. https://doi.org/10.1126/science.abd5777

95. Kalawapudi, K., Singh, T., Vijay, R., Goyal, N. and Kumar, R. (2020). Effects of COVID-19 pandemic on festival celebrations and noise pollution levels. *Noise Mapping* 8, 89-93. https://doi.org/10.1515/noise-2021-0006

96. Lecocq, T., Hicks, S.P., Van Noten, K., Van Wijk, K., Koelemeijer, P., De Plaen *et al*. (2020). Global quieting of high-frequency seismic noise due to COVID-19 pandemic lockdown measures. *Science*, 369(6509), 1338-1343. https://doi.org/10.1126/science.abd2438

97. Frumkin, H. (2021). COVID-19, the Built Environment, and Health. *Environmental Health Perspectives*, 129(7), 075001. https://doi.org/10.1289/EHP8888

98. Berdejo Espinola, V., Suárez Castro, A.F., Amano, T., Fielding, K.S., Oh, R.R.Y., and Fuller, R.A. (2021). Urban green space use during a time of stress: A case study during the COVID-19 pandemic in Brisbane, Australia. *People and Nature*. https://doi.org/10.1002/pan3.10218

99. Ugolini, F., Massetti, L., Calaza-Martínez, P., Cariñanos, P., Dobbs, C., Ostoić, S.K. *et al*. (2020). Effects of the COVID-19 pandemic on the use and perceptions of urban green space: An international exploratory study. *Urban Forestry & Urban Greening*, 56, 126888. https://doi.org/10.1016/j.ufug.2020.126888

100. Geary, R.S., Wheeler, B., Lovell, R., Jepson, R., Hunter, R., and Rodgers, S. (2021). A call to action: Improving urban green spaces to reduce health inequalities exacerbated by COVID-19. *Preventive Medicine*, 145, 106425. https://doi.org/10.1016/j.ypmed.2021.106425

101. Mell, I. and Whitten, M. (2021). Access to nature in a post Covid-19 world: Opportunities for green infrastructure financing, distribution and equitability in urban planning. *International Journal of Environmental Research and Public Health*, 18(4), 1527. https://doi.org/10.3390/ijerph18041527

图表参考文献

噪声测量

Encyclopedia Britannica. (2021). The decibel scale. https://www.britannica.com/science/sound-physics/The-decibel-scale Accessed 30 December 2021

Hearing Health Foundation. (2021). What are safe decibels? https://hearinghealthfoundation.org/keeplistening/decibels Accessed 31 August 2021.

Münzel, T., Sørensen, M., Gori, T., Schmidt, F.P., Rao, X., Brook, J. *et al.* (2017). Environmental stressors and cardio-metabolic disease: part I-epidemiologic evidence supporting a role for noise and air pollution and effects of mitigation strategies. European Heart Journal 38(8), 550-556. https://doi.org/10.1093/eurheartj/ehw269

声音测试：城市有多嘈杂?

非洲

尼日利亚阿布贾 – 阿尔及利亚阿尔及尔 – 加纳海岸角 -尼日利亚伊巴丹 – 坦桑尼亚莫罗戈罗 – 肯尼亚内罗毕

Schwela, D. (2021). Environmental noise challenges and policies in low-and middle-income countries. *South Florida Journal of Health* 2(1), 26-45. https://doi.org/10.46981/sfjhv2n1-003

埃及开罗

Abas, S. and Tamura, A. (2003). Analysis of road traffic noise level and control in Greater Cairo, Egypt. *Acoustical Science and Technology* 24(6), 358-364. https://doi.org/10.1250/ast.24.358

北美洲

美国亚特兰大、美国洛杉矶

Lee, E. Y., Jerrett, M., Ross, Z., Coogan, P. F. and Seto, E. Y. (2014). Assessment of traffic-related noise in three cities in the United States. *Environmental Research* 132, 182-189. https://doi.org/10.1016/j.envres.2014.03.005

加拿大蒙特利尔

Ragettli, M. S., Goudreau, S., Plante, C., Fournier, M., Hatzopoulou, M., Perron, S. *et al.* (2016). Statistical modeling of the spatial variability of environmental noise levels in Montreal, Canada, using noise measurements and land use characteristics. *Journal of Exposure Science & Environmental Epidemiology* 26(6), 597-605. https://doi.org/10.1038/jes.2015.82

美国纽约

McAlexander, T.P., Gershon, R.R. and Neitzel, R.L. (2015). Street-level noise in an urban setting: assessment and contribution to personal exposure. *Environmental Health* 14(1), 1-10. https://doi.org/10.1186/s12940-015-0006-y

Neitzel, R.L., Gershon, R.R.M., McAlexander, T.P., Magda, L.A. and Pearson, J.M. (2012). Exposures to Transit and Other Sources of Noise among New York City Residents. *Environmental Science and Technology* 46(1), 500–508. https://doi.org/10.1021/es2025406

United States of America, Department of Commerce (2019). *Commuting by public transportation in the United States: 2019.* American Community Survey Reports. U.S. Census Bureau. https://www.census.gov/content/dam/Census/library/publications/2021/acs/acs-48.pdf

美国圣地亚哥

San Diego County Government (2015). Noise Element. City of San Diego General Plan, 29 June. https://www.sandiego.gov/planning/programs/genplan. Accessed 7 July 2021

加拿大多伦多

16. Bai *et al.* 2020

17. Shin *et al.* 2020

Drudge, C., Johnson, J., MacIntyre, E., Li, Y., Copes, R., Ing, S. *et al*. (2018). Exploring night-time road traffic noise: A comprehensive predictive surface for Toronto, Canada. *Journal of Occupational and Environmental Hygiene* 15(5), 389-398. https://doi.org/10.1080/15459624.2018.1442006

拉丁美洲

哥伦比亚波哥大-墨西哥巴亚尔塔港

Schwela, D. (2021). Environmental noise challenges and policies in low-and middle-income countries. *South Florida Journal of Health* 2(1), 26-45. https://doi.org/10.46981/sfjhv2n1-003

29. Dorado-Correa *et al.* (2016)

智利圣地亚哥

Suárez, E. and Barros, J.L. (2014). Traffic noise mapping of the city of Santiago de Chile. *Science of the Total Environment* 466, 539-546. https://doi.org/10.1016/j.scitotenv.2013.07.013

智利塔尔卡

Calquín, F., Ponce-Donoso, M., Vallejos-Barra, Ó. and Plaza, E. (2019). Influence of urban trees on noise levels in a central Chilean city. *Revista de la Facultad de Ciencias Agrarias UNCuyo* 51(1), 41-53. https://revistas.uncu.edu.ar/ojs3/index.php/RFCA/article/view/2336/1709

欧洲

西班牙巴塞罗那

2. European Environment Agency (2020)

Lagonigro, R., Martori, J. C. and Apparicio, P. (2018). Environmental noise inequity in the city of Barcelona. *Transportation Research Part D: Transport and Environment* 63, 309-319. https://doi.org/10.1016/j.trd.2018.06.007

塞尔维亚贝尔格莱德

Paunović, K., Belojević, G. and Jakovljević, B. (2014). Noise annoyance is related to the presence of urban public transport. *Science of the Total Environment* 481, 479-487. https://doi.org/10.1016/j.scitotenv.2014.02.092

英国伦敦

Smith, R.B., Beevers, S.D., Gulliver, J., Dajnak, D., Fecht, D., Blangiardo, M. *et al.* (2020). Impacts of air pollution and noise on risk of preterm birth and stillbirth in London. *Environment International* 134, 105290. https://doi.org/10.1016/j.envint.2019.105290

法国里昂

Pierrette, M., Marquis-Favre, C., Morel, J., Rioux, L., Vallet, M., Viollon, S. *et al.* (2012). Noise annoyance from industrial and road traffic combined noises: A survey and a total annoyance model comparison. *Journal of Environmental Psychology* 32(2), 178-186. https://doi.org/10.1016/j.jenvp.2012.01.006

西班牙马德里

Linares, C., Culqui, D., Carmona, R., Ortiz, C. and Díaz, J. (2017). Short-term association between environmental factors and hospital admissions due to dementia in Madrid. *Environmental Research* 152, 214-220. https://doi.org/10.1016/j.envres.2016.10.020

塞尔维亚尼什

Prascevic, M.R., Mihajlov, D.I. and Cvetkovic, D.S. (2014). Measurement and evaluation of the environmental noise levels in the urban areas of the city of Nis (Serbia). *Environmental Monitoring and Assessment* 186(2), 1157-1165. https://doi.org/10.1007/s10661-013-3446-2

法国巴黎

Méline, J., Van Hulst, A., Thomas, F., Karusisi, N. and Chaix, B. (2013). Transportation noise and annoyance related to road traffic in the French RECORD study. *International Journal of Health Geographics* 12(1), 1-13. https://doi.org/10.1186/1476-072X-12-44

意大利罗马

Ancona, C., Badaloni, C., Mattei, F., Cesaroni, G., Stafoggia, M. and Forastiere, F. (2017). 2053-Health impact assessment of air pollution, noise, and lack of green in Rome. *Journal of Transport & Health* 5, S42-S43. https://doi.org/10.1016/j.jth.2017.05.331

瑞典斯德哥尔摩

Edqvist, M. and Wärnsby, M. (2014). Environmental Noise in Urban Areas - Moving towards Greater Acceptance?. *Noise & Vibration Worldwide*, 45(2). https://doi.org/10.1260%2F0957-4565.45.2.25

阿尔巴尼亚地拉那

Laze, K. (2017). Findings from measurements of noise levels in indoor and outdoor environments in an expanding urban area: a case of Tirana. *Noise Mapping* 4(1), 45-56. https://doi.org/10.1515/noise-2017-0003

土耳其托卡特

Ozer, S., Yilmaz, H., Yeşil, M. and Yeşil, P. (2009). Evaluation of noise pollution caused by vehicles in the city of Tokat, Turkey. *Scientific Research and Essays* 4(11), 1205-1212. https://academicjournals.org/journal/SRE/article-abstract/5C0659218851

西亚

伊朗阿瓦士

Mohammadi, M. J., Charkhloo, E., Geravandi, S., Takdastan, A., Rahimi, S., Yari, A. R. *et al.* (2017). Road traffic noise in urban environments in Ahvaz city, Iran. *Fresenius Environmental Bulletin* 26(4), 2746-2751. https://core.ac.uk/download/pdf/211573334.pdf

约旦安曼

Jamrah, A., Al-Omari, A. and Sharabi, R. (2006). Evaluation of traffic noise pollution in Amman, Jordan. *Environmental Monitoring and Assessment* 120(1), 499-525. https://doi.org/10.1007/s10661-005-9077-5

黎巴嫩贝鲁特-叙利亚大马士革-伊朗大不里士

43. Schwela, D. (2021).

伊拉克埃尔比勒

Saber, S. (2014). Environmental noise with solutions: A case study. *International Journal of Advanced and Applied Sciences* 1(2), 6-14. http://www.science-gate.com/IJAAS/V1I2.html

希伯伦

Salhab, Z. and Amro, H. (2012). Evaluation Of Vehicular Noise Pollution In The City Of Hebron, Palestine. *International Journal of Modern Engineering Research* 2(6), 4307-4310. https://www.semanticscholar.org/paper/Evaluation-Of-Vehicular-Noise-Pollution-In-The-City-Salhab-Amro/1b657b61eeee5caffeab7b7a98f8fbe5b9c750f6

约旦伊尔比德

Odat, S.A. (2015). Noise Pollution in Irbid City-Jordan. *Fluctuation and Noise Letters* 14(04), 1550037. https://doi.org/10.1142/S0219477515500376

南亚

印度阿三索尔

Banerjee, D. and Chakraborty, S.K. (2021). Monthly variation in night time noise levels at residential areas of Asansol city (India). Journal of Environmental Science & Engineering 48(1), 39-44. https://pubmed.ncbi.nlm.nih.gov/17913200

斯里兰卡科伦坡

Nagodawithana, N. S., Pathmeswaran, A., Pannila, A. S., Wickramasinghe, A. R. and Sathiakumar, N. (2016). Environmental pollution by traffic noise in the city of Colombo, Sri Lanka. *Asian Journal of Water, Environment and Pollution* 13(3), 67-72. https://doi.org/10.3233/AJW-160028

印度德里

Akhtar, N., Ahmad, K. and Gangopadhyay, S. (2012). Road traffic noise mapping and a case study for Delhi region. *International Journal of Applied Engineering and Technology* 2(4), 39-45. https://www.cibtech.org/J-ENGINEERING-TECHNOLOGY/PUBLICATIONS/2012/Vol_2_No_4/06-015...Nasim...Road...Region...39-45.pdf

孟加拉国达卡

Riyad, R.H., Amin, A. and Mazumder, M. (2020). A Study of Noise Pollution by Traffic during Peak and Off Peak Hour in Dhaka City. *Journal of Innovations in Civil Engineering and Technology*, 2(2), 43-53. https://dergipark.org.tr/en/pub/jiciviltech/issue/58477/787543

巴基斯坦费萨拉巴德-巴基斯坦伊斯兰堡-巴基斯坦卡拉奇

Rahman Farooqi, Z. U., Nasir, M. S., Nasir, A., Zeeshan, N., Ayub, I., Rashid, H. *et al.* (2017). Evaluation and analysis of traffic noise in different zones of Faisalabad–an industrial city of Pakistan. *Geology, Ecology, and Landscapes* 1(4), 232-240. https://doi.org/10.1080/24749508.2017.1389454

印度斋浦尔

Agarwal, S. and Swami, B. L. (2010). Status of ambient noise levels in Jaipur City. *Environment Conservation Journal* 11(1-2), 105-108. https://environcj.in/wp-content/uploads/issues/2010/12/105-108.pdf

尼泊尔加德满都

43. Schwela, D. (2021).

印度加尔各答

Buragohain, D. (2020). A report on noise level status in different areas of South Kolkata, India. International Research Journal of Modernization in En-gineering Technology and Science 2(3), 395-398. https://www.irjmets.com/uploadedfiles/paper/volume2/issue_3_march_2020/249/1628082963.pdf

印度莫拉达巴德

Chauhan, A., Pawar, M., Kumar, D., Kumar, N. and Kumar, R. (2010). Assessment of Noise Level Status in Different Areas of Moradabad City. Report and Opinion 2(5), 59-61. https://doi.org/10.7537/marsroj020510.10

孟加拉国拉杰沙希

Bari, M.N., Biswas, A. and Baki, A.A. (2018). *Conference*: *Determination of Noise Level of Different Places of Rajshahi City*. Khulna, 9-11 February 2018. Khulna University of Engineering & Technology, Bangladesh

孟加拉国坦盖尔

Hoque, M. M. M., Basak, L. K., Rokanuzzaman, M. and Roy, S. (2013). Level of noise pollution at different locations in Tangail municipal area, Bangladesh. *Bangladesh Journal of Scientific Research* 26(1-2), 29-36. https://doi.org/10.3329/bjsr.v26i1-2.20228

东亚、东南亚和太平洋地区

新西兰奥克兰

Auckland Council (2016). Noise and vibration, 8 July. https://unitaryplan.aucklandcouncil.govt.nz/HTMLSept/Part%203/Chapter%20H/6%20General/Chapter%20H%20-%206.2%20Noise%20and%20vibration.htm. Accessed 7 July 2021

泰国曼谷-马来西亚哥打巴鲁-马来西亚吉隆坡

Schwela, D. (2021). Environmental noise challenges and policies in low-and middle-income countries. *South Florida Journal of Health* 2(1), 26-45. https://doi.org/10.46981/sfjhv2n1-003

中国香港

52. Lam *et al.* (2013)

53. Cai *et al.* (2019)

Lam, K.C. and Chan, P.K. (2008). Socio-economic status and inequalities in exposure to transportation noise in Hong Kong. *Open Environmental Sciences Journal* 2(1). https:/doi.org/10.2174/1876325100802010107

To, W. M., Mak, C. M. and Chung, W. L. (2015). Are the noise levels acceptable in a built environment like Hong Kong? *Noise & Health* 17(79), 429. https://doi.org/10.4103/1463-1741.169739

越南河内-越南胡志明市

Nguyen, T.L., Nguyen, H.Q., Yano, T., Nishimura, T., Sato, T. Morihara, T. et al. (2012). Comparison of models to predict annoyance from combined noise in Ho Chi Minh City and Hanoi. *Applied Acoustics* 73(9), 952-959. https://doi.org/10.1016/j.apacoust.2012.04.005

越南顺化

Gelb, J. and Apparicio, P. (2019). Noise exposure of cyclists in Ho Chi Minh City: A spatio-temporal analysis using non-linear models. *Applied Acoustics* 148, 332–343. https://doi.org/10.1016/j.apacoust.2018.12.031

Nguyen, M. K. (2014). Community response to road traffic noise in Hue City, Vietnam. *Environment and Natural Resources J* 12(2), 24-28. https://ssrn.com/abstract=3237251

Ky, N.M., Lap, B.Q., Hung, N.T.Q., Thanh, L.M. and Linh, P.G. (2021). Investigation and assessment of road traffic noise: a case study in Ho Chi Minh City, Vietnam. *Water, Air, & Soil Pollution* 232, 259. https://doi.org/10.1007/s11270-021-05210-3

印度尼西亚雅加达

Prasetyo, S., Kusnoputranto, H., Alikodra, H. and Koestoer, R. (2016). Model of noise propagation in urban area: A case study in Jakarta. *OIDA International Journal of Sustainable Development* 9(02), 45-50. https://ssrn.com/abstract=2739810

菲律宾马尼拉

Dulay, L.E.R., Galvan, M.D.K.P., Puyaoan, R.J.M., Sison, A.A.Y., Natanauan, N.S. and Hernandez, P.M.R. (2018). Occupational noise exposure of traffic enforcers in selected streets in the city of Manila. *Acta Medica Philippina* 52(3). https://doi.org/10.47895/amp.v52i3.406

澳大利亚墨尔本

Hanigan, I. C., Chaston, T. B., Hinze, B., Dennekamp, M., Jalaludin, B., Kinfu, Y. *et al*. (2019). A statistical downscaling approach for generating high spatial resolution health risk maps: a case study of road noise and ischemic heart disease mortality in Melbourne, Australia. *International Journal of Health Geographics* 18(1), 1-10. https://doi.org/10.1186/s12942-019-0184-x

声景管理：从噪声缓解到理想声景

景观和声音

Ratcliffe, E. (2021). Sound and soundscape in restorative natural environments. *Frontiers in Psychology* 12:570563. https://doi.org/10.3389/fpsyg.2021.570563

绿色解决方案

Van Renterghem, T. (2019). Towards explaining the positive effect of vegetation on the perception of environmental noise. *Urban Forestry & Urban Greening* 40. https://doi.org/10.1016/j.ufug.2018.03.007

声景

Brown, L. A. (2012). A Review of Progress in Soundscapes and an Approach to Soundscape Planning. *International Journal of Acoustics and Vibration* 17(2), 73-81. https://doi.org/10.20855/ijav.2012.17.2302

Epstein, M.J. (2019). Healing the urban soundscape: reflections and reverberations. *Cities & Health* 5, 74-81. https://doi.org/10.1080/23748834.2019.1676628

Kang, J., Aletta, F., Gjestland, T.T., Brown, L.A., Botteldooren, D., Schulte-Fortkamp, B., Lercher, P. et al. (2016). Ten questions on the soundscapes of the built environment. *Building and Environment* 108, 284-294. https://doi.org/10.1016/j.buildenv.2016.08.011

Sztubecka, M., Skiba, M., Mrówczy´, M. and Mathias, M. (2020). Noise as a Factor of Green Areas Soundscape Creation. *Sustainability* 12, 999. https://doi.org/10.3390/su12030999

树带

Van Renterghem, T. (2014). Guidelines for optimizing road traffic noise shielding by non-deep tree belts. *Ecological Engineering* 69, 276-286. http://dx.doi.org/10.1016/j.ecoleng.2014.04.029

绿色屋顶

Nilsson, M., Klæboe, R., Bengtsson, J., Forssén, J., Hornikx, M., Van der Aa, B., Rådsten-Ekman, M. *et al.* (2013). Novel solutions for quieter and greener cities. Report of the research project "HOlistic and Sustainable Abatement of Noise by optimized combinations of Natural and Artificial means" (HOSANNA). Chalmers University of Technology. https://research.chalmers.se/en/publication/208780

电动汽车

Campello-Vicente, H., Peral-Orts, R., Campillo-Davo, N. and Velasco-Sanchez, E., (2017). The effect of electric vehicles on urban noise maps. *Applied Acoustics*, 116. http://dx.doi.org/10.1016/j.apacoust.2016.09.018

Cesbron, J., Bianchetti, S., Pallas, M-A., Le Bellec, A., Gary, V. and Klein, P. (2021). Road surface influence on electric vehicle noise emission at urban speed. *Noise Mapping* 8(1), 217-227. https://doi.org/10.1515/noise-2021-0017

途径干预

Brown, A.L. and van Kamp, I. (2017). WHO Environmental Noise Guidelines for the European Region: A Systematic Review of Transport Noise Interventions and Their Impacts on Health. *International Journal of Environmental Research and Public Health* 14, 873. https://doi.org/10.3390/ijerph14080873

源头减轻措施

Nilsson, M., Klæboe, R., Bengtsson, J., Forssén, J., Hornikx, M., Van der Aa, B., Rådsten-Ekman, M. *et al.* (2013). Novel solutions for quieter and greener cities. Report of the research project "HOlistic and Sustainable Abatement of Noise by optimized combinations of Natural and Artificial means" (HOSANNA). Chalmers University of Technology. https://research.chalmers.se/en/publication/208780

隔音屏障

European Environment Agency (2020). Environmental noise in Europe — 2020. *Luxembourg: Publications Office of the European Union*. https://doi.org/10.2800/686249

植被隔音屏障

Nilsson, M., Klæboe, R., Bengtsson, J., Forssén, J., Hornikx, M., Van der Aa, B., Rådsten-Ekman, M. *et al.* (2013). Novel solutions for quieter and greener cities. Report of the research project "HOlistic and Sustainable Abatement of Noise by optimized combinations of Natural and Artificial means" (HOSANNA). Chalmers University of Technology. https://research.chalmers.se/en/publication/208780

Van Renterghem, T., Forssén, J., Attenborough, K., Jean, P., Defrance, J., Hornikx, M. and Kang, J. (2015). Using natural means to reduce surface transport noise during propagation outdoors. *Applied Acoustics*, 92. http://dx.doi.org/10.1016/j.apacoust.2015.01.004

生态系统服务

Bratman, G.N., Hamilton, J.P. and Daily, G.C. (2012). The impacts of nature experience on human cognitive function and mental health. *Annals of the New York Academy of Sciences* 1249(1), 118-136. http://doi.org/10.1111/j.1749-6632.2011.06400.x

Francis, C.D., Newman, P., Taff, B.D., White, C., Monz, C.A., Levenhagen, M. *et al.* (2017). Acoustic environments matter: Synergistic benefits to humans and ecological communities. *Journal of Environmental Management* 203, 245-254. http://doi.org/10.1016/j.jenvman.2017.07.041

Ratcliffe, E. (2021). Sound and soundscape in restorative natural environments. *Frontiers in Psychology* 12:570563. https://doi.org/10.3389/fpsyg.2021.570563

Veisten, K., Smyrnova, Y., Klæboe, R., Hornikx, M., Mosslemi, M. and Kang, J. (2012). Valuation of Green Walls and Green Roofs as Soundscape Measures: Including Monetised Amenity Values Together with Noise-attenuation Values in a Cost-benefit Analysis of a Green Wall Affecting Courtyards. *International Journal of Environmental Research and Public Health* 9, 3770-3788. https://doi.org/10.3390/ijerph9113770

绿地

Alvarsson, J.J., Wiens, S. and Nilsson, M.E. (2010). Stress recovery during exposure to nature sound and environmental noise. *International Journal of Environment & Public Health* 7, 1036–1046. https://doi.org/10.3390/ijerph7031036

Van Renterghem, T. (2019). Towards explaining the positive effect of vegetation on the perception of environmental noise. *Urban Forestry & Urban Greening* 40. https://doi.org/10.1016/j.ufug.2018.03.007

安静的空间

Cerwén, G. (2019). Listening to Japanese Gardens: An Autoethnographic Study on the Soundscape Action Design Tool. *International Journal of Environmental Research and Public Health* 16(23), 4648; https://doi.org/10.3390/ijerph16234648

Matsinos, G.Y., Tsaligopoulos, A. and Economou, C. (2017). Identifying the Quiet Areas of a Small Urban Setting: The Case of Mytilene. *Global NEST Journal* 19, 674–681. https://doi.org/10.30955/gnj.001817

场所创造

Yelmi, P. (2016). Protecting contemporary cultural soundscapes as intangible cultural heritage: sounds of Istanbul. *International Journal of Heritage Studies* 22(4), 302-311. http://dx.doi.org/10.1080/13527258.2016.1138237

气候变化引发的野火

迫在眉睫的问题

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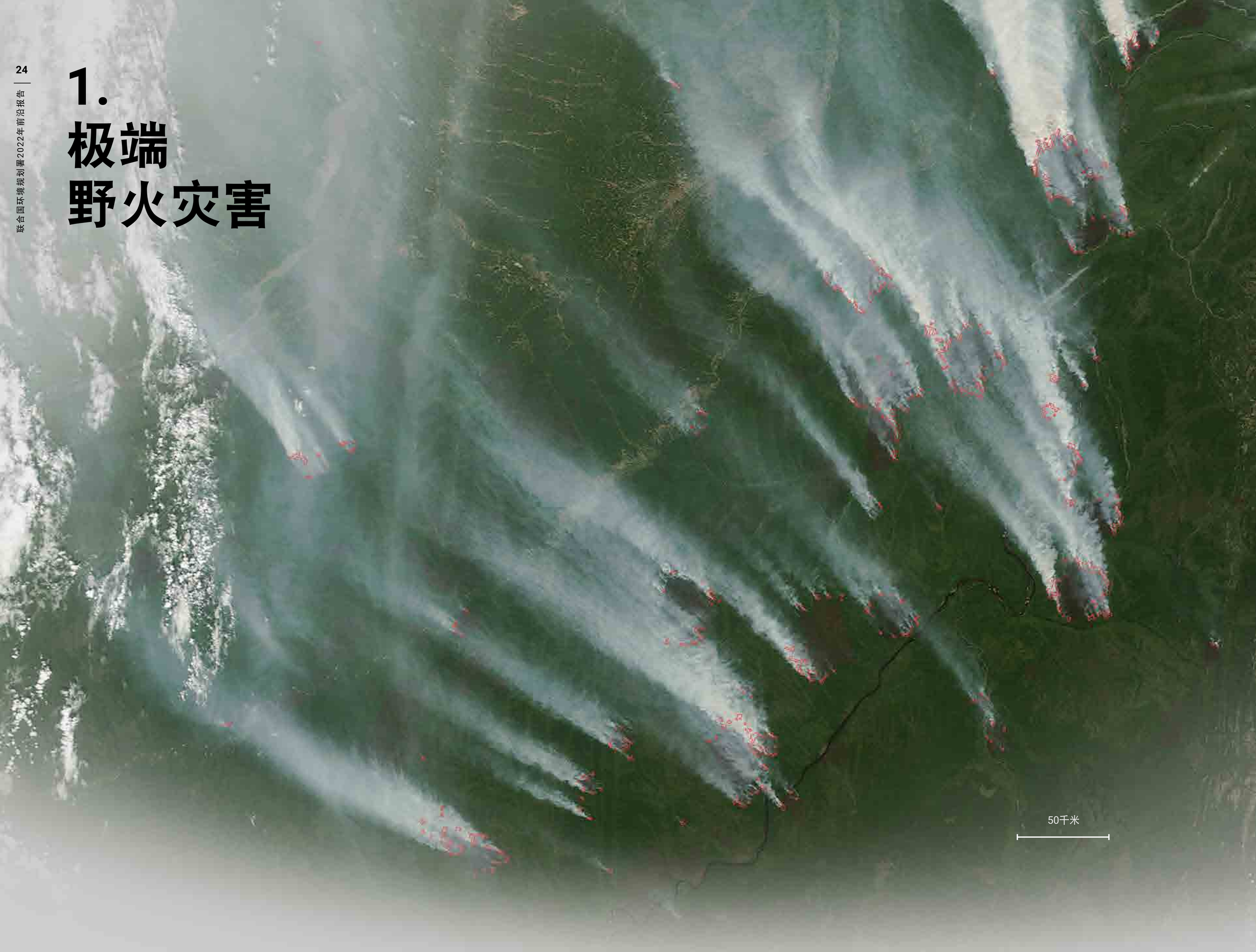
1. 极端野火灾害



2012年7月11日，俄罗斯西伯利亚中部和东部共有25,000多公顷的北方森林被烧毁。野火从西部尤格拉一路失控蔓延至东部库页岛。这张卫星图像显示了2012年7月10日雅库特阿尔丹河附近的熊熊大火。

来源： 美国国家航空和航天局地球观测站

近年来，继热浪和干旱之后，全球许多区域都发生了毁灭性的野火。许多新闻报道都关注了北半球野火摧毁城镇的事件，如2020年美国西部重大火灾季节的野火。[1] 2021年希腊埃维厄岛的大规模撤离景象令人难忘，研究人员认为地中海国家将更频繁地发生这种事件。[2]

灾难性的野火也在全球南方肆虐。2019至2020年，澳大利亚遭遇了被称为“黑色夏天”的史无前例的火灾，新闻报道和令人震惊的图片传遍全球。[3]尽管澳大利亚在许多方面都受到火灾影响，但“黑色夏天”火灾的规模和强度之大使得人们开始关注全球变暖如何增加野火风险。[4-7]大火烧毁了2,400多万公顷土地和数千座房屋，并导致33人丧生。[3] 2019至2020年的大火摧毁了数百种物种的重要生境，包括那些已经濒临灭绝的物种。[8]

近几十年来，拉丁美洲的热带草原和热带雨林很快被大面积砍伐，再加上干旱和现有火灾管理政策的局限性，导致发生了多起灾难性野火。[9-11]2019年，玻利维亚、巴西、哥伦比亚、巴拉圭和秘鲁的奇基塔尼亚、塞拉多和亚马逊地区有600多万公顷的土地被烧毁，其中大部分在原生植被保护区内。[12,13]在2020年的旱季期间，又一波漫长且具有破坏性的野火席卷了该地区。[14,15]在整个非洲，全年都可以通过卫星图像观测到火灾，导致观测和监测记录中有大面积的烧毁区域。[1]

> “据观察，由于大气温室气体浓度上升以及风险因素升级，预计更危险的野火天气条件会日趋恶化。”

就各大陆和生物群落而言，这些极端野火事件在潜在风险因素、危害以及对社会和环境的影响等方面存在相似之处。对身心健康的长期影响不仅局限于负责灭火、疏散或遭受重大损失的人员。[16-20]野火产生的烟雾和颗粒物会对下风口居住区（有时距离火源数千公里远）居民的健康造成重大影响。[21-23]研究表明，妇女、儿童、老年人、残疾人和贫困人口这些最脆弱群体因暴露于野火而遭受的持续损害最为严重，这一结果与大众观念一致，即这也是大多数灾难的普遍结果。[24,25]

据观察，由于大气温室气体浓度上升以及随之而来的极端野火风险因素升级，发生野火的更危险的火灾天气条件可能会日趋恶化。[4,6,26-34]除气候变化外，由于土地利用变化和火灾管理方法不注重植被和火灾之间经数千年演变的密切关系，可能会导致一些野火愈发严重。[11,35-38]

气候变暖会延长火灾季节并可能导致自然起火事件增加，土地利用变化会增加可燃燃料和起火风险，越来越多的社区建设在野地-城区结合部，在这些因素的共同作用下，我们在进一步了解如何与我们所处的生态系统中的火灾因素共处时面临重大挑战。

过去二十年内的过火面积

该图表根据美国国家航空航天局中分辨率成像光谱仪(MODIS) 获取的遥感数据集，绘制了2000年至2021年3月的全球过火面积图。

从2002年到2016年，每年约4.23亿公顷的地球陆地表面被烧毁，其中大部分(67%)在非洲大陆。[39] 一项相关分析估计，从2003年到2016年，全球共发生了1,300多万起火灾，每起持续4-5天。[15] 全球每起火灾烧毁面积平均达440公顷，而在澳大利亚，每起火灾烧毁面积达1,790公顷。[15]

数据涵盖观测到的农田、牧场和天然植被等各类烧毁区域，不论火源、火灾类型或起火原因。

数据来源：每月MODIS过火面积数据(MCD64A1v006) 在全球森林观察网(https://globalforestwatch.org/topics/fires)上公开 供下载。

按总过火面积大小排列

自2000年以来，过火面积超过100万公顷的森林大火呈逐年上升趋势，而这与更频繁的危险火灾天气条件有关，其中包括火灾引发的雷暴和干雷电起火事件的发生率增加。

安哥拉每年有30%的地表被烧毁，其中森林密集、天然灌丛和草地面积少的地区受到的影响最为严重。砍伐森林为草地生长提供空地的做法导致旱季火灾更加严重。

巴西热带草原或塞拉多地区约占陆地总面积的23%，是仅次于亚马逊雨林(48%)的第二大生物群落区。塞拉多地区的火灾在旱季更加频繁且集中，现在往往每2到3年就会发生一次火灾，如2004年、2007年、2010年、2012年、2015年和2017年的火灾。

俄罗斯总过火面积的70-90%位于西伯利亚，且大部分西伯利亚山火发生在落叶松林中。2003年，在西伯利亚南部永久冻土上生长的落叶松林中发生的极端火灾主要是受地表湿度低、前一年降水不足以及2003年初气温升高的影响。

2004年玻利维亚不寻常的火灾事件与干旱和森林损失带来的影响有关。

根据对野火长期趋势的研究，巴拉圭2005年的野火与森林砍伐增加有关。

2011年，墨西哥森林火灾次数创新高，这很可能与前一年冬季降雨量减少导致长期干旱有关。

加拿大西北地区和美国阿拉斯加的北方森林分别在2014年和2015年发生了大规模火灾，起因是气候导致的雷电火灾次数创新高。

原始森林变为高度易燃植被区，再加上智利中部持续性特大干旱，助长了2016至2017年火灾季节发生大火。

*南苏丹于2011年7月9日从苏丹独立出来。在此之前的过火面积数据按两国目前的边界划分进行绘制。

完整参考见第38页。

2. 人类对野火的影响

2020年6月13日，美国亚利桑那州凤凰城的一条高速公路附近车辆起火点燃了植被，3天内过火面积约26,000公顷。

Landsat 8卫星上的陆地成像仪(OLI)获取的卫星图像显示了2020年6月14日出现的火烧迹地和熊熊燃烧的火势前线。天然色与火势红外特征相结合，增强了通过烟雾探测正在发生的火灾的能力。

来源：美国国家航空和航天局地球观测站

野火是地球系统的自然特征，对于许多生态系统的运作是必需的。植被和气候之间的长期相互作用在特定的生态系统中建立了一种特定的野火复发模式，称为火灾范式。[40]偏离涉及野火的时机、频率、规模和强度的现行火灾范式会导致火灾依赖型和火灾敏感型生态系统发生重大生态变化，前者需要通过火灾茁壮成长，而火灾对于后者的负面影响多于正面影响。[37,41-45]

人类通过改变景观及其植被、在极少发生自然火灾的地区将放火作为一种土地管理做法、遏制并防止火灾以保护人类社区以及改善气候等手段来直接或间接改变火灾范式。[42]土地开垦、森林砍伐、农业扩张、资源开采和城乡发展都是重大的土地利用变化，能够影响自然火灾范式。[41]

因为在潮湿的植被环境中，火灾很少能持续燃烧，所以火灾敏感型热带雨林很少发生自然火灾。[45]如今在本不会发生火灾的地区野火变得越来越常见，原因包括气候变化以及土地利用变化和森林砍伐等其他因素。亚马逊雨林的火灾是由人类引发的：原始植被被砍伐，价值更高的树木被选中砍伐，树墩晾干，直到被烧掉腾出地方修建农场和牧场。[10,11]森林片断化，最终分为热带草原和普通草原，为未来野火肆虐创造了有利条件，最终导致热带森林生态系统永久丧失。[46]

随着城市向野地扩张，不断发展的城市化是土地利用变化和景观转型的另一种重要形式。近几十年来，许多区域的城市迅速向森林地区扩张。[47]这种野地-城区结合部是野火高风险地区。[48]

激进的灭火措施等不合理的火灾管理政策和对传统火灾管理做法和本土知识的认知度低会产生一系列挑战。[11,49-51]在其他一些情况下，试图消灭生态系统（包括火灾依赖型生态系统）中的火灾可能会造成可燃物负荷量增加，从而使起火风险上升。[52-55]诸如此类的火灾管理政策可能导致火灾范式发生变化，大规模野火频发变成普遍现象。[37,56]

近几十年来，人们越来越认识到需要结合当地土地管理的文化和生态意义来形成一个系统和一种整体景观方法，以促进生态健康并防止生态系统发生大规模且破坏力更强的失控火灾。[57,58]例如，澳大利亚大草原的火灾管理举措测定并监测了采用当地野火管理技术的规划内烧荒的影响，并取得了积极成果。[57]这种方法鼓舞了其他国家，包括巴西的塞拉多和博茨瓦纳的稀树草原生态系统。[59]

人类世野火

火灾生态

野火是什么？

野火是一种自由燃烧的植被火灾，包括可能对社会、经济或环境价值构成重大风险的火灾。它可能是恶意纵火、意外起火或自然起火。[26]

野火持续时间可以很短且波及范围小，但更常见的是燃烧时间长且波及范围广。野火的大小无论是很大还是很小，但有时会出现意延且大快延的，在这种情况下，灭火和其他风险缓解措施都是无济于事的。野火的影响可能会立即直接显现出来，也可能会在大火扑灭后的一段时间内显现出来。[27]

虽然野火可能会自然发生，但大多数是人类行为的结果，例如工业砍伐森林后清理土地、开垦土地用于农业生产或人类居住，管理牧场用于放牧牲畜以及人为过失等。[28]

根据被被与气候之间的相互作用，野火火势通常与周围生态系统特有的模式有关，这被称为火状况范式。火灾范式的属性包括发生频率、燃烧程度、强度、严重性和季节性。

当满足下列三个要素时，野火就会自然发生：

起火
来自大因的热量或雷击引发火灾

可燃物
足够的可燃材料来助燃

天气
气温、风或相对湿度等条件促进蔓延

野火与生态系统

野火在维持生态功能和保护生物多样性方面发挥着关键作用。许多生态系统的演变涉及野火复苏并恢复野火在维持生态系统理解。例如，一些植物需要频发火灾来触发发芽开烧掉与其竞争的植物。由于一个生境的物种已经适应了特定的火灾范式，因此任何变化都会影响物种和整个生态系统。

野火类型

根据生物质燃料和天气条件，有三种类型的野火，单起火灾事件可能表现出三种或两种野火类型。

树冠火
这类野火从地面烧到树冠，并沿林冠蔓延。常见于地中海气候林地和北方森林。火势最迅猛且最危险的野火往往最难扑灭，延续通常需要大量可燃物和大风。

地表火
这类野火会燃烧地面上的落叶、死物和植被。主要能发于生产力高的草原和热带草原，也常见于以垃圾为主要燃料的林地和森林中。地表火可以向上延烧树冠和灌木丛，最终蔓延成为树冠火。

地下火
这类野火燃烧经分解的有机地下土壤层，通常燃烧火焰很难用肉眼观察。地下火难以完全扑灭，可能在冬季闷烧，但在春季又重新燃烧起来。最常见于泥炭地和沼泽，并可能发展成地表火。

火灾依赖型植物

在易发生火灾的生态系统中，许多植物物种在生命周期中依赖于频发的火灾，火灾触发植物开花、种子散步或种子发芽。[29]

一些常见于北方森林和地中海气候地区的植物会把种子贮藏在球果中，直到一场大火触发它们释放种子。

野火可以触发兰花和百合等球茎植物以及多年生草本植物开花。

烟雾和烧焦的树木也可以触发易发生火灾的灌木丛中的许多植物的种子发芽。

火灾依赖型植物

该地图显示了2021年1月1日至9月20日观测到的各类活跃的火灾。该图是由从美国国家航空和航天局的活跃火灾延时模频中截取的静止画面合成的。若想更好地查看火灾强度随时间的动态变化，请访问美国国家航空和航天局科学可视化工作室。

观看延时视频

2003–2016年间观测到的火灾数量

从2003至2016年，全球共发生1,300多万起火次，平均持续4和5天，具体因各大陆和火灾情况而异。[19]每起火灾的过火面积平均达440公顷。[19]

火灾范式正在改变

特定生物群落的火灾范式不断变化

下表基根据Bowman等人(2011年)的研究改编的，[30]总结了低纬度和高纬度地区的特定生物群落的火灾范式是如何随着全球工业化而变化的。

生物群落	热带雨林	热带草原	中纬度沙漠	中纬度北美枣节性干草森林	北方森林
工业化前的火灾范式	低强度地表火很少发生，对生物多样性的长期影响可忽略不计	草季火灾频发，造成树木密度的区间波动	雨季过后，不常发生火灾，导致可燃物堆积	低强度地表火频发，限制了树木的增长	不常见的高强度树冠火烧毁整个林分
工业化后的火灾范式	森林开垦导致地表火频发，使森林变为结果燃烧的草原或农田	过度放牧减少了火灾，促进了木本物种的增长	由于外来易燃草类的引入，导致火灾频发	灭火措施促成高密度幼林，且高强度树冠火不常发生	全球变暖导致高强度野火增加，造成土壤碳流失，并形成无树植被

来源：改编自Bowman等人(2011年) 的研究。[30]由John Wiley & Sons Ltd 许可出版。

中纬度北美枣节性干草森林的图片来源：kenkistler / Shutterstock.com

土地利用变化

与农业、森林砍伐和城市发展相关的土地利用变化正在影响着大范围生态系统的火灾模式发生重大变化。[31]

在野火罕见的地区，人们经常通过改火来管理土地，而在野火多发地区则是灭火，原生植被的土地变化会改变燃料属性，可能使野火更严重、更频繁。

在地中海地区，畜牧活动减少，草原变成了高度易燃的灌木丛。[34]

在热带雨林中，大多数物种尚未进化完全，无法从火灾中迅速恢复过来，而野火经常被用来开垦森林，建设牧场和农田。这种土地开垦方式在局部范围内改变了火灾范式，而在更大范围内改变了生态系统。[32]

在巴西，森林砍伐和农业等土地利用变化导致全国（包括以前火灾罕见的亚马逊雨林地区）的火灾数量增加。

来源：MapBiomas项目—巴西土地利用和土地覆盖地图年度系列第4卷，可访问http://mapbiomas.org。MapBiomas项目是多个机构联合采取的一项举措，旨在利用应用于卫星图像的自动分类程序绘制年度土地利用和土地覆盖地图。

野地-城区结合部扩张

野地-城区结合部的城市发展需要管理并积极控制火灾风险，从而改变自然火灾范式。[42]

土地开发不仅会改变植被，而且旨在保护人类生命和财产安全的灭火和消除火灾的政策也会造成燃料堆积，并在燃料燃烧时引发重大火灾。[35, 37]

在过去的几十年里，美国加利福尼亚州的野火过火面积和平均规模有所增长。森林边缘的快速城市化、数十年灭火累积的生物质燃料以及气候变化加剧的极端干旱和高温等都是大火激增的原因。

来源：美国国家航空和航天局地球观测站(https://earthobservatory.nasa.gov/images/148908/whats-behind-californias-surge-of-large-fires)

火灾和入侵物种

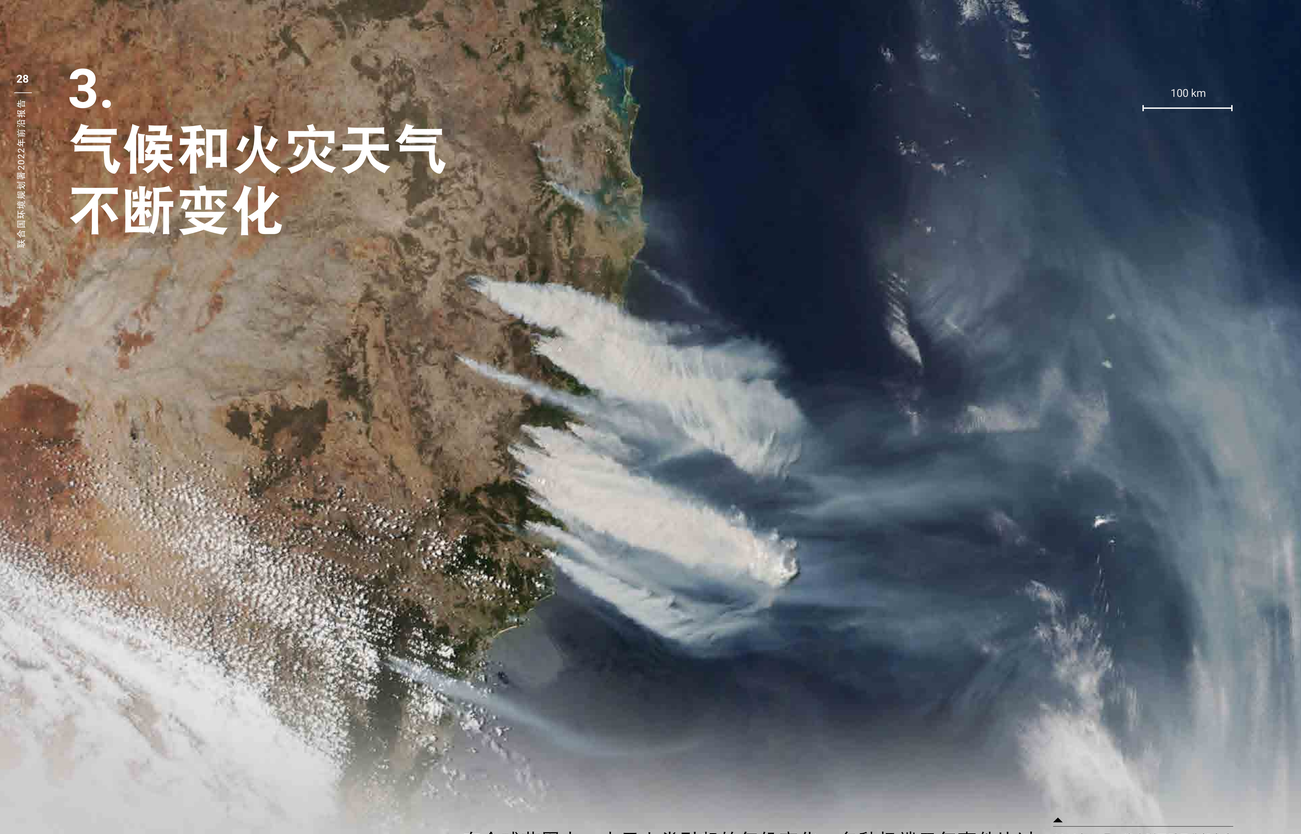
人类活动是引入入侵物种的主要原因，引入入侵物种会改变生态系统内的植被结构、燃料数量和特性，进而改变火灾范式。[37]

火灾范式改变创造的条件可能并不适合原始植被在野火后恢复过来，但适合入侵的耐火物种繁衍。

在美国许多生态区，某些非本土草类的入侵使火灾发生率增加了230%，火灾发生频率增加了150%。[43]

许多入侵草类富易燃生物质且水分少，办野火创造了有利条件。一些最成功的入侵草类的种子在高温和烟雾的影响下会发芽。

3. 气候和火灾天气不断变化



2019年11月，澳大利亚悉尼北部发生多起丛林大火，浓烟向科夫斯港和麦觉理港附近的沿海城市扩散。

受影响城市的空气质量达到有害水平。气温突破纪录、强风和持续缺乏降水导致新南威尔士州发生大规模丛林大火。

来源： 美国宇航局地球观测站。

在全球范围内，由于人类引起的气候变化，多种极端天气事件比过去发生的更加频繁且更为严重。[27,28]长期变暖趋势表明，在全球45个地区中的41个，近年来大多数时候都比1950年之前观测过的年份炎热。[28]高温和干旱频发延长了火灾季节，且更可能出现危险的火灾天气条件。[1,26-34,60,66]

以北美西部为重点的研究表明，热浪和多年干旱不仅助长了野火频发，而且野火变得更加严重且烧毁的范围更广。[30,34,61]在南美洲，长期重大干旱和高温天气与湿热带地区和季节性洪水泛滥的湿地（包括未发生过野火的地区）的火灾发生率和严重程度增加有关。[14,62-65]在澳大利亚的温带气候地区，火灾季节期间的降雨量自1990年代后期以来减少了10%。[67]根据100多年的数据，2019年是澳大利亚有记录以来最热和最干旱的一年。[5,66,67]在智利、新西兰和非洲部分地区，研究还表明了气候变化对干旱条件和森林火灾活动增加的影响。[62,68-71]在南欧和地中海地区，随着整个流域转变为一个更加干旱的生态系统，气候变化也在造成更危险的火灾天气条件。[2,28,35,72,73]

> “在全球范围内，由于人类引起的气候变化，多种极端天气事件比过去发生的更加频繁且更为严重。高温和干旱频发延长了火灾季节，且更可能出现危险的火灾天气条件。”

雷电是野火自然起火的一大原因，预计全球部分地区的雷击频率会随着气候的变化而增加。[74-81]近年来，北美北方森林中大多数被烧毁区域皆是由气候变化引发的雷电起火。[82]干雷电通常伴有少量降水或无降水，近几十年来，在澳大利亚东南部的一些地区发生干雷电的频率增加，但也有一些地区发生干雷电的频率下降。[83]被野火烧毁的总面积中有很大一部分可归因于雷电起火，因为雷电可随时随地发生，而且会传播到应对能力无法触及的偏远地区。[74]

近几十年来，澳大利亚和北美频繁报道的另一个现象是火灾引发的雷暴。[4,6,84-89]雷暴是极端火灾事件的一个特征，在野火产生的烟羽中形成，进而形成所谓的热积雨云。在澳大利亚南部部分地区，随着时间的推移，与火灾引发的雷暴的发生有关的天气条件的发生频率正在增加，预计会继续增加。[4,77,86,90]火灾引发的雷暴可能导致更不稳定的风速和风向变化等更危险的地面火灾条件，并可能产生闪电，在远离火线的地方引发新的火灾。[85]它们说明了火灾与大气过程之间的危险反馈循环的风险。

在气候变化的影响尚不确定的情况下，现有的生物质燃料是决定火灾强度的关键因素。当地面二氧化碳浓度升高，促进某些植物生长时，可燃物负荷量可能会因二氧化碳施肥效应而增加。[91-93]虽然可能会增加大量有机物质，但相对湿度较低会将大量有机物质转变为野火的干燃料。在某些情况下，消除野火的做法也会增加可燃物负荷量。[26,94]更好地了解火灾依赖型生态系统和整个火灾生态有助于向综合火灾管理转型，包括在适当的时间和适当的条件下开展可控制的规划内烧荒，以减少可燃物负荷量。[42,95]

虽然气候变化已经影响了野火，但野火也可能影响气候变化。[28,96,97]亚马逊热带雨林的消失和北极永久冻土的融化被认为是可能加快气候变化的两个潜在触发因素。[28,98,99]最近的研究表明，随着亚马逊雨林遭到砍伐，该地区正在从碳汇变为碳源，同时西伯利亚北极地区的永久冻土正在加速融化，而火灾是这两种情况的促发因素。[87,88,100]

气候变化：
火灾天气变得越来越极端

气候变化正在增加大规模重大火灾的风险。[5, 6, 42]气候直接影响生物质的生产和状况，以及助长起火和蔓延的天气条件。在火灾季节的前几个月，温暖干燥的天气持续，植被水分被蒸发，可能发展成野火并蔓延的火灾风险增加。相比之下，降雨量异常偏多会促进植物生长，植物在下一个旱季可能是燃料。例如在受厄尔尼诺变化影响的区域，长期干旱事件会导致木本生态系统发生重大火灾。[5, 36]

雷电起火

雷电是野火自然起火的一大原因。随着气候变化，预计全球部分地区发生雷击的次数将增加。雷电起火是北美和西伯利亚北部北方森林中大规模野火的主要原因。[60]

火灾引发的雷暴

极端大火会促使形成烟雾弥漫的雷暴，而这会造成更危险的火势，并通过雷电引发新的火灾。

1 烟羽
在一大片熊熊燃烧的大火上方升起一股湍流的热烟气。

2 羽流冷却
羽流在上升过程中卷入冷空气，随之扩大并冷却。

3 云
当羽流上升到一定高度时，遇到低气压会凝结形成云。

4 雷暴
在适当的环境条件(不稳定的大气)下，可能会形成雷暴。

5 下击暴流
雨水从云层中落下，有时在下落过程中蒸发，并遇干燥空气发生冷却，从而产生一股下冲风。

6 雷电
雷电可以人工引发，并且可以在远离火线的地方引起新的火灾。

来源： 改编自澳大利亚政府2020年国家环境科学计划

极端野火对地球生态系统的影响

大气污染
大规模野火产生碳黑、颗粒物和温室气体等大量大气污染物。这些污染物可能飘散得很远并在冰川等偏远地区沉积下来。

改变反照率
烟尘在空气中传播并沉积，降低了地表反照率并加快了冰雪融化。研究发现亚马逊流域野火产生的烟尘沉积物会加快安第斯冰川的融化。

碳汇变成碳源
北方森林和热带森林中频繁发生的大规模野火可能会将陆地封存的碳变为温室气体的主要来源。

水污染
严重的野火之后，河流中沉积物增加，河水变浑浊，水温改变， 并影响鱼类丰度。

野火后侵蚀导致大量营养物质和污染物流入水体，影响水质和水生物。

排入水体中的氮、磷等营养物质会造成富营养化并降低溶解氧的含量，进而对水生生物构成威胁。

侵蚀
火灾后降雨，土壤更易受到侵蚀。侵蚀通常发生在植被重新生长之前。在某些环境中，斜坡崩塌会导致灾难性的泥石流和山体滑坡。

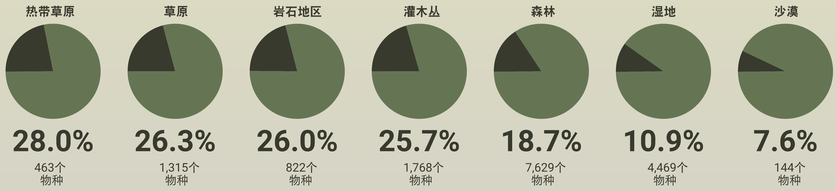
海洋肥沃化
严重的大规模野火释放出大量气溶胶，包括铁等生物必需的微量金属。2019至2020年，澳大利亚极端野火产生的富铁气溶胶在大气中扩散，导致南太平洋出现大规模藻华现象且持续了4个月。

生物多样性丧失
野火变得更频发且更猛烈，导致植物物种组成和森林生态系统结构发生长期变化。复燃也可能会变得更常见，可能减少火灾后的再生。根据原始森林类型，复燃可能会导致向非森林植被转变。

完整参考见第40页。

受火灾范式改变影响的物种

受火灾范式（包括每个生境的火灾消除情况）改变威胁的物种百分比



来源： Kelly等人(2020年)。完整参考见第40页。

4. 面对进一步的气候变化改进野火管理

随着极端野火造成的损失和损害不断增加，对预防和响应管理方法的需求正受到关注。随着人类引起的气候变化加剧，包括在土地利用变化未能遵循最佳做法以保护生态系统恢复力和景观完整性的情况下，威胁只会越来越多。

虽然发达国家的做法经常强调消除火灾，但许多发展中国家的火灾管理能力不足，仅具备在灾害直接威胁生命和财产安全时的应对能力。有效的火灾管理对热带草原和普通草原等火灾依赖型生态系统非常重要，这些地方会堆积可燃物，增加火灾风险，尤其在旱季高峰期。[53]不论是雷电起火或人为纵火，数年或数十年堆积下来的可燃物负荷量可能会引发失控的野火。与完全消除火灾的方法相比，承认通过定期受控的烧除来维持可管理的可燃物负荷量和具有生产力的生态系统的本土做法在某些区域已成为普遍做法。[50,57,59,107,110]然而，某些国家仍然沿用野火扑灭政策，试图彻底消除环境中的火灾会让旱季的野火变得更加猛烈和严重。[55]

拉丁美洲各社区的解决方案

巴西米纳斯吉拉斯州通博诺波利斯 **图片来源：** Christyam de Lima / Shutterstock.com

拉丁美洲缺乏适当火灾管理政策的情况可以追溯到几个世纪前。[55,101,102]然而，极端野火频发事件要求对乡村社区、传统社区和土著社区给予特别关注，它们不仅直接受到这些干扰影响，而且在某些情况下，在管理自己的土地方面也受到限制。[10]因此，这些人口沿用古老的火灾管理做法，通过保护自己、保护对其生计至关重要的自然生态系统、种植农作物和防止野火蔓延来取得最安全的成果。[10,50,103]

在过去十年里，一些拉丁美洲国家已经认可了传统的火灾知识，并通过借鉴这些古老的火灾管理技术来调整其野火预防策略。[55,103]在巴西-德国合作项目“塞拉多丛林大火的预防、控制和监测”的鼓舞下和澳大利亚成功减排和碳封存核算方法的启发下，巴西于2014年实行了一项综合火灾管理试点计划。[104,105]

该计划首先在3个塞拉多保护区实施，5年后扩大到分布在巴西所有生物群落的74个区域。

这种综合火灾管理措施在旱季后期的野火烧毁面积减少了57%，相关温室气体排放量减少了36%。[50,106]此外，每年雇用和培训2,000多名当地、传统和土著消防队员，以从事防火和灭火工作，并收集数据用以评估不同火灾范式对动植物的影响。[107,108]为雇用并培训Xerente社区土著妇女所做出的一致努力包括对注重设备、动员和受控的消防技术，以及注重安全和一般环境教育。[108]

该计划的覆盖范围仍仅限于一些保护区，巴西大部分地区仍极易遭受灾难性野火，例如2019年和2020年发生的野火。尽管如此，农村土地所有者和政府仍有极大的机会去推广成功的管理做法，从而降低每年反复发生的野火损失和风险。

因气候变暖而延长的火灾季节可能会妨碍受控的烧除，因为安全烧除可燃物的条件是特定的。随着生长季变长、天气变得更热、更干燥，气温上升且可燃物数量增加，安全受控的烧除的时机可能会有所变化，而这会对野火风险的长期管理产生影响。[91]

长期规划取决于世界各国和各区域的各种合作内容，包括南北半球共享飞机和消防员等资源。当各地火灾季节不重叠时，这种方法效果很好。如今，随着火灾季节变长，极端野火期间对消防资源的需求更强烈，这种能力共享会变得越来越难。[3,34]

澳大利亚皇家委员会调查了该国2019至2020年的火灾，并提出了一系列建议，包括改进规划、政策和做法，提高消防能力，加强社区抗灾能力，以及制定纳入受控烧除本土做法的土地管理策略。[3]这些建议可用于改进野地-城区结合部的建筑物和基础设施的设计标准。这可以提供一种实用的方法，将气候变化科学纳入提高抗灾能力的日常实践中，了解风险因素如何发生变化并可能继续变化。

未来十年对于加强野火抵御力和适应力至关重要。采用参与式方法并让脆弱群体参与火灾防备和应对的各个阶段都是必要的。[109]无论是在极端事件发生之际还是在事件发生后几年，对儿童、妇女、老年人、残疾人和其他高危群体的影响可能会影响整个社区和整个社会。对当地的了解有助于解决生态完整性和社会正义问题。[110]进一步研究需要解决脆弱群体在极端野火发生前、中、后面临灾害风险的问题。

关于减少火灾风险的其他深入研究应包括与社会科学相结合的成本评估，以及关于不同行动有效性的环境评估。[111]加强对极端野火的科学认识，应探讨土地利用变化或土地管理如何影响这些事件。进一步研究应探讨未来雷电和植被条件可能发生何种变化，并注意到由于现有气候建模方法（特别是通过对野火引发的雷暴系统等极端事件的观测和数据收集）的局限性而存在相当大的不确定性。[84]

随着气候变化带来更多的损失和损害，压力将变得更加明显。为了避免极端野火恶化产生灾难性后果，社区对这些极端火灾事件的防备、应对和管理能力必须赶上或超过气候变化影响加速极端火灾事件威胁的速度。

建设抗灾能力：野火管理的新工具和新方法

图像摄于2020年1月6日，显示了一场前所未有的野火产生的气溶胶通过大气从澳大利亚东南海岸一路扩散至南太平洋。野火产生的气溶胶在海面沉积引发了浮游植物大规模繁殖。 **来源：** 日本气象厅和美国国家航空航天局

自然灾害的发生频率和强度的增加对降低灾害风险的现有方法提出了更大的挑战。新方法加强了应对系统性灾害风险的能力。在全球范围内，通过遥感能力（包括卫星、地面雷达、雷电探测和数据处理）等改进建模和观测数据有助于改进野火监测、预测和管理系统。

欧盟哥白尼地球观测计划和美国国家航空航天局等体系提供的监测和数据处理能力为全球范围内的努力付出提供支持。[112]拉丁美洲遥感和森林火灾区域网络促使拉丁美洲地区共同努力并制定火灾管理行动方案。[113]巴西国家空间研究所通过Queimadas计划促进研究并提高整个区域的监测能力，开发创新工具以探测野火风险并时常更新热源信息。[114]

南非通过“消防工作”计划采用火灾预防和管理嵌套模式，省级消防协会与地区和地方机构协调，围绕火灾管理和消防发展社区技能并促进就业。[115]

澳大利亚现在有长期预测火灾天气状况的能力，在很长的一段时间内指导并帮助消防机构做出决定。同时给消防机构和规划人员等应急管理团体提供气候变化预测结果。这有助于针对与环境管理、能源、基础设施、健康和金融部门相关的气候危害做出循证决策。[116]

《澳大利亚国家减少灾害风险框架》于2020年3月获批纳入国家政策，将气候变化确定为建设抗灾能力和采取系统方法来管理减灾应灾固有复杂性的根本原因。[117]该框架认识到通过社会和经济网络发展具有抵御能力的社区的重要性，这些网络在应对灾害和适应气候变化方面开展合作并共担责任。[118,119]近年来，澳大利亚的灾害管理方法强调在灾害发生前加强抗灾能力。117通过各部门间的合作以及教育和专业项目建立知识和技能网络并培养国家能力不仅对野火管理很重要，也对提升自然灾害抵御能力同样重要。[120]

参考文献

1. Higuera, P.E. and Abatzoglou, J.T. (2021). Record-setting climate enabled the extraordinary 2020 fire season in the western United States. *Global Change Biology* 27(1), 1-2. https://doi.org/10.1111/gcb.15388

2. Ruffault, J., Curt, T., Moron, V., Trigo, R.M., Mouillot, F., Koutsias, N. *et al.* (2020). Increased likelihood of heat-induced large wildfires in the Mediterranean Basin. *Scientific Reports* 10(1), 1-9. https://doi.org/10.1038/s41598-020-70069-z

3. Australia, Commonwealth of Australia (2020). Royal Commission into National Natural Disaster Arrangements. Australian Government. https://naturaldisaster.royalcommission.gov.au

4. Dowdy, A.J., Ye, H., Pepler, A., Thatcher, M., Osbrough, S.L., Evans, J.P. et al. (2019). Future changes in extreme weather and pyroconvection risk factors for Australian wildfires. *Scientific Reports* 9(1), 1-11. https://doi.org/10.1038/s41598-019-46362-x

5. Abram, N.J., Henley, B.J., Gupta, A.S., Lippmann, T.J., Clarke, H., Dowdy, A.J. *et al.* (2021). Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Communications Earth & Environment* 2(1), 1-17. https://doi.org/10.1038/s43247-020-00065-8

6. Canadell, J.G., Meyer, C.P., Cook, G.D., Dowdy, A., Briggs, P.R., Knauer, J. *et al.* (2021). Multi-decadal increase of forest burned area in Australia is linked to climate change. *Nature Communications* 12, 6921. https://doi.org/10.1038/s41467-021-27225-4

7. Van Oldenborgh, G.J., Krikken, F., Lewis, S., Leach, N.J., Lehner, F., Saunders, K.R. *et al.* (2021). Attribution of the Australian bushfire risk to anthropogenic climate change. *Natural Hazards and Earth System Sciences* 21(3), 941-960. https://doi.org/10.5194/nhess-21-941-2021

8. Ward, M., Tulloch, A.I., Radford, J.Q., Williams, B.A., Reside, A.E., Macdonald, S.L. *et al.* (2020). Impact of 2019–2020 mega-fires on Australian fauna habitat. *Nature Ecology & Evolution* 4(10), 1321-1326. https://doi.org/10.1038/s41559-020-1251-1

9. Holz, A., Paritsis, J., Mundo, I.A., Veblen, T.T., Kitzberger, T., Williamson, G.J. *et al*. (2017). Southern Annular Mode drives multicentury wildfire activity in southern South America. *Proceedings of the National Academy of Sciences* 114(36), 9552–9557. https://doi.org/10.1073/pnas.1705168114

10. Eloy, L., Hecht, S., Steward, A., Mistry, J. (2019). Firing up: Policy, politics and polemics under new and old burning regimes. *The Geographical Journal* 185(1), 2–9. https://doi.org/10.1111/geoj.12293

11. Schmidt, I.B. and Eloy, L. (2020). Fire regime in the Brazilian Savanna: Recent changes, policy and management. *Flora* 268, 151613. https://doi.org/10.1016/j.flora.2020.151613

12. INPE (2020). Portal de dados abertos e sistema de monitoramento do Programa Queimadas. *Instuto Nacional de Pesquisas Espacias*. https://queimadas.dgi.inpe.br/queimadas/dados-abertos/

13. Vargas-Cuentas, N.I. and Roman-Gonzalez, A. (2021). Satellite-Based Analysis of Forest Fires in the Bolivian Chiquitania and Amazon Region: Case 2019. *IEEE Aerospace and Electronic Systems Magazine* 36(2), 38-54. https://doi.org/10.1109/MAES.2020.3033392

14. Garcia, L.C., Szabo, J.K., de Oliveira Roque, F., Pereira, A.D.M.M., da Cunha, C.N., Damasceno-Júnior, G.A. *et al.* (2021). Record-breaking wildfires in the world's largest continuous tropical wetland: Integrative fire management is urgently needed for both biodiversity and humans. *Journal of Environmental Management* 293, 112870. https://doi.org/10.1016/j.jenvman.2021.112870

15. Andela, N., Morton, D.C., Giglio, L., Paugam, R., Chen, Y., Hantson, S. *et al.* (2019). The Global Fire Atlas of individual fire size, duration, speed and direction. *Earth System Science Data*, 11, 529–552. https://doi.org/10.5194/essd-11-529-2019

16. Navarro, K.M., Kleinman, M.T., Mackay, C.E., Reinhardt, T.E., Balmes, J.R., Broyles, G.A. *et al.* (2019). Wildland firefighter smoke exposure and risk of lung cancer and cardiovascular disease mortality. *Environmental Research* 173, 462-468. https://doi.org/10.1016/j.envres.2019.03.060

17. Marlier, M.E., Bonilla, E.X. and Mickley, L.J. (2020). How do Brazilian fires affect air pollution and public health?. *GeoHealth* 4(12), e2020GH000331. https://doi.org/10.1029/2020GH000331

18. Aguilera, R., Corringham, T., Gershunov, A., and Benmarhnia, T. (2021). Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California. *Nature Communications*, 12(1), 1-8. https://doi.org/10.1038/s41467-021-21708-0

19. Chen, G., Guo, Y., Yue, X., Tong, S., Gasparrini, A., Bell, M.L. *et al*. (2021). Mortality risk attributable to wildfire-related PM2.5 pollution: a global time series study in 749 locations. *The Lancet Planetary Health*, 5(9), E579-E587. https://doi.org/10.1016/S2542-5196(21)00200-X

20. Silveira, S., Kornbluh, M., Withers, M.C., Grennan, G., Ramanathan, V. and Mishra, J. (2021). Chronic Mental Health Sequelae of Climate Change Extremes: A Case Study of the Deadliest Californian Wildfire. *International Journal of Environmental Research and Public Health* 18(4), 1487. https://doi.org/10.3390/ijerph18041487

21. Ikeda, K. and Tanimoto, H. (2015). Exceedances of air quality standard level of PM2.5 in Japan caused by Siberian wildfires. *Environmental Research Letters* 10(10), 105001. https://doi.org/10.1088/1748-9326/10/10/105001

22. Ford, B., Val Martin, M., Zelasky, S.E., Fischer, E.V., Anenberg, S.C., Heald, C.L. *et al.* (2018). Future fire impacts on smoke concentrations, visibility, and health in the contiguous United States. *GeoHealth* 2(8), 229-247. https://doi.org/10.1029/2018GH000144

23. Bencherif, H., Bègue, N., Kirsch Pinheiro, D., du Preez, D.J., Cadet, J-M, da Silva Lopes, F.J. *et al.* (2019). Investigating the Long-Range Transport of Aerosol Plumes Following the Amazon Fires (August 2019): A Multi-Instrumental Approach from Ground-Based and Satellite Observations. *Remote Sensing* 12(22), 3846. https://doi.org/10.3390/rs12223846

24. Machado-Silva, F., Libonati, R., Melo de Lima, T.F., Peixoto, R.B., de Almeida França, J.R., de Avelar Figueiredo Mafra Magalhães, M. *et al.* (2020). Drought and fires influence the respiratory diseases hospitalizations in the Amazon. *Ecological Indicators* 109, 105817. https://doi.org/10.1016/j.ecolind.2019.105817

25. Masri, S., Scaduto, E., Jin, Y. and Wu, J. (2021). Disproportionate Impacts of Wildfires among Elderly and Low-Income Communities in California from 2000–2020. *International Journal of Environmental Research and Public Health* 18(8), 3921. https://doi.org/10.3390/ijerph18083921

26. Abatzoglou, J.T. and Williams, A.P. (2016). Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* 113(42), 11770-11775. https://doi.org/10.1073/pnas.1607171113

27. Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I. *et al*. (2018). Impacts of 1.5°C Global Warming on Natural and Human Systems. In *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R. *et al*. (eds.). In Press. https://www.ipcc.ch/sr15/

28. The Intergovernmental Panel on Climate Change (2021). Summary for Policymakers. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/

29. Kirchmeier-Young, M.C., Gillett, N.P., Zwiers, F.W., Cannon, A.J. and Anslow, F.S. (2019). Attribution of the influence of human-induced climate change on an extreme fire season. *Earth's Future* 7(1), 2–10. https://doi.org/10.1029/2018EF001050

30. Williams, A.P., Abatzoglou, J.T., Gershunov, A., Guzman-Morales, J., Bishop, D.A., Balch, J.K. *et al.* (2019). Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future* 7(8), 892-910. https://doi.org/10.1029/2019EF001210

31. Australia, Bureau of Meteorology (2020). Special Climate Statement #73. Bureau of Meteorology, Victoria, Australia. http://www.bom.gov.au/climate/current/statements/

32. Barbero, R., Abatzoglou, J.T., Pimont, F., Ruffault, J. and Curt, T. (2020). Attributing increases in fire weather to anthropogenic climate change over France. *Frontiers in Earth Science* 8, 104. https://doi.org/10.3389/feart.2020.00104

33. Lewis, S.C., Blake, S.A., Trewin, B., Black, M.T., Dowdy, A.J., Perkins-Kirkpatrick, S.E. *et al.* (2020). Deconstructing factors contributing to the 2018 fire weather in Queensland, Australia. *Bulletin of the American Meteorological Society* 101(1), S115-S122. https://doi.org/10.1175/BAMS-D-19-0144.1

34. Abatzoglou, J.T., Juang, C.S., Williams, A.P., Kolden, C.A. and Westerling, A.L. (2021). Increasing synchronous fire danger in forests of the western United States. *Geophysical Research Letters* 48(2), e2020GL091377. https://doi.org/10.1029/2020GL091377

35. Bowman, D.M.J.S., Balch, J., Artaxo, P., Bond, W.J., Cochrane, M.A., D'Antonio, C.M. *et al*. (2011). The human dimension of fire regimes on Earth. *Journal of Biogeography* 38(12), 2223-2236. https://doi.org/10.1111/j.1365-2699.2011.02595.x

36. Bond, W.J. and Keane, R.E. (2017). Fires, Ecological Effects of. *Elsevier*. https://doi.org/10.1016/B978-0-12-809633-8.02098-7

37. Cochrane, M.A. and Bowman, D.M.J.S. (2021). Manage fire regimes, not fires. *Nature Geoscience* 14(7), 455-457. https://doi.org/10.1038/s41561-021-00791-4

38. United Nations Environment Programme and GRID-Arendal (2021). Spreading like Wildfire: The Rising Threat of Extraordinary Landscape Fires. UNEP: Nairobi, GRID-Arendal, Arendal. https://www.grida.no

39. Giglio, L., Boschetti, L., Roy, D.P., Humber, M.L. and Justice, C.O. (2018). The Collection 6 MODIS burned area mapping algorithm and product. Remote Sensing of Environment, 217, 72-85. https://doi.org/10.1016/j.rse.2018.08.005

    Giglio, L., Boschetti, L., Roy, D.P., Humber, M.L. and Justice, C.O. (2018). Monthly MODIS Burned Area Product (MCD64A1 v006). Accessed on 07/10/2021 from Global Forest Watch (https://globalforestwatch.org/)

40. Krebs, P., Pezzatti, G.B., Mazzoleni, S., Talbot, L.M. and Conedera, M. (2010). Fire regime: history and definition of a key concept in disturbance ecology. *Theory in Biosciences*, 129(1), 53–69. https://doi.org/10.1007/s12064-010-0082-z

41. Myers, R.L. (2006). Living with Fire – Sustaining Ecosystems & Livelihoods through Integrated Fire Management. *The Nature Conservancy.* https://www.cbd.int/doc/pa/tools/Living%20with%20Fire.pdf

42. Bowman, D.M., Kolden, C.A., Abatzoglou, J.T., Johnston, F.H., van der Werf, G.R. and Flannigan, M. (2020). Vegetation fires in the Anthropocene. *Nature Reviews Earth & Environment* 1(10), 500-515. https://doi.org/10.1038/s43017-020-0085-3

43. Fidelis, A. (2020). Is fire always the "bad guy"?. *Flora* 268, 151611. https://doi.org/10.1016/j.flora.2020.151611

44. Fusco, E.J., Finn, J.T., Balch, J.K., Chelsea Nagy, R. and Bradley, B.A. (2019). Invasive grasses increase fire occurrence and frequency across US ecoregions. *Proceedings of the National Academy of Sciences* 116(47) 23594-23599. https://doi.org/10.1073/pnas.1908253116

45. Pivello, V.R., Vieira, I., Christianini, A.V., Ribeiro, D.B., da Silva Menezes, L., Berlinck, C.N. *et al.* (2021). Understanding Brazil's catastrophic fires: Causes, consequences and policy needed to prevent future tragedies. *Perspectives in Ecology and Conservation* 19(3), 233-255. https://doi.org/10.1016/j.pecon.2021.06.005.

46. Armenteras, D., Dávalos, L.M., Barreto, J.S., Miranda, A., Hernández-Moreno, A., Zamorano-Elgueta, C. *et al.* (2021). Fire-induced loss of the world's most biodiverse forests in Latin America. *Science Advances* 7(33), eabd3357. https://doi.org/10.1126/sciadv.abd3357

47. Bento-Gonçalves, A. and Vieira, A. (2020). Wildfires in the wildland-urban interface: Key concepts and evaluation methodologies. *Science of the Total Environment* 707, 135592. https://doi.org/10.1016/j.scitotenv.2019.135592

48. Baylis, P. and Boomhower, J. (2019). *Moral hazard, wildfires, and the economic incidence of natural disasters.* National Bureau of Economic Research, Working paper 26550. https://doi.org/10.3386/w26550

49. Laris, P. and Wardell, D.A. (2006). Good, bad or 'necessary evil'? Reinterpreting the colonial burning experiments in the savanna landscapes of West Africa. *Geographical Journal* 172(4), 271-290. https://doi.org/10.1111/j.1475-4959.2006.00215.x

50. Mistry, J., Bilbao, B.A. and Berardi, A. (2016). Community owned solutions for fire management in tropical ecosystems: case studies from Indigenous communities of South America. *Philosophical Transactions of the Royal Society B: Biological Sciences* 371(1696), 20150174. http://dx.doi.org/10.1098/rstb.2015.0174

51. Thompson, M.P., MacGregor, D.G., Dunn, C.J., Calkin, D.E. and Phipps, J. (2018). Rethinking the Wildland Fire Management System. *Journal of Forestry* 116(4), 382–390. https://doi.org/10.1093/jofore/fvy020

52. Brotons, L., Aquilué, N., de Cáceres, M., Fortin, M-J. and Fall, A. (2013) How Fire History, Fire Suppression Practices and Climate Change Affect Wildfire Regimes in Mediterranean Landscapes. *PLoS ONE* 8(5), e62392. https://doi.org/10.1371/journal.pone.0062392

53. Durigan, G. and Ratter, J.A. (2016). The need for a consistent fire policy for Cerrado conservation. *Journal of Applied Ecology* 53(1), 11-15. https://doi.org/10.1111/1365-2664.12559

54. Batista, E.K.L., Russell-Smith, J., França, H. and Figueira, J.E.C. (2018). An evaluation of contemporary savanna fire regimes in the Canastra National Park, Brazil: Outcomes of fire suppression policies. *Journal of Environmental Management* 205, 40-49. https://doi.org/10.1016/j.jenvman.2017.09.053

55. Moura, L.C., Scariot, A.O., Schmidt, I.B., Beatty, R. and Russell-Smith, J. (2019). The legacy of colonial fire management policies on traditional livelihoods and ecological sustainability in savannas: Impacts, consequences, new directions. *Journal of Environmental Management* 232, 600-606. https://doi.org/10.1016/j.jenvman.2018.11.057

56. Cochrane, M.A. (2019). Burning questions about ecosystems. *Nature Geoscience* 12, 86–87. https://doi.org/10.1038/s41561-019-0306-x

57. Russell-Smith, J., Cook, G.D., Cooke, P.M., Edwards, A.C., Lendrum, M., Meyer, C.P. and Whitehead P.J. (2013). Managing fire regimes in north Australian savannas: applying Aboriginal approaches to contemporary global problems. *Frontiers in Ecology and the Environment* 11(s1), e55-e63. https://doi.org/10.1890/120251

58. Russell-Smith, J., McCaw, L. and Leavesley, A. (2020). Adaptive prescribed burning in Australia for the early 21st Century–context, status, challenges. *International Journal of Wildland Fire* 29(5), 305-313. https://doi.org/10.1071/WF20027

59. Russell-Smith, J., Moura, L.C., Yates, C., Beatty, R., Mafoko, J. and Johnston, S. (2021). Market-based options for supporting sustainable fire management of fire-prone Cerrado (savanna) remnant landscapes. *Biodiversidade Brasileira - BioBrasil* (2), 153–167. https://doi.org/10.37002/biobrasil.v11i2.1725

60. Kharuk, V.I., Ponomarev, E.I., Ivanova, G.A., Dvinskaya, M.L., Coogan, S.C. and Flannigan, M.D. (2021). Wildfires in the Siberian taiga. *Ambio* 50(11), 1953-1974. https://doi.org/10.1007/s13280-020-01490-x

61. Hanes, C.C., Wang, X., Jain, P., Parisien, M.A., Little, J.M. and Flannigan, M.D. (2019). Fire-regime changes in Canada over the last half century. *Canadian Journal of Forest Research* 49(3), 256-269. https://doi.org/10.1139/cjfr-2018-0293

62. Kitzberger, T., Perry, G.L.W., Paritsis, J., Gowda, J.H., Tepley, A.J., Holz, A. *et al.* (2016). Fire-vegetation feedbacks and alternative states: common mechanisms of temperate forest vulnerability to fire in southern South America and New Zealand. *New Zealand Journal of Botany* 54(2), 247-272. https://doi.org/10.1080/0028825X.2016.1151903

63. Brando, P., Macedo, M., Silvério, D., Rattis, L., Paolucci, L., Alencar, A. *et al*. (2020). Amazon wildfires: Scenes from a foreseeable disaster. *Flora* 268, 151609. https://doi.org/10.1016/j.flora.2020.151609

64. Marengo, J.A., Cunha, A.P., Cuartas, L.A., Deusdará Leal, K.R., Broedel, E., Seluchi, M.E. *et al.* (2021). Extreme Drought in the Brazilian Pantanal in 2019–2020: Characterization, Causes, and Impacts. *Frontiers in Water* 3, 13. https://doi.org/10.3389/frwa.2021.639204

65. Naumann, G., Podesta, G., Marengo, J., Luterbacher, J., Bavera, D., Arias-Muñoz, C. et al. (2021). The 2019-2021 extreme drought episode in La Plata Basin. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/773

66. Dowdy, A.J. (2018). Climatological Variability of Fire Weather in Australia. *Journal of Applied Meteorology and Climatology* 57(2), 221-234. https://doi.org/10.1175/JAMC-D-17-0167.1

67. Australia, Bureau of Meteorology and CSIRO (2020). State of the Climate 2020. http://www.bom.gov.au/state-of-the-climate/

68. Strydom, S. and Savage, M.J. (2017). Potential impacts of climate change on wildfire dynamics in the midlands of KwaZulu-Natal, South Africa. *Climatic Change* 143(3), 385-397. https://doi.org/10.1007/s10584-017-2019-8

69. González, M.E., Gómez-González, S., Lara, A., Garreaud, R. and Díaz-Hormazábal, I. (2018). The 2010–2015 Megadrought and its influence on the fire regime in central and south-central Chile. *Ecosphere* 9(8), e02300. https://doi.org/10.1002/ecs2.2300

70. Kouassi, J-L.K., Wandan, N.E. and Mbow, C. (2018). Assessing the Impact of Climate Variability on Wildfires in the N’Zi River Watershed in Central Côte d’Ivoire. *Fire* 1(3),36. https://doi.org/10.3390/fire1030036

71. Kraaij, T., Baard, J.A., Arndt, J., Vhengani, L. and Van Wilgen, B.W. (2018). An assessment of climate, weather, and fuel factors influencing a large, destructive wildfire in the Knysna region, South Africa. *Fire Ecology* 14(2), 1-12. https://doi.org/10.1186/s42408-018-0001-0

72. Dupuy, J., Fargeon, H., Martin, N., Pimont, F., Ruffault, J., Guijarro, M. *et al*. (2019). Climate Change Impact on Future Wildfire Danger and Activityin Southern Europe: A Review. *Annals of Forest Science* 77(2), 1-24. https://doi.org/10.1007/s13595-020-00933-5

73. Ertugrul, M., Varol, T., Ozel, H.B., Cetin, M. and Sevik, H. (2021). Influence of climatic factor of changes in forest fire danger and fire season length in Turkey. *Environmental Monitoring and Assessment* 193(1), 1-17. https://doi.org/10.1007/s10661-020-08800-6

74. Dowdy, A.J. and Mills, G.A. (2012). Characteristics of lightning-attributed wildland fires in south-east Australia. *International Journal of Wildland Fire* 21(5), 521-524. https://doi.org/10.1071/WF10145

75. Ganteaume, A., Camia, A., Jappiot, M., San-Miguel-Ayanz, J., Long-Fournel, M. and Lampin, C. (2012). A review of the main driving factors of forest fire ignition over Europe. *Environmental Management* 51(3), 651-662. https://doi.org/10.1007/s00267-012-9961-z

76. Romps, D.M., Seeley, J.T., Vollaro, D. and Molinari, J. (2014). Projected increase in lightning strikes in the United States due to global warming. *Science* 346(6211), 851-854. https://doi.org/10.1126/science.1259100

77. Collins, K.M., Price, O.F. and Penman, T.D. (2015). Spatial patterns of wildfire ignitions in south-eastern Australia. *International Journal of Wildland Fire* 24(8), 1098-1108. https://doi.org/10.1071/WF15054

78. Abatzoglou, J.T., Kolden, C.A., Balch, J.K., and Bradley, B.A. (2016). Controls on interannual variability in lightning-caused fire activity in the western US. *Environmental Research Letters* 11(4), 045005. https://doi.org/10.1088/1748-9326/11/4/045005r

79. Balch, J.K., Bradley, B.A., Abatzoglou, J.T., Nagy, R.C., Fusco, E.J. and Mahood, A.L. (2017). Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences* 114(11), 2946-2951. https://doi.org/10.1073/pnas.1617394114

80. Mariani, M., Holz, A., Veblen, T.T., Williamson, G., Fletcher, M.-S., and Bowman, D.M.J.S. (2018). Climate change amplifications of climate-fire teleconnections in the Southern Hemisphere. *Geophysical Research Letters* 45(10), 5071–5081. https://doi.org/10.1029/2018GL078294

81. Nagy, R., Fusco, E., Bradley, B., Abatzoglou, J.T. and Balch, J. (2018). Human-related ignitions increase the number of large wildfires across US ecoregions. *Fire* 1(1), 4. https://doi.org/10.3390/fire1010004

82. Veraverbeke, S., Rogers, B., Goulden, M., Jandt, R.R., Miller, C.E., Wiggins, E.B. *et al*. (2017). Lightning as a major driver of recent large fire years in North American boreal forests. *Nature Climate Change* 7(7), 529–534. https://doi.org/10.1038/nclimate3329

83. Dowdy, A. J. (2020). Climatology of thunderstorms, convective rainfall and dry lightning environments in Australia. *Climate Dynamics* 54(5), 3041-3052. https://doi.org/10.1007/s00382-020-05167-9

84. Fromm, M., Lindsey, D.T., Servranckx, R., Yue, G., Trickl, T., Sica, R. *et al*. (2010). The untold story of pyrocumulonimbus. *Bulletin of the American Meteorological Society* 91(9),1193-1210. https://doi.org/10.1175/2010BAMS3004.1

85. Dowdy, A.J., Fromm, M.D and McCarthy, N. (2017). Pyrocumulonimbus lightning and fire ignition on Black Saturday in southeast Australia. *Journal of Geophysical Research: Atmospheres* 122(14), 7342-7354. https://doi.org/10.1002/2017JD026577

86. Dowdy, A.J. and Pepler, A. (2018). Pyroconvection risk in Australia: Climatological changes in atmospheric stability and surface fire weather conditions. *Geophysical Research Letters* 45(4), 2005-2013. https://doi.org/10.1002/2017GL076654

87. Kablick III, G., Fromm, M., Miller, S., Partain, P., Peterson, D., Lee, S. *et al*. (2018). The Great Slave Lake pyroCb of 5 August 2014: Observations, simulations, comparisons with regular convection, and impact on UTLS water vapor. *Journal of Geophysical Research: Atmospheres* 123(21), 12-332. https://doi.org/10.1029/2018JD028965

88. Peterson, D.A., Campbell, J.R., Hyer, E.J., Fromm, M.D., Kablick, G.P., Cossuth, J.H. *et al*. (2018). Wildfire-driven thunderstorms cause a volcano-like stratospheric injection of smoke. *NPJ Climate and Atmospheric Science* 1(1), 1-8. https://doi.org/10.1038/s41612-018-0039-3

89. Zuev, V.V., Gerasimov, V.V., Nevzorov, A.V. and Savelieva, E.S. (2019). Lidar observations of pyrocumulonimbus smoke plumes in the UTLS over Tomsk (Western Siberia, Russia) from 2000 to 2017. *Atmospheric Chemistry and Physics* 19(5), 3341-3356. https://doi.org/10.5194/acp-19-3341-2019

90. Di Virgilio, G., Evans, J.P., Blake, S.A., Armstrong, M., Dowdy, A.J., Sharples, J. *et al.* (2019). Climate change increases the potential for extreme wildfires. *Geophysical Research Letters* 46(14), 8517-8526. https://doi.org/10.1029/2019GL083699

91. Clarke, H., Pitman, A.J., Kala, J., Carouge, C., Haverd, V. and Evans, J. (2016). An investigation of future fuel load and fire weather in Australia. *Climatic Change* 139(3), 591-605. https://doi.org/10.1007/s10584-016-1808-9

92. Haverd, V., Smith, B., Canadell, J.G., Cuntz, M., Mikaloff-Fletcher, S., Farquhar, G. *et al*. (2020). Higher than expected CO2 fertilization inferred from leaf to global observations. *Global Change Biology*, 26(4), 2390-2402. https://doi.org/10.1111/gcb.14950

93. Mondal, P. and McDermid, S.S. (2021). Editorial for Special Issue: "Global Vegetation and Land Surface Dynamics in a Changing Climate". *Land* 10(1), 45. https://doi.org/10.3390/land10010045

94. Moreira, F., Ascoli, D., Safford, H., Adams, M.A., Moreno, J.M., Pereira, J.M.C. *et al.* (2020). Wildfire management in Mediterranean-type regions: paradigm change needed. *Environmental Research Letters* 15(1), 011001. https://doi.org/10.1088/1748-9326/ab541e

95. Ingalsbee, T. (2017). Whither the paradigm shift? Large wildland fires and the wildfire paradox offer opportunities for a new paradigm of ecological fire management. *International Journal of Wildland Fire*, 26(7), 557-561. https://doi.org/10.1071/WF17062

96. Hugelius, G., Loisel, J., Chadburn, S., Jackson, R.B., Jones, M., MacDonald, G. *et al*. (2020). Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw. *Proceedings of the National Academy of Science*s 117(34), 20438-20446. https://doi.org/10.1073/pnas.1916387117

97. Yanagiya, K. and Furuya, M. (2020). Post-Wildfire Surface Deformation Near Batagay, Eastern Siberia, Detected by L-Band and C-Band InSAR. *Journal of Geophysical Research: Earth Surface* 125(7), e2019JF005473. https://doi.org/10.1029/2019JF005473

98. Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S. and Schellnhuber, H.J. (2008). Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences* 105(6), 1786-1793. https://doi.org/10.1073/pnas.0705414105

99. Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D. *et al*. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences* 115(33), 8252-8259. https://doi.org/10.1073/pnas.1810141115

100. Gatti, L.V., Basso, L.S., Miller, J.B., Gloor, M., Gatti Domingues, L., Cassol, H.L. *et al*. (2021). Amazonia as a carbon source linked to deforestation and climate change. *Nature* 595(7867), 388-393. https://doi.org/10.1038/s41586-021-03629-6

101. Rodríguez-Trejo, D. A., Martínez-Hernández, P. A., Ortiz-Contla, H., Chavarría-Sánchez, M. R. and Hernandez-Santiago, F. (2011). The present status of fire ecology, traditional use of fire, and fire management in Mexico and Central America. *Fire Ecology* 7(1), 40-56. https://doi.org/10.4996/fireecology.0701040

102. Sletto, B. (2008). The knowledge that counts: institutional identities, policy science, and the conflict over fire management in the Gran Sabana, Venezuela. *World Development* 36(10), 1938-1955. https://doi.org/10.1016/j.worlddev.2008.02.008

103. Bilbao, B., Mistry, J., Millán, A. and Berardi, A. (2019). Sharing Multiple Perspectives on Burning: Towards a Participatory and Intercultural Fire Management Policy in Venezuela, Brazil, and Guyana. *Fire* 2(3), 39. https://doi.org/10.3390/fire2030039

104. Australia, Commonwealth of Australia (2018). Carbon Credits (Carbon Farming Initiative – Savanna Fire Management – Emissions Avoidance) Methodology Determination. https://www.industry.gov.au/regulations-and-standards/methods-for-the-emissions-reduction-fund/savanna-fire-management-emissions-avoidance-method

105. Schmidt, I.B., Moura, L.C., Ferreira, M.C., Eloy, L., Sampaio, A.B., Dias, P.A. *et al*. (2018). Fire management in the Brazilian savanna: First steps and the way forward. *Journal of Applied Ecology* 55(5), 2094-2101. https://doi.org/10.1111/1365-2664.13118

106. Berlinck, C.N. and Batista, E.K. (2020). Good fire, bad fire: It depends on who burns. *Flora* 268, 151610. https://doi.org/10.1016/j.flora.2020.151610

107. de Moraes Falleiro, R., Steil, L., de Oliveira, M.S., Lando, I., Machado, L.D.O.R., Cunha, A.M.C. *et al*. (2021). Histórico, Avaliação, Oportunidades e Desafios do Manejo Integrado do Fogo nas Terras Indígenas Brasileiras. *Biodiversidade Brasileira - BioBrasil* (2), 75-98. https://revistaeletronica.icmbio.gov.br/BioBR/article/view/1742

108. Government of Brazil (2021). Ibama contrata mais de 1,5 mil brigadistas, o equivalente a 89,8% do previsto no edital. 22 September 2021. https://www.gov.br/pt-br/noticias/meio-ambiente-e-clima/2021/09/ibama-contrata-mais-de-1-5-mil-brigadistas-o-equivalente-a-89-8-do-previsto-no-edital. Accessed 12 January 2022

109. Bello, O., Bustamante, A. and Pizarro, P. (2021). Planning for disaster risk reduction within the flamework of the 2030 Agenda for Sustainable Development. *Project Documents* (LC/TS.2020/108), Santiago, Economic Commission for Latin America and the Caribbean (ECLAC). https://repositorio.cepal.org/bitstream/handle/11362/46639/1/S2000452_en.pdf

110. Douglas K. Bardsley, Thomas A.A. Prowse & Caren Siegfriedt (2019). Seeking knowledge of traditional Indigenous burning practices to inform regional bushfire management. *Local Environment* 24:8, 727-745, https://doi.org/10.1080/13549839.2019.1640667

111. Paveglio, T.B. (2021). From Checkers to Chess: Using Social Science Lessons to Advance Wildfire Adaptation Processes. *Journal of Forestry*, 119(6), 618-639. https://doi.org/10.1093/jofore/fvab028

112. United States of America, National Aeronautics and Space Administration. (2022). Fire Information for Resource Management System. https://firms.modaps.eosdis.nasa.gov/. Accessed 4 February 2022.

113. RedLaTIF (2021). Red Latinoamericana de Teledetección e Incendios Forestales. http://www.redlatif.org/en/. Accessed 10 December 2021.

114. Instituto Nacional de Pesquisas Espaciais (2021). Situação Atual, 9 December. https://queimadas.dgi.inpe.br/queimadas/portal-static/situacao-atual. Accessed 9 December 2021.

115. South Africa, Department of Forestry, Fisheries, and the Environment (2021). Working on Fire. https://www.dffe.gov.za/projectsprogrammes/workingonfire

116. AFAC (2018). Fire and Emergency Services and Climate Change. Position Version 1.0, 24 October 2018. https://www.afac.com.au/docs/default-source/doctrine/afac-position-fire-and-emergency-services-and-climate-change.pdf

117. Australia, Department of Home Affairs (2018). *National Disaster Risk Reduction Framework*. https://www.homeaffairs.gov.au/emergency/files/national-disaster-risk-reduction-framework.pdf

118. Westcott, R., Ronan, K., Bambrick, H. and Taylor, M. (2020). Natural hazards and adaptive response choices in a changing climate: Promoting bushfire preparedness and risk reduction decision-making. *Social Sciences & Humanities Open* 2(1), 100065. https://doi.org/10.1016/j.ssaho.2020.100065

119. Wunder, S., Calkin, D.E., Charlton, V., Feder, S., de Arano, I.M., Moore, P. *et al*. (2021). Resilient landscapes to prevent catastrophic forest fires: Socioeconomic insights towards a new paradigm. *Forest Policy and Economics* 128, 102458. http://dx.doi.org/10.1016/j.forpol.2021.102458

120. Australian Institute for Disaster Resilience (2021). AIDR Service Statement 2021-2025 - Our approach. https://www.aidr.org.au/media/8807/aidr-approach-2021-25_2021-07-13_v11_digital.pdf

图表参考文献

过去二十年内的过火面积

安哥拉

Catarino, S., Romeiras, M.M., Figueira, R., Aubard, V., Silva, J.M.N. and Pereira, J.M.C. (2020). Spatial and Temporal Trends of Burnt Area in Angola: Implications for Natural Vegetation and Protected Area Management. *Diversity*, 12, 307. https://doi.org/10.3390/d12080307

澳大利亚

Canadell, J.G., Meyer, C.P., Cook, G.D., Dowdy, A., Briggs, P.R., Knauer, J. *et al.* (2021). Multi-decadal increase of forest burned area in Australia is linked to climate change. *Nature Communications* 12, 6921. https://doi.org/10.1038/s41467-021-27225-4

玻利维亚

Heyer, J.P., Power, M.J., Field, R.D. and van Marle, M.J. (2018). The impacts of recent drought and fire in lowland Bolivia on forest loss and regional smoke emissions. *Biogeosciences*. https://doi.org/10.5194/bg-2017-462

巴西

Le Stradic, S. and Buisson, E. (2021). Restoring savannas and tropical herbaceous ecosystems, Encyclopedia of the Environment: The Cerrado biome. https://www.encyclopedie-environnement.org/en/zoom/cerrado-biome/

Schmidt, I.B. and Eloy, L. (2020). Fire regime in the Brazilian Savanna: Recent changes, policy and management. *Flora* 268, 151613. https://doi.org/10.1016/j.flora.2020.151613

加拿大

Veraverbeke, S., Rogers, B., Goulden, M., Jandt, R.R., Miller, C.E., Wiggins, E.B. *et al*. (2017) Lightning as a major driver of recent large fire years in North American boreal forests. *Nature Climate Change* 7, 529–534. https://doi.org/10.1038/nclimate3329

智利

McWethy, D.B., Pauchard, A., Garcı´a, R.A., Holz, A., Gonza´lez, M.E., Veblen, T.T. *et al*. (2018) Landscape drivers of recent fire activity (2001-2017) in south-central Chile. *PLoS ONE* 13(8):e0201195. https://doi.org/10.1371/journal.pone.0201195

墨西哥

Zúñiga-Vásquez, J.M., Cisneros-González, D. and Pompa-García, M. (2017). Drought regulates the burned forest areas in Mexico: the case of 2011, a record year. *Geocarto International* 34, 1–14. https://doi.org/10.1080/10106049.2017.1415986

巴拉圭

Chen, Y., Morton, D.C., Jin, Y., Collatz, G.J., Kasibhatla, P.S., van der Werf, G.R. *et al*. (2013). Long-term trends and interannual variability of forest, savanna and agricultural fires in South America. *Carbon Management*, 4(6), 617-638. https://doi.org/10.4155/cmt.13.61

俄罗斯2003年

Forkel, M., Thonicke, K., Beer, C., Cramer, W., Bartalev, S. and Schmullius, C. (2012). Extreme fire events are related to previous-year surface moisture conditions in permafrost-underlain larch forests of Siberia. *Environmental Research Letters*, 7(4), 044021. https://doi.org/10.1088/1748-9326/7/4/044021

Ponomarev E.I., Kharuk, V.I. and Ranson, K.J. (2016). Wildfires Dynamics in Siberian Larch Forests. *Forests*, 7(6), 125. https://doi.org/10.3390/f7060125

人类世野火

野火是什么?

38. UNEP and GRID-Arendal (2021).

野火与生态系统

36. Bond and Keane (2017).

Keane R.E. (2019). Fire Ecology. In: Manzello S. (eds) Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires. Springer, Cham. https://doi.org/10.1007/978-3-319-51727-8_254-1

野火类型

Keeley, J. E. (2012). Ecology and evolution of pine life histories. *Annals of Forest Science* 69, 445–453. https://doi.org/10.1007/s13595-012-0201-8

Pyne, S. (2010). The Ecology of Fire. *Nature Education Knowledge* 3(10):30. https://www.nature.com/scitable/knowledge/library/the-ecology-of-fire-13259892/

Xanthopoulos G. and Athanasiou, M. (2020). Crown Fire. In: Manzello S.L. (eds) Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires. Springer, Cham. https://doi.org/10.1007/978-3-319-52090-2_13

火灾依赖型植物

36. Bond and Keane (2017)

Keeley, J. E. (2012). Ecology and evolution of pine life histories. *Annals of Forest Science* 69, 445–453. https://doi.org/10.1007/s13595-012-0201-8

Keeley, J.E. and Fotheringham, C.J. (2000). Role of fire in regeneration from seed. In Fenner, M. (ed.), Seeds: the ecology of regeneration in plant communities. Chapter 13. CAB International. http://dx.doi.org/10.1079/9780851994321.0000

火灾发生地区

15. Andela *et al*. (2019)

Giglio, L., Boschetti, L., Roy, D.P., Humber, M.L. and Justice, C.O. (2018). The Collection 6 MODIS burned area mapping algorithm and product. *Remote Sensing of Environment*, 217, 72-85. https://doi.org/10.1016/j.rse.2018.08.005

火灾范式正在改变

特定生物群落的火灾范式不断变化和土地利用变化

35. Bowman *et al*. (2011)

36. Bond and Keane (2017)

42. Bowman *et al*. (2020)

Shlisky, A. (2007). Fire, ecosystems and people: Threats and strategies for global biodiversity conservation. Wildfire conference 2007, Seville, Spain. https://www.researchgate.net/publication/259657820

MapBiomas Project (2020). Collection 6 of the Annual Series of Land Use and Land Cover Maps of Brazil, 16 August. https://mapbiomas.org/infograficos-1?cama_set_language=en. Accessed 1 December 2021.

Souza, C.M. Jr., Shimbo, Z.J., Rosa, M.R., Parente, L.L., Alencar, A.A., Rudorff, B.F.T. *et al*. (2020). Reconstructing Three Decades of Land Use and Land Cover Changes in Brazilian Biomes with Landsat Archive and Earth Engine. *Remote Sensing* 12(17), 2735. https://doi.org/10.3390/rs12172735

NASA Earth Observatory (2022). What’s behind California’s surge of large fires? https://earthobservatory.nasa.gov/images/148908/whats-behind-californias-surge-of-large-fires

火灾和入侵物种

44. Fusco et al. (2019)

Halofsky, J.E., Peterson, D.L. and Harvey, B.J. (2020). Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology*, 16, 4 https://doi.org/10.1186/s42408-019-0062-8

Hamilton, N.P., Yelenik, S.G., Durboraw, T.D., Cox, R.D. and Gill, N.S. (2021). Understanding Grass Invasion, Fire Severity, and *Acacia koa* Regeneration for Forest Restoration in Hawai‘i Volcanoes National Park. *Land* 10, 962. https://doi.org/10.3390/land10090962

Pausas, J.G. and Keeley, J.E. (2014). Abrupt Climate-Independent Fire Regime Changes. *Ecosystems* 17, 1109–1120. https://doi.org/10.1007/s10021-014-9773-5

气候变化：
火灾天气变得越来越极端

36. Bond and Keane (2017)

42. Bowman *et al*. (2020)

Keeley, J.E. and Syphard, A.D. (2016). Climate Change and Future Fire Regimes: Examples from California. *Geosciences*, 6(3):37. https://doi.org/10.3390/geosciences6030037

Rogers, B.M., Balch, J.K., Goetz, S.J., Lehmann, C.E.R. and Turetsky, M. (2020). Focus on changing fire regimes: interactions with climate, ecosystems, and society. *Environmental Research Letters*, 15(3), p.030201. https://doi.org/10.1088/1748-9326/ab6d3a

雷电起火

36. Bond and Keane (2017)

42. Bowman *et al*. (2020)

Kharuk, V.I., Ponomarev, E.I., Ivanova, G.A. Dvinskaya, M.L., Coogan, S.C.P. and Flannigan, M.D. (2021). Wildfires in the Siberian taiga. Ambio. https://doi.org/10.1007/s13280-020-01490-x

Veraverbeke, S., Rogers, B., Goulden, M., Jandt, R.R., Miller, C.E., Wiggins, E.B. *et al*. (2017). Lightning as a major driver of recent large fire years in North American boreal forests. *Nature Climate Change* 7, 529–534. https://doi.org/10.1038/nclimate3329

火灾引发的雷暴

Australia, National Environmental Science Programme (2020). Fire-generated thunderstorms and climate change in Australia. https://nespclimate.com.au/wp-content/uploads/2021/05/ESCC_Fire-Generated-Thunderstorms_Brochure.pdf

极端野火对地球生态系统的影响

大气污染

Lapere, R., Mailler, S. and Menut, L. (2021). The 2017 Mega-Fires in Central Chile: Impacts on Regional Atmospheric Composition and Meteorology Assessed from Satellite Data and Chemistry-Transport Modeling. *Atmosphere* 12, 344. https://doi.org/10.3390/atmos12030344

改变反照率

42. Bowman *et al*. (2020)

de Magalhães, N., Evangelista, H., Condom, T., Rabatel, A. and Ginot, P. (2019). Amazonian biomass burning enhances tropical Andean glaciers melting. *Scientific Reports*, 9(1), 1-12. https://doi.org/10.1038/s41598-019-53284-1

碳汇变成碳源

42. Bowman *et al*. (2020)

水污染

Bladon, K.D., Emelko, M.B., Silins, U. and Stone, M. (2014). Wildfire and the future of water supply. *International Journal of Environmental Science and Technology* 48(16), 8936–8943. https://doi.org/10.1021/es500130g

Hauer, F.R. and Spencer, C.N. (1998). Phosphorus and nitrogen dynamics in streams associated with wildfire: a study of immediate and longterm effects. *International Journal of Wildland Fire* 8(4), 183-198. https://doi.org/10.1071/WF9980183

Yu, M., Bishop, T.F. and Van Ogtrop, F.F. (2019). Assessment of the decadal impact of wildfire on water quality in forested catchments. *Water* 11(3) 533. https://doi.org/10.3390/w11030533

侵蚀

Bladon, K.D., Emelko, M.B., Silins, U. and Stone, M. (2014). Wildfire and the future of water supply. *International Journal of Environmental Science and Technology* 48(16), 8936–8943. https:/doi.org/10.1021/es500130g

海洋肥沃化

Tang, W., Llort, J., Weis, J., Perron, M.M.G., Basart, S., Li, Z. *et al*. (2021). Widespread phytoplankton blooms triggered by 2019–2020 Australian wildfires. *Nature*, 597(7876), 370–375. https://doi.org/10.1038/s41586-021-03805-8

生物多样性丧失

Halofsky, J.E., Peterson, D.L. and Harvey, B.J. (2020). Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology* 16(4), 1-26. https://doi.org/10.1186/s42408-019-0062-8

受火灾范式改变影响的物种

Kelly, L.T., Giljohann, K.M., Duane, A., Aquilué, N., Archibald, S., Batllori, E. *et al*. (2020). Fire and biodiversity in the Anthropocene. *Science*, 370(6519). https://doi.org/10.1126/science.abb0355

物候

气候变化正在改变自然节奏

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1.
时机对生态系统和谐至关重要

在自然界中，时机至关重要。雏鸟必须有食物喂养才能孵化，寄主植物开花时传粉昆虫开始忙碌，雪兔在雪融化过程中须把白色毛变为棕色。物候学研究在环境因素的驱动下，循环往复的各个生命周期阶段的时间，以及在一个生态系统内互相影响的物种如何应对时节更替。[1,2]动植物经常会通过气温、日长、降雨或其他自然变化来判断季节阶段的更替。当春天提早到来，许多鸟类也会提前繁殖，随着温度回升，为它们的雏鸟匹配提前出现的食物。由于气温对季节更替迹象的影响很大，因此在过去几十年，物候变化是全球气候变化最明显的一个后果，至少在世界温带和极地地区是这样。

气温并不是影响物候的唯一环境变量。在高纬度地区，另一个关键变量是在一年中会随时间发生变化的光照周期或日长。[3-5]虽然光照周期本身不受气候变化的影响，但气温对物候的影响程度可能取决于光照周期。在某些生态系统中，高温且光照时间长（而不是光照时间短）预示着下一个时节的到来。[3,6,7]在高纬度地区，一些植物和昆虫还需要度过一段低温时期，即冬寒期，以便在气温回暖时更好地适应环境。[8-10]一些物种通过火灾来判断生命周期阶段，例如火灾触发球果释放种子和种子发芽。[11,12]以水生态系统为例：降雨影响河流量，再加上水温和光照周期等因素，进而影响鱼类洄游的时机和持续时间。[13-15]

由于气温和日照变化幅度较小，要了解热带地区的物候比一年四季分明的地区复杂得多。[16-18]热带物种的物候策略各不相同，同一个种群中的个体可能并不同步，生命周期可能不足12个月。在热带地区，降雨、干旱、湿度和日照充足等不同因素可以触发下一个生命周期阶段的到来。[17-21]

气候变化引起物候变化的一大问题是，在某个特定生态系统中，并非所有相互依存的物种都朝着同一个方向或以相同的速度发生变化。[16,22-26]变化不同的原因是每种生物对不同的环境因素敏感，或对单个环境因素表现出不同程度的敏感性。[5,17,27,28]在食物链中，植物可能比以其为食的动物更快地改变生长进程，从而导致物候不匹配。针对大量动植物物种的不同生命周期阶段的详细研究发现了显著的物候不匹配。[16,22,30-34]食物网中捕食者和食物源之间的不匹配将影响生物个体的生长率、繁殖率和存活率，最终对整个种群和生态系统产生影响。

图片来源：Meyers Lexicon book from 1908 and Nicku / Shutterstock.com.

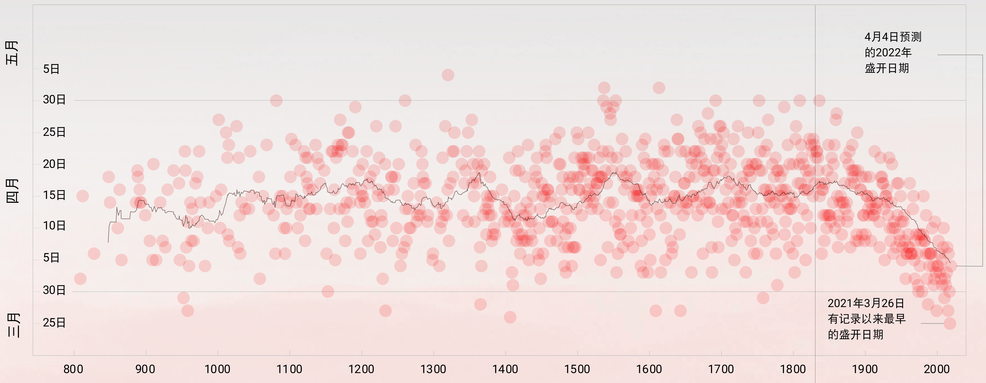
热带地区的物候

热带气候的一个关键特征是四季气温变化不明显。[18]相比之下，降雨量的变化以及旱季和雨季的交替更清楚地划分了热带地区一年周期中的各个阶段。[16,18]降雨的频率和强度或无降雨，以及日照、湿度和气温小幅度变化都是热带植物物候变化的关键推动因素。[16-21]鉴于热带生态系统中物种的高度多样性，物种和群落对这些因素的物候反应多种多样且非常复杂。[19,35]

热带地区的降雨模式深受厄尔尼诺/拉尼娜南方涛动（ENSO）的影响，其特点是赤道太平洋海表温度的冷暖交替。[36]这些异常现象会每2-7年发生一次，每次通常持续9-12个月。[36]热带植物群落对ENSO事件的反应各不相同，例如厄尔尼诺现象会引起大规模开花或干旱会影响结果。[17,18,20,37]ENSO和气候变化导致的更频繁且更严重的极端天气事件可能会进一步干扰生叶、开花和结果的时间。[17,18]这种物候变化将会对依赖型食草动物、食蜜动物和食果动物以及生态系统内的其他功能种群产生连锁效应。[17,19]对热带地区物候变化的长期观测仍然很少，预测物候变化和不匹配程度的仍是一项挑战。[18]

1,200多年来樱花盛开日期分布

趋势曲线是每50年平均盛开日期的变化曲线



数据来源：
历史数据由日本大阪府立大学的Yasuyuki Aono提供，见http://atmenv.envi.osakafu-u.ac.jp/aono/kyophenotemp4/

1950年的数据由日本气象厅提供，见http://www.data.jma.go.jp/sakura/data/index.html

在日本，樱花（*Prunus jamasakura*）盛开标志着春天的到来，樱花是日本文化的核心。樱花的庆祝活动可以追溯到公元712年左右。[38]京都以往的物候观测数据记录在旧日志和编年史中。[39-41]研究人员根据最早可追溯到公元812年的这些文件汇编了一系列关于樱花盛开日期的物候数据。[39-41]

在过去1,200多年来，樱花盛开期最早在3月下旬，最晚在5月上旬。[24]

自1830年代以来，开花期呈逐渐提前趋势，而根据气象观测，这一趋势恰好与气温升高相吻合，且城市高温的偏差效应已经消除。[41,42]

2. 对生态和谐的破坏

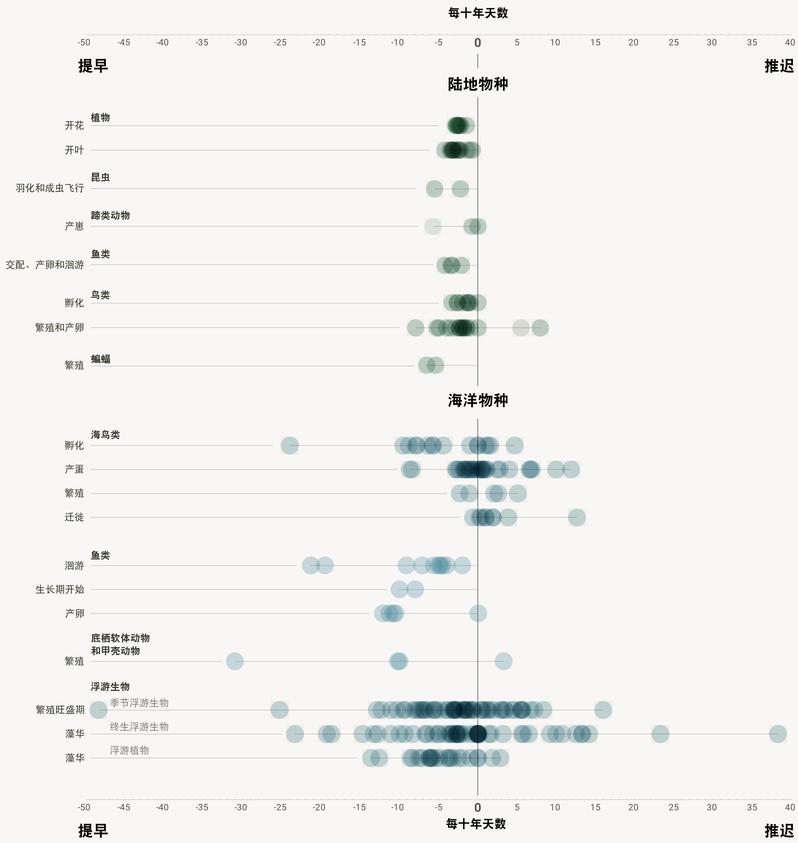
气候变化导致的物候变化已在繁殖、开花、生叶、幼虫开始发育、羽化、冬眠、迁徙等多个生长阶段有所体现。支持数据来自比较大量物种（植物、昆虫、鱼类、两栖动物、鸟类和哺乳动物）间的物候变化的研究，通过在南北半球的长期观测记录了这些物种的物候事件。[16,23,29-33,43-51]研究人员还发现在多个地区，物候不匹配的可能性呈增加趋势，这是根据有关全英国动植物和阿尔卑斯山陆地物种的10,000个数据集、南半球1,200多个物候趋势的时间序列以及各大洋的海洋物种等得出的。[16,19,23,32,43,51]

识别变化跟踪趋势

2000年代初，研究人员发表了一些关于物候变化的广泛开创性评估报告，这些评估报告成为正在开展的工作的典范。[22,29,30]这些数据库综合表明，203个动植物物种的生长阶段每十年会提前约2.8天。[30]此后评估了其他生态系统和生物群落的物候趋势。下图的可视化数据显示了最近评估报告中记录的在分类种群中观察到的物候变化。[31-33,49]

每个圆圈代表某个物种量化的物候反应速率，即每十年物种提前或推迟进入下一个生长阶段的天数。圆圈重叠代表同一分类种群中的两个或多个物种以相似的速率进入下一个生长阶段。

完整参考见第57页。



鸟类研究充分证明了物候不匹配影响成功繁殖。斑姬鹟（*Ficedula hypoleuca*）和大山雀（*Parus major*）等物种需要在它们的常规食物毛毛虫供应最充足的时候孵化雏鸟。[52-55]而这一食物供应高峰期很短，仅持续几周，所以准确的孵化时间至关重要。崖海鸦（*Uria aalge*）等其他鸟类需要根据它们的主要食物小型饵料鱼向近岸回游的时间精准地确定繁殖时间。[56]

在年周期内，不同的生长阶段需要同步。对于迁徙物种，年周期包括迁移到繁殖地、繁殖、换羽并回到越冬地等阶段。繁殖等其他生命周期阶段对气温高度敏感。随着气温升高，生殖物候正在发生变化，而换羽等其他阶段对光照周期更敏感，因此它们不会同步发生。[57,58]

在整个海洋生态系统和季节周期中，物候反应各不相同，导致食物网中的物种和种群不匹配。[31,32,43,59]研究表明，气候变化引起的物候反应在海洋环境中比在陆地上发生得更快。[31,32]从浮游生物到高级捕食者，不同的海洋群体都以不同的速度改变着它们的物候，这表明气候变化也会在整个海洋群落中引起物候不匹配。[31,32,60,61]

陆地、淡水和海洋生态系统对气候变暖的物候反应速率的差异最终会影响依赖不同生态系统来完成物候交替以进入下一个生命周期阶段的物种。这类物种包括在海洋和淡水生态系统之间洄游的鱼类，以及生命周期阶段依赖于陆地和水生生态系统的许多昆虫、两栖动物和鸟类。[24,62-64]物候不匹配会导致食物网遭到破坏并对生态产生影响。[26]

虽然气候变化引起的物候反应有充分的证据，但与种群的联系和对生态系统的影响等遗留问题值得更多关注。[34,51]在北极，雪融化后，雌性北美驯（*Rangifer tarandus*）和其幼崽赖以生存的植被由于气温回暖已显著提前生长。目前，幼崽鹿出生太晚，导致后代数量减少了75%。[65]孢子（*Capreolus capreolus*）的产崽时间和可获得的植物生长期不匹配也减少了幼崽的存活机会。[66]

大量相互影响的物种的非同步物候变化可能会破坏整个生态系统的运作和人类系统赖以生存的生态系统服务的提供。[34,61]具有重要商业价值的海洋物种及其捕食对象的物候变化对渔业的各方面产生了显著影响。[47,67-69]随着气候变化，农作物针对季节交替的物候反应将是粮食生产的一大挑战。例如，果树提前开花，接着遭遇晚霜冻，给果园带来了巨大的经济损失。[70]物候变化已经使全球主要农作物的气候智慧型农业适应性变得复杂。[71]

饥饿的鸟儿和提早繁殖的毛毛虫

一个长期存在且众所周知的物候不匹配例子是关于大山雀（*Parus major*）和它的食物毛毛虫。[54,55]这种小型筑巢鸣禽遍布亚洲和欧洲，而且产下的雏鸟体型很大。大山雀成鸟必须给雏鸟喂养大量食物，让雏鸟在18天内快速成长并发育完全。在此期间，母鸟可能会每分钟给雏鸟喂一条虫子。[72]为确保充足的食物供应，大山雀会通过气温来判断下蛋时间，以便在橡树上的毛毛虫繁殖旺盛期孵化雏鸟。出于同样的原因，毛毛虫在橡树长出嫩叶的时候孵化虫卵。[73]

通过实地观察发现，这两种相互影响的物种在不同地点的物候反应不同。[54,55,74,75]在荷兰，大山雀种群已提前下蛋以应对气候变暖趋势，但这种变化不足以与毛毛虫的繁殖旺盛期相匹配。[54,55,74]预测表明，未来几十年毛毛虫的物候变化将继续早于大山雀，使不匹配现象变得更加严重。[76]相比之下，英国一项为期47年的种群研究发现，鸟类和毛毛虫在以基本相同的速度改变着它们的生长繁殖时间，使它们的相互影响保持同步。[75]在比利时和捷克共和国也得出了类似的结果。[77,78]这些研究结果表明了在不同的环境中不同物种和种群复杂的物候反应。[27,80]

奇妙之旅：

不合时机的迁徙带来的挑战

迁徙是适应季节交替的一种行为。[81]动物在生境之间周期性迁徙使它们能够在一年中的不同时间充分利用多个地区的资源。当季节性气温或水温不再适合繁殖或饲养后代时，也必须迁徙。因此，大多数迁徙物种来自高纬度地区。在这里，季节和可用资源变化最明显。[81]昆虫、甲壳类动物、爬行动物、鱼类和哺乳动物等不同物种都会迁徙，其中许多物种迁徙的距离很远。一些候鸟在北极高地筑巢，但在低纬度地区过冬。鲸类物种在赤道和极地觅食地区之间洄游。食草哺乳动物会在各大陆随着植被的季节性变化而迁徙。[81,82]

远距离迁徙物种特别容易受到气候变暖效应引起的物候变化的影响，而气候变暖效应因地区而异。可能无法再根据通常触发迁徙的当地气候状况来准确预测目的地和沿途停歇地点的条件。因为极地地区的气候变化最快且最猛烈，所以迁徙物种返回极地地区的挑战更大。[83,84]因此，许多迁徙物种努力在优质食物仍丰富、气候适合特定生命周期阶段、捕食或竞争压力较低或寄生虫和病原体较少的时候到达迁徙目的地。[34,81,85,86]高纬度地区春季物候提前导致迁徙物种的生态不匹配日益严重，并有可能对群体造成影响。[81,86,87]

从调整迁徙时间到改变迁徙路线和地点，物种已经展现出改变其迁徙行为的能力。[81,85,88,89]但其他持续存在的威胁削弱了它们应对气候变化的适应能力。生态退化、片断化以及觅食、繁殖和休息生境的丧失、人类狩猎、污染和长距离迁移中的其他危害正在威胁着迁徙物种，它们适应环境快速变化的压力越来越大。[88,90]

要想最大限度地发挥物种种群的适应潜力并提高它们的抵御力，需要减少传统威胁并根据气候变化修改现有的环境保护政策和战略。[81,91]由各种重点区域和受保护的生境组成的大规模网络有助于最大限度地发挥迁徙物种的适应潜力。[88]不仅是现在，在将来也必须确保并加强对物种传播至关重要的陆地和海洋生境的连通性。[88,92]改善生境连通性将有助于保留物种生存所需的适应性遗传变异和种群生存能力。

欧洲候鸟

对117种欧洲候鸟50年来春季回迁时间的分析表明，春季物候不匹配程度越来越严重，导致迁徙物种数量减少，特别是在撒哈拉以南非洲越冬的物种。[87]

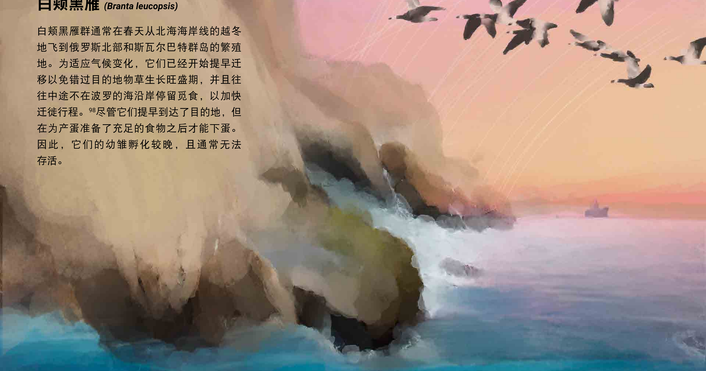
白鹳 *(Ciconia ciconia)*

白鹳是一种长寿的候鸟，在非洲越冬。[93]它们会调整迁徙时间以提前到达欧洲各个地区的繁殖地，并提前筑巢已避免与食物供应不匹配。

提早繁殖使幼雏处于不利的环境（如强风和强降雨）中。随着气候变化，极端天气事件预计将变得更加频繁，未来白鹳雏鸟死亡率可能会增加。[94,95]

白颊黑雁 *(Branta leucopsis)*

白颊黑雁群通常在春天从北海海岸线的越冬地飞到俄罗斯北部和斯瓦尔巴特群岛的繁殖地。为适应气候变化，它们已经开始提早迁移以免错过目的地物草生长旺盛期，并且往往中途不在波罗的海沿岸停留觅食，以加快迁徙行程。[98]尽管它们提早到达了目的地，但在为产蛋准备了充足的食物之后才能下蛋。因此，它们的幼雏孵化较晚，且通常无法存活。



帝王蝶 *(Danaus plexippus)*

北美帝王蝶夏季在加拿大南部和美国北部完成繁殖，在墨西哥中部越冬，因长达4,300公里的迁徙距离而闻名。[96]

秋季日照时间短且气温较低，通常会迫使帝王蝶南飞。超过29年的分析表明，由于气温高于正常水平，它们的迁移时间每十年会推迟6天。与季节早期迁徙物种相比，季节晚期迁徙物种抵达越冬地的可能性似乎更小，这可能是由于一路迁徙的时间与食物供应期不匹配。[97]

海龟

各种洄游海龟通过改变筑巢时间来应对不断升高的海水温度。研究发现，蠵龟（*Caretta caretta*）会提早筑巢，而棱皮海龟（*Dermochelys coriacea*）则会推迟筑巢。[99-102]

然而，观测到的筑巢物候变化可能还不足以判定最佳的环境条件。[101-103]孵化期间的海滩温度会影响孵化成功率并直接决定幼崽性别（在较高的气温条件下孵化雌性龟）。由于快速变化的气候，孵化成功率和性别比例偏差将对海龟种群产生影响。

须鲸类

大多数须鲸类会随季节化在低纬度产崽地和高纬度觅食地（捕食群或饵料鱼群）之间洄游。[85,104,105]

众所周知，许多须鲸物种会根据捕食对象的繁殖情况改变洄游时间。在过去27年中，长须鲸和座头鲸每年都会提早1天洄游到加拿大东部附近的圣劳伦斯湾觅食地，而这可能是由于冰层破裂提前且海面温度不断上升，进而引发浮游生物提前繁殖并影响猎物丰度。[85]长须鲸等短距离洄游物种可能会因气温变化和冬季海冰减少而减少洄游，但对座头鲸等长距离洄游物种来说，要在猎物丰足的时候准确抵达目的地很难。[85]

哥伦比亚戈尔戈纳国家自然公园是东南太平洋座头鲸的重要繁殖地和产崽地。在过去30年中，东南太平洋座头鲸累积提早1个月到达这里。这可能是由于南极觅食地海冰形成发生变化影响了磷虾数量，而且猎物减少说明了要返回热带水域。[105]

众所周知，东北太平洋蓝鲸改变了洄游习惯，比10年前提前约42天抵达加利福尼亚附近的觅食地。这种变化与海面温度至少升高2°C以及由此产生的磷虾丰度有关。[106]

尽管表型可塑性（适应不断变化的环境信号的能力）可以帮助这些物种调整洄游时间，但改变生命周期中某个阶段的时间会对另一个阶段产生负面影响。在觅食地停留的时间延长，会缩短繁殖期，反之亦然。[106]也需要调整渔业、海上交通和地震探测等人类活动，以适应鲸鱼在保护区内外不断变化的停留时间。[105]

3.
向新物候同步性演化

气候变化对已观测到的物候不匹配的影响需经过对生态系统内相互影响物种的物候的长期研究得出。长期研究是必不可少的，但主要挑战是证明因果关系。气候变化可能会影响气温和降雨，但土地利用变化、资源过度开发、入侵物种和其他生态压力源等其他因素可能同时影响物种反应。通过最小化变量可以提高因果关系的确定性：观察不同地区的物候反应，比较变暖幅度明显和不明显地区的种群，或在不同时期，比较气温迅速升高年份和气温缓慢上升年份的种群。[76,107]这些方法有助于更好地估计气温升高对物种物候的具体影响，但无法解决涉及受气温影响的其他环境因素的问题。例如在许多区域，降水模式会随着气候条件的变化而发生巨大变化，从而改变雨季的时间、频率和强度。[108,109]随着数据的积累，研究人员认识到物候机制（温度、光照周期和降水等）的组合可能需要保持一致，物候线索才会有效。

某个种群因环境变化而发生的巨大物候变化表明，该物种的很大一部分能够朝着同一方向改变物候时间，这被称为物候可塑性。[110]经验证据表明，这种可塑性是观测到的气候相关物候变化的主要原因。[111]但单个物种或种群的可塑性可能跟不上我们正面临的快速变化的环境。[112]物种还需要遗传变异才能成功适应环境变化。与需要几十年才能再生的树木相比，昆虫等生长时间短的物种更有可能发生遗传变异。[113]因气候变化而发生的遗传变异可以视为微进化，这种例子很多且主要发生在昆虫和一些鸟类中。[114,115]总而言之，遗传变异的速度比气候变化要慢得多。

物候微进化是自然选择的过程，其中遗传变异改变物种的物候，以使其更好地适应气候变化。过去，微进化在物种和生态系统适应气候变暖方面发挥了重要作用。[113]尽管如此，由于现在气候变暖的速度要快得多（可能是过去的100倍），所以，就当前的气候变化速度而言，即使是微进化也可能太慢。[116]

在实践中，可以采取环境保护和生态系统管理措施，为微进化创造有利条件。[117]应采取措施支持和培育种群的遗传多样性，因为遗传多样性是微进化和自然选择的关键先决条件。通过生境走廊提高生态连通性，可以在特定生态系统内促进植物定殖和有新遗传物质的动物物种的迁徙，从而促进遗传多样性并提高成功适应环境的可能性。[118]

长距离迁徙

红腹滨鹬（*Calidris canutus*）是鹬科中的一种中型滨鸟，全球数量呈减少趋势，并被视为近危物种。它的6个亚种在北极高地繁殖地和各大陆的越冬地之间迁徙，迁徙距离极远。[119]

其中一个亚种（*Calidriscanutus canutus*）在西伯利亚中部和北部繁殖，迁往毛里塔尼亚沿岸温暖的地区，尤其是邦克达阿让国家公园。当雪开始融化时，它们进行交配并产卵。红腹滨鹬雏鸟以随季节从解冻的苔原冻土长出的昆虫，为迁往非洲的长途征程做准备。[120]

在过去的30年中，北极高地的融雪期以每年0.5天的速度逐渐提前，导致昆虫提早繁殖并发育。昆虫物候的这种变化对它们的生命后期造成了一系列影响。[120,121]

由于它们还未调整繁殖物候，其后代会错过食物丰足的高峰期。食物资源匮乏意味着生长不良。在融雪提早的夏季，幼鸟体型变得更小，喙也更短。[120]

一旦到了西非，它们的主要食物来源变为埋在潮间带沉积物中的软体动物。这些喙变短的鸟不太能吃到埋在沉积物深处的大量双壳类动物（*Loripes lucinalis*）。相反，它们只能以生活在沉积物浅层的海草根茎（*Zostera noltii*）和少数双壳类物种（*Dosinia isocardia*）为食。

这种连锁反应导致短喙红腹滨鹬的死亡率增加，这表明某个地区、生命阶段的某一部分与远在地球另一端的生命阶段的令一部分之间的物候不匹配会产生复杂的影响。[120]

注：插图未按比例绘制。

4. 通往新和谐的桥梁

物候变化只能根据长期记录得出。由科研机构、大学、政府和非政府组织收集数据。非洲物候网络、澳大利亚陆地生态系统研究网络（TERN）项目、印度季节观测（SeasonWatch）项目、美国自然日历（Nature's Calendar）项目和美国国家物候网络等举措涵盖公民对植物、昆虫、鸟类和哺乳动物的观测结果。科学家利用这些详实的数据阵选出风险最大的物种和地区，同时向政府间气候变化专门委员会（IPCC）提供数据以估计生态系统可容许的变暖速度，并支持各国政府将全球变暖幅度降至《巴黎协定》规定的限度的目标。[122]

物候观测和公民科学

几个世纪以来，世界各地的农民、园丁和大自然爱好者一直在坚持他们对物候阶段的看法。区域和当地网络的参与者可以通过这些网络就环境和生态系统多样性交流知识和建议。在许多国家，借助现代通讯工具来识别和跟踪动植物的生长过程已成为一种常见的消遣活动。[123]

正规的物候观测网种有各类选定的植物，并监测它们对当地环境变化的反应。通过与国家植物园合作的科学家以及其他长期努力，在规定的范围内设立了一些区域来种植生长在不同地形、经度和海拔的选定的植物，并收集数据比较一段时间内的物候反应。这种大规模植物行为观测系统为其他研究人员提供数据，以便为他们的研究工作确立基准并跟踪发展趋势。[124]

收集到的数据通过研究重要物种的物候和适应性变化，为气候变化和生物多样性适应性反应提供了可靠的生物学证据，这些证据支持对气候变化生物学的长期监测。[125]

不太正规的物候观测园是天于物种生命周期中关键阶段的重要教学工具，但它们同样必须遵循某些数据质量协议。有益于环境的全球学习和观测（GLOBE）计划为来自125个国家的数千所参与学校提供指导并打造了。[126]三十年前，这一计划正在扩展其方法、协议和数据库，以便也纳入公民科学家的观测结果。[127]公民科学家对物候知识的贡献包括记录观测同中植物的开花日期、观察迁徙种群以验证航拍图像和卫星图像。[128]美国国家奥杜邦学会于1900年发起的圣诞节鸟类统计活动是一个历史悠久的市民科学项目，涵盖北美大部分地区，并且提供了可靠的数据，证明一个多世纪以来鸟类数量呈下降趋势。[129]

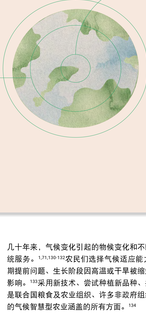
物候公民科学项目和活动精选

全球性

- "为地球而潜水"活动
- 全球物候监测项目
- GLOBE项目物候协议
- 国际水鸟普查
- WorldBirds项目

区域性

- 非洲物候网
- e-Butterfly项目
- 蜂鸟保护网
- 欧洲国际物候观测网
- 帝王蝶观测项目(MonarchWatch)
- 泛欧洲物候项目



国家性

- 巴西野生物健康信息中心
- 中国物候观测网
- 澳大利亚ClimateWatch应用程序
- 爱尔兰"农民的自然日历"项目
- 荷兰Nature Today应用程序
- 加拿大自然观测项目(NatureWatch)
- 瑞士Phaenonet平台
- 瑞士PhenoRangers项目
- 印度季节观测项目(SeasonWatch)
- 英国环境宝化观测网
- 美国国家物候网

几十年来，气候变化引起的物候变化和不匹配一直在影响农业生态系统服务。[1,71,130-133]农民们选择气候适应能力强的作物品种来应对生长期提前问题、生长阶段因高温或干旱被缩短的问题以及其他气候变化影响。[134]采用新技术、尝试种植新品种、共享种子库和利用推广服务是联合国粮食及农业组织、许多非政府组织以及国家和地方机构提倡的气候智慧型农业渔业的所有方面。[134]

有限的研究探究了物候变化和不匹配如何影响自然资源管理和生物多样性保护，而管理人员往往不明白如何在实践中使用数据。[135-136]物候数据可以为气候应对措施提供依据，优化监测操作，以及支持气候变化脆弱性评估。[135]这对于研究不足的地区（如许多南半球地区）尤其重要。[18,137]管理人员需要考虑物候变化如何影响他们现有的战略。例如，渔业管理者通常每年会调查鱼类种群，确定某个水域以往种群数量最多的日期。物候变化可能导致在一年中的错误时间开展调查，从而错估种群数量和捕捞限额。[60]

最近对多个具体案例研究的回顾广泛地列出了物候、物候变化和物候不匹配的具体例子。[27,32,33,45]这种广泛的视角考虑了大量物种、生态系统和区域以及现有的不同物候机制，并对帮助人类社区和生态系统适应气候改变的条件所需的方法提供了依据。

加大力度增强生物多样性完整性，将提高整个生态系统的抵御能力和适应能力[137]。恢复生境、建设生境走廊以加强生态连通性和迁徙传多样性，隔着物种分布范围的变化调整保护区边界，以及保护生产性景观中的生物多样性，这些都是必要的直接管理干预措施。[138,139]

总而言之，人类引起的气候变化导致陆地和水生生态系统的物候变化。这些变化可能导致物候不匹配，对单个物种、种群、群落和整个生态系统产生重大影响。气候变化飞快加速，使许多物种无法靠天生的物候能力适应变化。[140]保护正在发挥作用的生物多样性的完整性、停止破坏生境并努力恢复生态系统，将会改善我们的粮以生存的自然系统。然而，如果不继续努力大幅减少温室气体排放，这些保护措施也只能延缓这些基本生态系统服务的丧失。为了让物种和生态系统适应因气候变化而加快的自然节奏，需要时间和机会来实现新的和谐。

粮食生产与物候

从高温天气导致小麦收成欠佳或海洋热浪影响当地鱼类种群，到反常的天气影响出行和旅游业等所有季节相关的活动本质上都有风险。但随着气候变化加速，粮食生产是受物候变化影响的最重要的社会经济活动。[2]

几十年来，全球变暖趋势改变了各大陆上各种主要农作物的物候阶段。[71,141-145]生长阶段的变化对作物产量和质量产生了影响。[141-147]在大麦、玉米、水稻、黑麦、高粱、大豆和小麦等谷物以及纯花、葡萄酒和苹果、樱桃、梨、芒果等果树上都观察到了这种变化。[71,143,148-154]同时，天于播种时间和品种选择的农作物管理决定对农作物物候有直接影响。[71,155]它们通常被视为适应策略，用来应对气候引起的物候变化。[71]

随着不断引进新品种和播种时间的变化，耕作方式和气候会共同影响农作物物候的各种变化。[71,151,155-160]

许多高产地区通常受更频繁的极端天气事件，这些事件也会干扰关键的生阶段。[161]气候情景农作物模型预测，全球许多地区将面临粮食产量下降以及土壤退化、不可持续的耕作、害虫和缺水等其他挑战。[162]

适应变化的做法侧重于实施可持续的管理，包括使用有机肥料、豆科植物与草类间种、优化灌溉、选育植物以及选用抵御能力更强的品种等。[71]对农业生产力的预测通常会考虑对气候变化的适应能力，并需要更多的观测资料来证明这种适应做法的有效性。[161]

渔业

鱼群顺利生长至成熟及其繁殖深受因气候导致的鱼类和捕食对象物候和分布变化的影响。[47]对于许多海洋鱼类而言，产卵物候对温度信号十分敏感。[69,163]鱼类产卵时间、随后在浮游生物繁殖阶段投放鱼苗和充足的适当食物均是决定鱼类早期发育和存活的关键因素。[42,67,164,165]生命早期阶段存活率降低导致成鱼种群增量减少。[42]在一些区域对内陆和海洋渔业十分重要的鱼类物种中观察开放洞穴繁殖和洞游时间发生了变化以及由此引发的物候不匹配（俗称"了捕食对象旺盛期）。[166]

气候变化带来的物种物候和环境条件的改变对渔业管理提出了挑战。[167]已经观测到物种关键生长阶段的时间和地理分布发生变化，渔业当局采取的一贯做法（例如限禁渔期和禁渔区）可能无法提供充分保护。[55,163,169]管理措施和限制应考虑现有的和新兴的重要生境以及产卵地、育苗地和洞游走廊的变化。适应气候和环境变化的全生态系统方法对于有韧性的生态系统内的可持续渔业管理至关重要。[166]

内陆渔业

气候变化改变的降雨和降雪模式会影响淡水的可利用量、质量和流态。对淡水生境中的物种而言，这些都是重要的物候迹象。水流和水位变化以及淡水事件都会影响洞游和产卵的时间。[166-168]

海洋热浪

2012年严重的海洋热浪导致北大西洋的海水温度升高了1-3°C，龙虾发生了物候反应，并严重影响了缅因湾的渔业。亚海水温度上升的影响，龙虾提早向近海洞游，提早完成蜕皮并长到合法捕捞的尺寸。渔汛期延长、过度捕捞和市场供不应求导致鱼类价格暴跌。[169]

沙丁鱼大洄游

随着季节交替，大量沙丁鱼（*Sardinops sagax*）每年会从巴加勒斯海岸洄游水域向南非奇迪鲁姆城市会北部海岸附近的亚热带水域洞游。每年5月到7月，这一景象都会吸引许多伺机而动的海洋捕食者，并促进捕鱼活动和旅游业。[170]

60多年的记录显示，沙丁鱼洄游到达南非德班的时间呈逐渐推迟趋势，每10年晚到1.3天。晚夏21℃等温线南移，这一趋势将好与沙丁鱼的温度阈值范围变化相吻合。[170]如果这种变化趋势继续下去，沙丁鱼大洄游可能不再向北延伸，或者从长远来看，可能会消失，这对捕食者、渔业和旅游业都会产生影响。[170,171]

参考文献

1. Lieth, H. (1974). Purposes of a Phenology Book. In *Phenology and Seasonality Modeling. Ecological Studies (Analysis and Synthesis)*. Lieth H. (ed.). Springer, Berlin, Heidelberg. Vol. 8. https://doi.org/10.1007/978-3-642-51863-8_1

2. Liang, L. (2019). Phenology. *Reference Module in Earth Systems and Environmental Sciences*. https://doi.org/10.1016/B978-0-12-409548-9.11739-7

3. Flynn, D.F.B. and Wolkovich, E.M. (2018). Temperature and photoperiod drive spring phenology across all species in a temperate forest community. *New Phytologist* 219(4), 1353-1362. https://doi.org/10.1111/nph.15232

4. Adole, T., Dash, J., Rodriguez-Galiano, V. and Atkinson, P.M. (2019). Photoperiod controls vegetation phenology across Africa. *Communications Biology*, 2, 391. https://doi.org/10.1038/s42003-019-0636-7

5. Ren, S., Vitasse, Y., Chen, X., Peichl, M. and An, S. (2022). Assessing the relative importance of sunshine, temperature, precipitation, and spring phenology in regulating leaf senescence timing of herbaceous species in China. *Agricultural and Forest Meteorology* 313, 108770. https://doi.org/10.1016/j.agrformet.2021.108770

6. Gienapp, P., Hemerik, L. and Visser, M.E. (2005). A new statistical tool to predict phenology under climate change scenarios. *Global Change Biology* 11(4), 600–606. https://doi.org/10.1111/j.1365-2486.2005.00925.x

7. Way, D.A. and Montgomery, R.A. (2014). Photoperiod constraints on tree phenology, performance and migration in a warming world. *Plant, Cell & Environment* 38(9), 1725-1736. https://doi.org/10.1111/pce.12431

8. Forrest, J.R.K. (2016). Complex responses of insect phenology to climate change. *Current Opinion in Insect Science* 17, 49-54. https://doi.org/10.1016/j.cois.2016.07.002

9. Marshall, K.E., Gotthard,K. and Williams, C.M. (2020). Evolutionary impacts of winter climate change on insects. *Current Opinion in Insect Science* 41, 54-62. https://doi.org/10.1016/j.cois.2020.06.003

10. Wang, H., Wang, H., Ge, Q. and Dai, J. (2020) The Interactive Effects of Chilling, Photoperiod, and Forcing Temperature on Flowering Phenology of Temperate Woody Plants. *Frontiers in Plant Science* 11(443), 1-12. https://doi.org/10.3389/fpls.2020.00443

11. Bowman, D.M.J.S., Kolden, C.A., Abatzoglou, J.T., Johnston, F.H., van der Werf, G.R., Flannigan, M. (2020). Vegetation fires in the Anthropocene. *Nature Reviews Earth & Environment* 1, 500–515. https://doi.org/10.1038/s43017-020-0085-3

12. Keeley, J.E. and Fotheringham, C.J. (2000). Role of fire in regeneration from seed. In *Seeds: the ecology of regeneration in plant communities*. Fenner, M. (Eds.). CABI. Chapter 14. 311-330. https://doi.org/10.1079/9780851994321.0311

13. Bailly, D., Agostinho, A.A. and Suzuki, H.I. (2008). Influence of the flood regime on the reproduction of fish species with different reproductive strategies in the Cuiabá River, Upper Pantanal, Brazil. *River Research and Applications* 24(9), 1218-1219. https://doi.org/10.1002/rra.1147

14. Arevalo, E., Maire, A., Tétard, S., Prévost, E., Lange, F., Marchand, F. *et al.* (2021). Does global change increase the risk of maladaptation of Atlantic salmon migration through joint modifications of river temperature and discharge? *Proceedings of the Royal Society B* 288(1964), 20211882. http://doi.org/10.1098/rspb.2021.1882

15. Teichert, N., Benitez, J.P., Dierckx, A., Tétard, S., De Oliveira, E., Trancart, T., Feunteun, E. and Ovidio, M. (2020). Development of an accurate model to predict the phenology of Atlantic salmon smolt spring migration. *Aquatic Conservation: Marine and Freshwater Ecosystems* 30(8), 1552-1565. https://doi.org/10.1002/aqc.3382

16. Chambers, L.E., Altwegg, R., Barbraud, C., Barnard, P., Beaumont, L.J. *et al*. (2013) Phenological Changes in the Southern Hemisphere. *PLOS ONE* 8(10), e75514. https://doi.org/10.1371/journal.pone.0075514

17. Butt, N., Seabrook, L., Maron, M., Law, B.S., Dawson, T.P., Syktus, J. *et al*. (2015). Cascading effects of climate extremes on vertebrate fauna through changes to low-latitude tree flowering and fruiting phenology. *Global Change Biology* 21(9), 3267-3277. https://doi.org/10.1111/gcb.12869

18. Sheldon, K.S. (2019). Climate Change in the Tropics: Ecological and Evolutionary Responses at Low Latitudes. *Annual Review of Ecology, Evolution, and Systematics* 50, 303–33. https://doi.org/10.1146/annurev-ecolsys-110218-025005

19. Morellato, L.P.C., Alberton, B., Alvarado, S.T., Borges, B., Buisson, E., Camargo, M.G.G. *et al.* (2016). Linking plant phenology to conservation biology. *Biological Conservation* 195, 60-72. https://doi.org/10.1016/j.biocon.2015.12.033

20. Ramaswami, G., Datta, A., Reddy, A., and Quader, S. (2018). Tracking phenology in the tropics and in India: the impacts of climate change. In *Biodiversity and Climate Change: An Indian Perspective*. Bhatt, J.R., Das, A. and Shanker, K. (eds.). 45-69. New Delhi: Ministry of Environment, Forest and Climate Change, Government of India. https://www.ncf-india.org/other/1116

21. Sakai, S. and Kitajima, K. (2019). Tropical phenology: Recent advances and perspectives. *Ecological Research*, 34(1), 50-54. https://doi.org/10.1111/1440-1703.1131

22. Parmesan, C. and Yohe, G. (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421(6918), 37-42. https://doi.org/10.1038/nature01286

23. Thackeray, S.J., Sparks, T.H., Frederiksen, M., Burthe, S., Bacon, P.J., Bell, J.R. *et al.* (2010). Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Global Change Biology* 16(12), 3304-3313. https://doi.org/10.1111/j.1365-2486.2010.02165.x

24. Donnelly, A., Caffarra, A. and O' Neill, B.F. (2011). A review of climate-driven mismatches between interdependent phenophases in terrestrial and aquatic ecosystems. *International Journal of Biometerology* 55(6), 805-817. https://doi.org/10.1007/s00484-011-0426-5

25. Stevenson, T.J., Visser, M.E., Arnold, W., Barrett, P., Biello, S., Dawson, A. *et al*. (2015). Disrupted seasonal biology impacts health, food security and ecosystems. *Proceedings of the Royal Society B: Biological Sciences* 282(1817), 20151453. https://doi.org/10.1098/rspb.2015.1453

26. Kharouba, H.M., Ehrlén, J., Gelman, A., Bolmgren, K., Allen, J.M., Travers, S.E. and Wolkovich, E.M. (2018). Global shifts in the phenological synchrony of species interactions over recent decades. *Proceedings of the National Academy of Sciences of the United States of America* 115(20), 5211–5216. https://doi.org/10.1073/pnas.1714511115

27. Chmura, H.E., Kharouba, H.M., Ashander, J., Ehlman, S.M., Rivest, E.B. and Yang, L.H. (2019). The mechanisms of phenology: the patterns and processes of phenological shifts. *Ecological Monographs* 89(1), e01337. https://doi.org/10.1002/ecm.1337

28. Stemkovski, M., Pearse, W.D., Griffin, S.R., Pardee, G.L., Gibbs, J., Griswold, T. *et al.* (2020). Bee phenology is predicted by climatic variation and functional traits. *Ecology Letters* 23(11), 1589-1598. https://doi.org/10.1111/ele.13583

29. Root, T.L., Price, J.T., Hall, K.R., Schneider, S.H., Rosenzweig, C. and Pounds, J.A. (2003). Fingerprints of global warming on wild animals and plants. *Nature* 421(6918), 57-60. https://doi.org/10.1038/nature01333

30. Parmesan, C. (2007). Influences of species, latitudes and methodologies on estimates of phenological response to global warming. *Global Change Biology* 13(9), 1860–1872. https://doi.org/10.1111/j.1365-2486.2007.01404.x

31. Poloczanska, E.S., Brown, C.J., Sydeman, W.J., Kiessling, W., Schoeman, D.S., Moore, P.J. *et al.* (2013). Global imprint of climate change on marine life. *Nature Climate Change* 3(10), 919-925. https://doi.org/10.1038/nclimate1958

32. Poloczanska, E.S., Burrows, M.T., Brown, C.J., Molinos, J.G., Halpern, B.S., Hoegh-Guldberg, O. *et al.* (2016). Responses of marine organisms to climate change across oceans. *Frontiers in Marine Science* 3(62). https://doi.org/10.3389/fmars.2016.00062

33. Renner, S.S. and Zohner, C.M. (2018). Climate change and phenological mismatch in trophic interactions among plants, insects, and vertebrates. *Annual Review of Ecology, Evolution, and Systematics* 49, 165-182. https://doi.org/10.1146/annurev-ecolsys-110617-062535

34. Visser, M.E. and Gienapp, P. (2019). Evolutionary and demographic consequences of phenological mismatches. *Nature Ecology & Evolution* 3(6), 879-885. https://doi.org/10.1038/s41559-019-0880-8

35. Staggemeier, V.G.,Camargo, M.G.G., Diniz-Filho, J.A.F., Freckleton, R., Jardim, L. and Morellato, L.P.C. (2019). The circular nature of recurrent life cycle events: a test comparing tropical and temperate phenology. *Journal of Ecology* 108(2), 393-404. https://doi.org/10.1111/1365-2745.13266

36. World Meteorological Organization (2021). FAQs - El Niño/La Niña. https://public.wmo.int/en/about-us/frequently-asked-questions/el-niño-la-niña. Accessed 22 January 2021.

37. Detto, M., Wright, S.J., Calderón, O. and Muller-Landau, H.C. (2018). Resource acquisition and reproductive strategies of tropical forest in response to the El Niño–Southern Oscillation. *Nature Communications* 9, 913. https://doi.org/10.1038/s41467-018-03306-9

38. Moriuchi E. and Basil, M. (2019). The Sustainability of Ohanami Cherry Blossom Festivals as a Cultural Icon. *Sustainability* 11(6), 1820. https://doi.org/10.3390/su11061820

39. Aono, Y. and Kazui, K. (2008). Phenological data series of cherry tree flowering in Kyoto, Japan, and its application to reconstruction of springtime temperatures since the 9th century. *International Journal of Climatology* 28(7), 905-914. https://doi.org/10.1002/joc.1594

40. Aono, Y. and Saito, S. (2010). Clarifying springtime temperature reconstructions of the medieval period by gap-filling the cherry blossom phenological data series at Kyoto, Japan. *International Journal of Biometeorology* 54, 211-219. https://doi.org/10.1007/s00484-009-0272-x

41. Aono, Y. (2015). Cherry blossom phenological data since the seventeenth century for Edo (Tokyo), Japan, and their application to estimation of March temperatures. *International Journal of Biometeorology* 59, 427–434. https://doi.org/10.1007/s00484-014-0854-0

42. Primack, R.B., Higuchi, H. and Miller-Rushing, A.J. (2009). The impact of climate change on cherry trees and other species in Japan. *Biological Conservation* 142(9),1943-1949. https://doi.org/10.1016/j.biocon.2009.03.016

43. Edwards, M. and Richardson, A.J. (2004). Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature* 430, 881–84. https://doi.org/10.1038/nature02808

44. Cleland, E.E., Chuine, I., Menzel, A., Mooney, H.A. and Schwartz, M.D. (2007). Shifting plant phenology in response to global change. *Trends in Ecology & Evolution* 22(7), 357-365. https://doi.org/10.1016/j.tree.2007.04.003

45. Morellato, L.P.C., Camargo, M.G.G. and Gressler, E. (2013). A review of plant phenology in South and Central America. In *Phenology: an integrative environmental science*. Schwartz, M.D. (eds.). Chapter 6. 91–113. Dordrecht: Springer. https://doi.org/10.1007/978-94-007-6925-0_6

46. Vitasse, Y., Signarbieux, C. and Fu, Y.H. (2018). More uniform spring phenology across elevations. *Proceedings of the National Academy of Sciences of the United States of America* 115(5), 1004-1008. https://doi.org/10.1073/pnas.1717342115

47. Staudinger, M.D., Mills, K.E., Stamieszkin, K., Record, N.R., Hudak, C.A. *et al.* (2019). It's about time: a synthesis of changing phenology in the Gulf of Maine ecosystem. *Fisheries Oceanography* 28(5), 532–566. https://doi.org/10.1111/fog.12429

48. Gérard, M., Vanderplanck, M., Wood, T. and Michez, D. (2020). Global warming and plant–pollinator mismatches. *Emerging Topics in Life Sciences* 4(1), 77–86. https://doi.org/10.1042/ETLS20190139

49. Iler, A.M., CaraDonna, P.J., Forrest, J.R.K. and Post, E. (2021). Demographic Consequences of Phenological Shifts in Response to Climate Change. *Annual Review of Ecology, Evolution, and Systematics* 52, 221–245. https://doi.org/10.1146/annurev-ecolsys-011921-032939

50. Lima, D.F., Mello, J.H.F., Lopes, I.T., Forzza, R.C., Goldenberg, R. and Freitas, L. (2021). Phenological responses to climate change based on a hundred years of herbarium collections of tropical Melastomataceae. *PLOS ONE* 16(5), e0251360. https://doi.org/10.1371/journal.pone.0251360

51. Vitasse, Y., Ursenbacher, S., Klein, G., Bohnenstengel, T., Chittaro, Y., Delestrade, A. *et al.* (2021). Phenological and elevational shifts of plants, animals and fungi under climate change in the European Alps. *Biological Reviews* 96(5),1816–1835. https://doi.org/10.1111/brv.12727

52. Visser, M.E., Noordwijk, A.V., Tinbergen, J.M. and Lessells, C.M. (1998). Warmer springs lead to mistimed reproduction in great tits (Parus major). *Proceedings of the Royal Society of London. Series B: Biological Sciences* 265(1408), 1867-1870. https://doi.org/10.1098/rspb.1998.0514

53. Both, C. and Visser, M.E. (2001). Adjustment to climate change is constrained by arrival date in a long-distance migrant bird. *Nature* 411(6835), 296–298. https://doi.org/10.1038/35077063

54. Visser, M.E., Holleman, L.J.M. and Gienapp, P. (2006). Shifts in caterpillar biomass phenology due to climate change and its impact on the breeding biology of an insectivorous bird. *Oecologia* 147, 164–172. https://doi.org/10.1007/s00442-005-0299-6

55. Visser, M.E., te Marvelde, L. and Lof, M.E. (2012). Adaptive phenological mismatches of birds and their food in a warming world. *Journal of Ornithology* 153(1), 75–84. https://doi.org/10.1007/s10336-011-0770-6

56. Regular, P.M., Hedd, A., Montevecchi, W.A., Robertson, G.J., Storey, A.E. and Walsh, C.J. (2014). Why timing is everything: Energetic costs and reproductive consequences of resource mismatch for a chick-rearing seabird. *Ecosphere* 5(12), 1-13. https://doi.org/10.1890/es14-00182.1

57. Moyes, K., Nussey, D.H., Clements, M.N., Guinness, F.E., Morris, A., Morris, S. *et al.* (2011). Advancing breeding phenology in response to environmental change in a wild red deer population. *Global Change Biology* 17(7), 2455–2469. https://doi.org/10.1111/j.1365-2486.2010.02382.x

58. Tomotani, B.M., van der Jeugd, H., Gienapp, P., de la Hera, I., Pilzecker, J., Teichmann, C. and Visser, M.E. (2018). Climate change leads to differential shifts in the timing of annual cycle stages in a migratory bird. *Global Change Biology* 24(2), 823-835. https://doi.org/10.1111/gcb.14006

59. Asch, R.G., Stock, C.A. and Sarmiento, J.L. (2019). Climate change impacts on mismatches between phytoplankton blooms and fish spawning phenology. *Global Change Biology* 25(8), 2544–2559. https://doi.org/10.1111/gcb.14650

60. Asch, R.G. (2015). Climate change and decadal shifts in the phenology of larval fishes in the California Current ecosystem. *Proceedings of the National Academy of Sciences of the United States of America* 112(30), E4065-E4074. https://doi.org/10.1073/pnas.1421946112

61. Asch, R.G. (2019). Changing seasonality of the sea: past, present, and future. In *Predicting Future Oceans, Sustainability of Ocean and Human Systems Amidst Global Environmental Change*. Cisneros-Montemayor, A.M., Cheung, W.W.L. and Ota, Y. (eds.). Chapter 4. 39-51. https://doi.org/10.1016/B978-0-12-817945-1.00004-6

62. Dahl, J., Dannewitz, J., Karlsson, L., Petersson, E., Löf, A. and Ragnarsson, B. (2004). The timing of spawning migration: implications of environmental variation, life history, and sex. *Canadian Journal of Zoology* 82(12), 1864–1870. https://doi.org/10.1139/z04-184

63. Li, Y., Cohen, J.M. and Rohr, J.R. (2013). Review and synthesis of the effects of climate change on amphibians. *Integrative Zoology* 8(2), 145-161. https://doi.org/10.1111/1749-4877.12001

64. Nash, L.N., Antiqueira, P.A.P., Romero, G.Q., de Omena, P.M. and Kratina, P. (2021). Warming of aquatic ecosystems disrupts aquatic–terrestrial linkages in the tropics. *Journal of Animal Ecology* 90(7), 1623-1634. https://doi.org/10.1111/1365-2656.13505

65. Post, E. and Forchhammer, M.C. (2008). Climate change reduces reproductive success of an Arctic herbivore through trophic mismatch. *Philosophical Transactions of the Royal Society B: Biological Sciences* 363(1501), 2367-2373. https://doi.org/10.1098/rstb.2007.2207

66. Plard, F., Gaillard, J.M., Coulson, T., Hewison, A.M., Delorme, D., Warnant, C. and Bonenfant, C. (2014). Mismatch between birth date and vegetation phenology slows the demography of roe deer. *PLoS Biology* 12(4), e1001828. https://doi.org/10.1371/journal.pbio.1001828

67. Brander, K. (2010). Impacts of climate change on fisheries. *Journal of Marine Systems* 79(3-4), 389-402. https://doi.org/10.1016/j.jmarsys.2008.12.015

68. The Food and Agriculture Organization of the United Nations (FAO) (2018). *Impacts of climate change on fisheries and aquaculture: Synthesis of current knowledge, adaptation and mitigation options*. http://www.fao.org/3/i9705en/I9705EN.pdf

69. Rogers, L.A. and Dougherty, A.B. (2019). Effects of climate and demography on reproductive phenology of a harvested marine fish population. *Global Change Biology* 25(2), 708-720. https://doi.org/10.1111/gcb.14483

70. Vitasse, Y., Schneider, L., Rixen, C., Christen, D. and Rebetez, M. (2018). Increase in the risk of exposure of forest and fruit trees to spring frosts at higher elevations in Switzerland over the last four decades. *Agricultural and Forest Meteorology* 248, 60-69. https://doi.org/10.1016/j.agrformet.2017.09.005

71. Fatima, Z., Ahmed, M., Hussain, M., Abbas, G., Ul-Allah, S., Ahmad, S. *et al.* (2020). The fingerprints of climate warming on cereal crops phenology and adaptation options. *Scientific Reports* 10(1), 18013. https://doi.org/10.1038/s41598-020-74740-3

72. Perrins, C.M. (1991). Tits and their caterpillar food supply. *Ibis* 133(1), 49-54. https://doi.org/10.1111/j.1474-919X.1991.tb07668.x

73. Van Asch, M., Tienderen, P.H., Holleman, L.J.M. and Visser, M.E. (2007). Predicting adaptation of phenology in response to climate change, an insect herbivore example. *Global Change Biology* 13(8), 1596–1604. https://doi.org/10.1111/j.1365-2486.2007.01400.x

74. Visser, M.E., Gienapp, P., Husby, A., Morrisey, M., de la Hera, I., Pulido, F. *et al*. (2015). Effects of spring temperatures on the strength of selection on timing of reproduction in a long-distance migratory bird. *PLoS Biology* 13(4), e1002120. https://doi.org/10.1371/journal.pbio.1002120

75. Charmantier, A., Mccleery, R.H., Cole, L.R., Perrins, C., Kruuk, L.E.B. and Sheldon, B.C. (2008). Adaptive Phenotypic Plasticity in Response to Climate Change in a Wild Bird Population. *Science* 320(5877), 800-803. https://doi.org/10.1126/science.1157174

76. Visser, M.E., Lindner, M., Gienapp, P., Long, M.C. and Jenouvrier, S. (2021). Recent natural variability in global warming weakened phenological mismatch and selection on seasonal timing in great tits (*Parus major*). *Proceedings of the Royal Society B* 288(1963), 20211337. https://doi.org/10.1098/rspb.2021.1337

77. Bauer, Z., Trnka, M., Bauerová, J., Možný, M., Št ě pánek, P., Bartošová, L. *et al*. (2010). Changing climate and the phenological response of great tit and collared flycatcher populations in floodplain forest ecosystems in Central Europe. *International Journal of Biometeorology* 54, 99–111. https://doi.org/10.1007/s00484-009-0259-7

78. Matthysen, E., Adriaensen, F. and Dhondt, A.A. (2010). Multiple responses to increasing spring temperatures in the breeding cycle of blue and great tits (*Cyanistes caeruleus, Parus major*). *Global Change Biology* 17(1), 1-16. https://doi.org/10.1111/j.1365-2486.2010.02213.x

79. Bonamour, S. (2021). Great tit response to climate change. *Nature Climate Change* 11, 802-807. https://doi.org/10.1038/s41558-021-01160-0

80. Cole, E.F., Regan, C.E. and Sheldon, B.C. (2021). Spatial variation in avian phenological response to climate change linked to tree health. *Nature Climate Change* 11, 872–878. https://doi.org/10.1038/s41558-021-01140-4

81. Robinson, R.A., Crick, H.Q.P., Learmonth, J.A., Maclean, I.M.D., Thomas, C.D., Bairlein, F. *et al*. (2009). Travelling through a warming world: climate change and migratory species. *Endangered Species Research* 7(2), 87-99. https://doi.org/10.3354/esr00095

82. Joly, K., Gurarie, E., Sorum, M.S., Kaczensky, P., Cameron, M.D., Jakes, A.F. *et al*. (2019). Longest terrestrial migrations and movements around the world. *Scientific Reports* 9, 15333. https://doi.org/10.1038/s41598-019-51884-5

83. Intergovernmental Panel on Climate Change (2019). Summary for Policymakers. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. https://www.ipcc.ch/srocc/chapter/summary-for-policymakers/

84. Intergovernmental Panel on Climate Change (2021). Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* https://www.ipcc.ch/report/ar6/wg1/

85. Ramp, C., Delarue, J., Palsbøll, P.J., Sears, R. and Hammond, P.S. (2015). Adapting to a Warmer Ocean—Seasonal Shift of Baleen Whale Movements over Three Decades. *PLOS ONE* 10(3), e0121374. https://doi.org/10.1371/journal.pone.0121374

86. Kubelka, V., Sandercock, B.K., Székely, R. and Freckleton, R.P. (2022). Animal migration to northern latitudes: environmental changes and increasing threats. *Trends in Ecology & Evolution* 37(1), 30-41. https://doi.org/10.1016/j.tree.2021.08.010

87. Saino, N., Ambrosini, R., Rubolini, D., von Hardenberg, J., Provenzale, A., Hüppop, K. *et al*. (2011). Climate warming, ecological mismatch at arrival and population decline in migratory birds. *Proceedings of the Royal Society B: Biological Sciences* 278(1707), 835–842. https://doi.org/10.1098/rspb.2010.1778

88. Secretariat of the Convention on the Conservation of Migratory Species of Wild Animals (2014). *A Review of Migratory Bird Flyways and Priorities for Management*. https://www.cms.int/sites/default/files/publication/CMS_Flyways_Reviews_Web.pdf

89. Lamaris, *et al*. (2018). Arctic geese tune migration to a warming climate but still suffer from a phenological mismatch. *Current Biology* 28(15), 2467–2473. https://doi.org/10.1016/j.cub.2018.05.077

90. Bairlein, F. (2016). Migratory birds under threat. *Science* 354(6312), 547-548. https://doi.org/10.1126/science.aah6647

91. The Zoological Society of London (ZSL) (2010*). Climate change impacts on migratory species - The path ahead*. https://www.cbd.int/cop/cop-10/doc/unep-cms-cop10-cc-en.pdf.

92. Secretariat of the Convention on the Conservation of Migratory Species of Wild Animals (2022). *Ecological Connectivity*. https://www.cms.int/en/topics/ecological-connectivity

93. BirdLife International (2021*). IUCN Red List for birds*. http://datazone.birdlife.org/species/factsheet/white-stork-ciconia-ciconia/text

94. Jovani, R. AND Tella, J.L. (2004) Age-related environmental sensitivity and weather mediated nestling mortality in white storks *Ciconia ciconia*. *Ecography* 27(5), 611–618. https://www.jstor.org/stable/3683463

95. Tobolka, M., Zolnierowicz, K.M. and Reeve, N.F. (2015). The effect of extreme weather events on breeding parameters of the White Stork *Ciconia ciconia*. *Bird Study* 62(3), 377-385. https://doi.org/10.1080/00063657.2015.1058745

96. Culbertson, K.A., Garland, M.S., Walton, R.K., Zemaitis, L. and Pocius, V.M. (2021). Long-term monitoring indicates shifting fall migration timing in monarch butterflies (*Danaus plexippus*). *Global Change Biology* 28(3), 727-738. https://doi.org/10.1111/gcb.15957

97. Taylor, O.R., Lovett, J.P., Gibo, D.L., Weiser, E.L., Thogmartin, W.E., Semmens, D.J. *et al.* (2019). Is the timing, pace, and success of the monarch migration associated with sun angle? *Frontiers in Ecology and Evolution*, 7, 442. https://doi.org/10.3389/fevo.2019.00442

98. Lameris, T.K., van der Jeugd, H.P., Eichhorn, G., Dokter, A.M., Bouten, W., Boom, M.P. *et al*. (2018). Arctic geese tune migration to a warming climate but still suffer from a phenological mismatch. *Current Biology*, *28*(15), 2467-2473. https://doi.org/10.1016/j.cub.2018.05.077

99. Robinson, N.J., Valentine, S.E., Tomillo, P.S., Saba, V.S., Spotila, J.R. and Paladino, F.V. (2014). Multidecadal trends in the nesting phenology of Pacific and Atlantic leatherback turtles are associated with population demography. *Endangered Species Research*, 24(3), 197-206. https://doi.org/10.3354/esr00604

100. Patrício, A.R., Hawkes, L.A., Monsinjon, J.R., Godley, B.J. and Fuentes, M.M.P.B. (2021). Climate change and marine turtles: recent advances and future directions. *Endangered Species Research* 44, 363-395. https://doi.org/10.3354/esr01110

101. Almpanidou, V., Katragkou, E. and Mazaris, A.D. (2017). The efficiency of phenological shifts as an adaptive response against climate change: a case study of loggerhead sea turtles (Caretta caretta) in the Mediterranean. *Mitigation and Adaptation Strategies for Global Change* 23(7), 1143–1158. https://doi.org/10.1007/s11027-017-9777-5

102. Butler, C.J. (2019). A Review of the Effects of Climate Change on Chelonians. *Diversity*11(8), 138. https://doi.org/10.3390/d11080138

103. Monsinjon, J., Lopez-Mendilaharsu, M., Lara, P., Santos, A., dei Marcovaldi, M.A., Girondot, M. and Fuentes, M.M. (2019). Effects of temperature and demography on the phenology of loggerhead sea turtles in Brazil. *Marine Ecology Progress Series*, *623*, 209-219. https://doi.org/10.3354/meps12988

104. Moore, S.E., Haug, T., Víkingsson, G.A. and Stenson, G.B. (2019). Baleen whale ecology in arctic and subarctic seas in an era of rapid habitat alteration. *Progress in Oceanography* 176, 102118. https://doi.org/10.1016/j.pocean.2019.05.010

105. Avila, I.C., Dormann, C.F., García, C., Payán, L.F. and Zorrilla, M.Z. (2020). Humpback whales extend their stay in a breeding ground in the Tropical Eastern Pacific. *ICES Journal of Marine Science* 77(1), 109–118. https://doi.org/10.1093/icesjms/fsz251

106. Szesciorka, A.R., Ballance, L.T., Širović, A., Rice, A., Ohman, M.D., Hildebrand, J.A. and Frank, P.J.S. (2020). Timing is everything: Drivers of interannual variability in blue whale migration. *Scientific Reports* 10, 7710. https://doi.org/10.1038/s41598-020-64855-y

107. Both, C., Artemyev, A.V., Blaauw, B., Cowie, R.J., Dekhuijzen, A.J., Eeva, T. *et al.* (2004). Large–scale geographical variation confirms that climate change causes birds to lay earlier. *Proceedings of the Royal Society of London Series B-Biological Sciences* 271(1549), 1657–1662. https://doi.org/10.1098/rspb.2004.2770

108. Dunham, A.E., Razafindratsima, O.H., Rakotonirina, P., Wright, P.C. (2018). Fruiting phenology is linked to rainfall variability in a tropical rain forest. *Biotropica* 50(3), 396-404. https://doi.org/10.1111/btp.12564

109. Suonan, J., Classen, A.T., Sanders, N.J. and He, J.S. (2019). Plant phenological sensitivity to climate change on the Tibetan Plateau and relative to other areas of the world. *Ecosphere* 10(1), e02543. https://doi.org/10.1002/ecs2.2543

110. Bradshaw, A.D. (1965). Evolutionary significance of phenotypic plasticity in plants. *Advances in Genetics* 13, 115–155. https://doi.org/10.1016/S0065-2660(08)60048-6

111. Charmantier, A. and Gienapp, P. (2014). Climate change and timing of avian breeding and migration: evolutionary versus plastic changes. *Evolutionary Applications* 7(1), 15–28. https://doi.org/10.1111/eva.12126

112. Zettlemoyer, M.A. and Peterson, M.L. (2021). Does Phenological Plasticity Help or Hinder Range Shifts Under Climate Change? *Frontiers in Ecology and Evolution* 9, 392. https://doi.org/10.3389/fevo.2021.689192

113. Visser, M.E. (2008). Keeping up with a warming world: assessing the rate of adaptation to climate change. *Proceedings of the Royal Society B: Biological Sciences* 275(1635), 649-659. https://doi.org/10.1098/rspb.2007.0997

114. Van Asch, M., Salis, L., Holleman, L.J., Van Lith, B. and Visser, M.E. (2013). Evolutionary response of the egg hatching date of a herbivorous insect under climate change. *Nature Climate Change* 3(3), 244–248. https://doi.org/10.1038/nclimate1717

115. Helm, B., Van Doren, B.M., Hoffmann, D. and Hoffmann, U. (2019). Evolutionary response to climate change in migratory pied flycatchers. *Current Biology* 29(21), 3714-3719. https://doi.org/10.1016/j.cub.2019.08.072

116. Diffenbaugh, N.S. and Field, C.B. (2013). Changes in ecologically critical terrestrial climate conditions. *Science* 341(6145), 486–492. https://doi.org/10.1126/science.1237123

117. Hoffmann, A.A. and Sgrò, C.M. (2011). Climate change and evolutionary adaptation. *Nature* 470(7335), 479-85. https://doi.org/10.1038/nature09670.

118. Tabor, G. (2019). Ecological connectivity: A bridge to preserving biodiversity. In *UNEP Frontiers 2018/19 – Emerging issues of environmental concern*. United Nations Environment Programme, Nairobi. https://www.unep.org/frontiers

119. BirdLife International (2018). *Species factsheet: Calidris canutus*. http://datazone.birdlife.org/species/factsheet/red-knot-calidris-canutus. Accessed on 09 December 2021.

120. van Gils, J.A., Lisovski, S., Lok, T., Meissner, W., Ożarowska, A., de Fouw, J. *et al.* (2016). Body shrinkage due to Arctic warming reduces red knot fitness in tropical wintering range. *Science* 352(6287), 819-821. https://doi.org/10.1126/science.aad6351

121. Bowden, J.J., Eskildsen, A., Hansen, R.R., Olsen, K., Kurle, C.M. and Høye, T.T. (2015). High-Arctic butterflies become smaller with rising temperatures. *Biology Letters* 11(10), 20150574. http://dx.doi.org/10.1098/rsbl.2015.0574

122. Intergovernmental Panel on Climate Change (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects*. Contribution of Working Group II to the Fifth Assessment. https://www.ipcc.ch/report/ar5/wg2/

123. Mäder, P., Boho, D., Rzanny, M., Seeland, M., Wittich, H.C., Deggelmann, A. *et al*. (2021). The Flora Incognita app – Interactive plant species identification. *Methods in Ecology and Evolution* 12(7), 1335-1342. https://doi.org/10.1111/2041-210X.13611

124. Renner, S.S. and Chmielewski, F.M. (2022). The International Phenological Garden network (1959 to 2021): its 131 gardens, cloned study species, data archiving, and future. *International Journal of Biometeorology* 66(1), 35-43. https://doi.org/10.1007/s00484-021-02185-y

125. Huang, H., Liao, J., Zhang, Z. and Zhan, Q. (2017). Ex situ flora of China. *Plant Diversity* 39(6), 357-364. https://doi.org/10.1016/j.pld.2017.12.001

126. The GLOBE Program (2021). GLOBE Impact Around the World. https://www.globe.gov/about/impact-and-metrics. Accessed 24 Dec 2021.

127. Murphy, T., Riebeek Kohl, H., Ristvey Jr, J.D., Chambers, L.H., and Bourgeault, J. (2018). Global citizen science using the GLOBE Program. https://ui.adsabs.harvard.edu/abs/2018AGUFMED54A..03M/abstract

128. Dickinson, J.L., Zuckerberg, B. and Bonter, D.N. (2010). Citizen science as an ecological research tool: challenges and benefits. *Annual Review of Ecology, Evolution, and Systematics* 41(1), 149–172. https://doi.org/10.1146/annurev-ecolsys-102209-144636

129. Langham, G.M., Schuetz, J.G., Distler, T., Soykan, C.U. and Wilsey, C. (2015). Conservation Status of North American Birds in the Face of Future Climate Change. *PLOS ONE* 10(9), e0135350. https://doi.org/10.1371/journal.pone.0135350

130. Castex, V., Beniston, M., Calanca, P., Fleury, D. and Moreau, J. (2018). Pest management under climate change: The importance of understanding tritrophic relations. *Science of The Total Environment* 616-617, 397-407. https://doi.org/10.1016/j.scitotenv.2017.11.027

131. Marcinkowski, P. and Piniewski, M. (2019). Effect of climate change on sowing and harvest dates of spring barley and maize in Poland. *International Agrophysics* 32(2), 265-271. https://doi.org/10.1515/intag-2017-0015

132. Bai, H., Xiao, D., Zhang, H., Tao, F. and Hu, Y. (2019). Impact of warming climate, sowing date, and cultivar shift on rice phenology across China during 1981–2010. *International Journal of Biometeorology* 63(8), 1077–1089. https://doi.org/10.1007/s00484-019-01723-z

133. Acevedo, M., Pixley, K., Zinyengere, N., Meng, S., Tufan, H., Cichy, K. *et al*. (2020). A scoping review of adoption of climate-resilient crops by small-scale producers in low-and middle-income countries. *Nature Plants* 6(10), 1231-1241. https://doi.org/10.1038/s41477-020-00783-z

134. Zilberman, D., Lipper, L., McCarthy, N., and Gordon, B. (2018). Innovation in response to climate change. In *Climate smart agriculture*. Lipper, L., Thornton, P., Campbell, B.M., Baedeker, T., Braimoh, A., Bwalya, M. *et al.* (Eds). Springer, Cham. Vol 52. 49-74. https://doi.org/10.1007/978-3-319-61194-5

135. Enquist, C.A., Kellermann, J.L., Gerst, K.L. and Miller-Rushing, A.J. (2014). Phenology research for natural resource management in the United States. *International Journal of Biometeorology* 58(4), 579–589. https://doi.org/10.1007/s00484-013-0772-6

136. Kharouba, H.M. and Wolkovich, E.M. (2020). Disconnects between ecological theory and data in phenological mismatch research. *Nature Climate Change* 10(5), 406-415. https://doi.org/10.1038/s41558-020-0752-x.

137. Seddon, N., Turner, B., Berry, P., Chausson, A. and Girardin, C.A.J. (2019). Grounding nature-based climate solutions in sound biodiversity science. *Nature Climate Change* 9(2), 84–87. https://doi.org/10.1038/s41558-019-0405-0

138. Prober, S.M., Doerr, V.A.J., Broadhurst, L.M., Williams, K.J. and Dickson, F. (2019). Shifting the conservation paradigm: a synthesis of options for renovating nature under climate change. *Ecological Monographs* 89(1), e01333. https://doi.org/10.1002/ecm.1333

139. Bergstrom, D. M., Wienecke, B. C., van den Hoff, J., Hughes, L., Lindenmayer, D. B., Ainsworth, T. D. *et al.* (2021). Combating ecosystem collapse from the tropics to the Antarctic. *Global change Biology* 27(9), 1692-1703. https://doi.org/10.1111/gcb.15539

140. Radchuk, V., Reed, T., Teplitsky, C. Van De Pol, M., Charmantier, A., Hassall, C. *et al*. (2019). Adaptive responses of animals to climate change are most likely insufficient. *Nature Communications* 10, 3109. https://doi.org/10.1038/s41467-019-10924-4

141. Estrella, N., Sparks, T.H. and Menzel, A. (2007). Trends and temperature response in the phenology of crops in Germany. *Global Change Biology* 13(8), 1737-1747. https://doi.org/10.1111/j.1365-2486.2007.01374.x

142. Wang, Z., Chen, J., Xing, F., Han, Y., Chen, F., Zhang, L. *et al*. (2017). Response of cotton phenology to climate change on the North China Plain from 1981 to 2012. *Scientific Reports* 7, 6628. https://doi.org/10.1038/s41598-017-07056-4

143. Abed, A., Bonhomme, M., Lacointe, A., Bourgeois, G. and Baali-Cherif, D. (2019). Climate change effect on the bud break and flowering dates of the apple trees in mountainous and plain regions of Algeria. *Advances in Horticultural Science* 33 (3), 417-431. https://doi.org/10.13128/ahs-24618

144. Chmielewski, F.-M., Müller, A. and Bruns, E. (2004). Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961–2000. *Agricultural and Forest Meteorology* 121(1–2), 69-78. https://doi.org/10.1016/S0168-1923(03)00161-8

145. Tao, F., Yokozawa, M., Xu, Y., Hayashi, Y. and Zhang, Z. (2006). Climate changes and trends in phenology and yields of field crops in China, 1981–2000. *Agricultural and Forest Meteorology* 138(1-4), 82–92. https://doi.org/10.1016/j.agrformet.2006.03.014

146. Nguyen-Sy, T., Cheng, W., Tawaraya, K., Sugawara, K. and Kobayashi, K. (2019). Impacts of climatic and varietal changes on phenology and yield components in rice production in Shonai region of Yamagata Prefecture, Northeast Japan for 36 years. *Agronomy & Crop Ecology* 22(3), 382-394. https://doi.org/10.1080/1343943X.2019.1571421

147. Azmat, M., Ilyas, F., Sarwar, A., Huggel, C., Ashra, S.V., Hui, T. *et al*. (2021). Impacts of climate change on wheat phenology and yield in Indus Basin, Pakistan. *Science of The Total Environment* 790, 148221. https://doi.org/10.1016/j.scitotenv.2021.148221

148. Tomasi, D., Jones, G.V., Giust, M., Lovat, L. and Gaiotti, F. (2011). Grapevine Phenology and Climate Change: Relationships and Trends in the Veneto Region of Italy for 1964–2009. *American Journal of Enology and Viticulture* 62, 329-339. https://doi.org/10.5344/ajev.2011.10108

149. Rajan, S. (2012). Phenological Responses to Temperature and Rainfall: A Case Study of Mango. In *Tropical Fruit Tree Species and Climate Change*. Sthapit, B.R., Ramanatha Rao, V. and Sthapit, S.R. (Eds.) Bioversity International, New Delhi, India. https://cgspace.cgiar.org/handle/10568/105191

150. Xiao, D., Tao, F., Liu, Y., Shi, W., Wang, M., Liu, F. *et al*. (2013) Observed changes in winter wheat phenology in the North China Plain for 1981–2009. *International Journal of Biometeorology* 57, 275–285. https://doi.org/10.1007/s00484-012-0552-8

151. Ahmad, S., Abbas, G., Fatima, Z., Khan, R.J., Anjum, M.A., Ahmed, M. *et al*. (2017). Quantification of the impacts of climate warming and crop management on canola phenology in Punjab, Pakistan. *Journal of Agronomy and Crop Science* 203(5), 442-452. https://doi.org/10.1111/jac.12206

152. Subedi, S. (2019). Climate change effects of Nepalese fruit production. *Advances in Plants & Agriculture Research* 9(1), 141-145. https://doi.org/10.15406/apar.2019.09.00426

153. Tan, Q., Liu, Y., Dai, L. and Pan, T. (2021). Shortened key growth periods of soybean observed in China under climate change. *Scientific Reports* 11, 8197. https://doi.org/10.1038/s41598-021-87618-9

154. Kunz, A. and Blanke, M. (2022). “60 Years on”—Effects of climatic change on tree phenology—A Case Study Using Pome Fruit. *Horticulturae* 8(2), 110. https://doi.org/10.3390/horticulturae8020110

155. Rezaei, E.E., Siebert, S. and Ewert, F. (2017). Climate and management interaction cause diverse crop phenology trends. *Agricultural and Forest Meteorology* 233, 55-70. https://doi.org/10.1016/j.agrformet.2016.11.003

156. Zhang, T., Huang, Y. and Yang, X. (2012). Climate warming over the past three decades has shortened rice growth duration in China and cultivar shifts have further accelerated the process for late rice. *Global Change Biology* 19(2), 563-570. https://doi.org/10.1111/gcb.12057

157. He, L., Asseng, S., Zhao, G., Wu, D., Yang, X., Zhuang, W. *et al*. (2015). Impacts of recent climate warming, cultivar changes, and crop management on winter wheat phenology across the Loess Plateau of China. *Agricultural and Forest Meteorology* 200, 135-143. https://doi.org/10.1016/j.agrformet.2014.09.001

158. Abbas, G., Ahmad, S., Ahmad, A., Nasim, W., Fatima, Z., Hussain, S. *et al*. (2017). Quantification the impacts of climate change and crop management on phenology of maize-based cropping system in Punjab, Pakistan. *Agricultural and Forest Meteorology* 247, 42-55. https://doi.org/10.1016/j.agrformet.2017.07.012

159. Karapinar, B. and Özertan, G. (2020). Yield implications of date and cultivar adaptation to wheat phenological shifts: a survey of farmers in Turkey. *Climatic Change* 158, 453–472. https://doi.org/10.1007/s10584-019-02532-4

160. Liu, Y., Chen, Q., Ge, Q., Dai, J. and Dou, Y. (2018). Effects of climate change and agronomic practice on changes in wheat phenology. *Climatic Change* 150(3-4), 273-287. https://doi.org/10.1007/s10584-018-2264-5

161. Porter, J.R., L. Xie, A.J., Challinor, K., Cochrane, S.M., Howden, M.M., Iqbal, D.B. *et al*. (2014) Food security and food production systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Field, C.B. Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E. *et al*. (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp. 485-533. https://www.ipcc.ch/report/ar5/wg2/

162. Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A. *et al*. (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences of the United States of America* 111(9), 3268-3273. https://doi.org/10.1073/pnas.1222463110

163. Peer, A.C. and Miller, T.J. (2014). Climate Change, Migration Phenology, and Fisheries Management Interact with Unanticipated Consequences. *North American Journal of Fisheries Management* 34, 94–110, 2014. https://doi.org/10.1080/02755947.2013.847877

164. Doney, S.C., Ruckelshaus, M., Emmett Duffy, J., Barry, J.P., Chan, F., English, C.A. *et al*. (2012). Climate Change Impacts on Marine Ecosystems. *Annual Review of Marine Science* 4(1), 11-37. https://doi.org/10.1146/annurev-marine-041911-111611

165. Thaxton, W., Taylor, J. and Asch, R. (2020). Climate-associated trends and variability in ichthyoplankton phenology from the longest continuous larval fish time series on the east coast of the United States. *Marine Ecology Progress Series* 650, 269–287. https://doi.org/10.3354/meps13404

166. The Food and Agriculture Organization of the United Nations (FAO) (2018). *Impacts of climate change on fisheries and aquaculture: Synthesis of current knowledge, adaptation and mitigation options*. http://www.fao.org/3/i9705en/I9705EN.pdf

167. Krabbenhoft, T.J., Platania, S.P. and Turner, T.F. (2014). Interannual variation in reproductive phenology in a riverine fish assemblage: implications for predicting the effects of climate change and altered flow regimes. *Freshwater Biology* 59(8), 1744-1754. https://doi.org/10.1111/fwb.12379

168. Woods, T., Kaz, A. and Giam, X. (2021). Phenology in freshwaters: a review and recommendations for future research. *Ecography*(44), 1-14. https://doi.org/10.1111/ecog.05564

169. Mills, K., Pershing, A., Brown, C., Chen, Y., Chiang, F.-S., Holland, D. *et al*. (2013). Fisheries management in a changing climate: Lessons from the 2012 ocean heat wave in the Northwest Atlantic. *Oceanography* 26(2), 191–195. https://doi.org/10.5670/oceanog.2013.27

170. Fitchett, J.M., Grab, S.W. and Portwig, H. (2019). Progressive delays in the timing of sardine migration in the southwest Indian Ocean. *South Africa Journal of Science* 115(7/8), 5887. https://doi.org/10.17159/sajs.2019/5887

171. Teske, P.R., Emami-Khoyi, A., Golla, T.R., Sandoval-Castillo, J., Lamont, T., Chiazzari, B. *et al*. (2021). The sardine run in southeastern Africa is a mass migration into an ecological trap. *Science Advances* 7(38), eabf4514. https://doi.org/10.1126/sciadv.abf4514

图表参考文献

识别变化、跟踪趋势

植物

33. Renner and Zohner (2018)

Anderson, J.T., Inouye, D.W., McKinney, A.M., Colautti, R.I. and Mitchell-Olds, T. (2012). Phenotypic plasticity and adaptive evolution contribute to advancing flowering phenology in response to climate change. *Proceedings of the Royal Society B: Biological Sciences* 279(1743), 3843-3852. https://doi.org/10.1098/rspb.2012.1051

Askeyev, O.V., Tischin, D., Sparks, T.H. and Askeyev, I.V. (2005). The effect of climate on the phenology, acorn crop and radial increment of pedunculate oak (*Quercus robur*) in the middle Volga region, Tatarstan, Russia. *International Journal of Biometeorology* 49(4), 262-266. https://doi.org/10.1007/s00484-004-0233-3

Ehrlén, J. and Valdés, A. (2020). Climate drives among-year variation in natural selection on flowering time. *Ecology Letters 23*(4), 653-662. https://doi.org/10.1111/ele.13468

Lambert, A.M., Miller-Rushing, A.J. and Inouye, D.W. (2010). Changes in snowmelt date and summer precipitation affect the flowering phenology of *Erythronium grandiflorum* (glacier lily; Liliaceae). *American Journal of Botany 97*(9), 1431-1437. https://doi.org/10.3732/ajb.1000095

Kudo, G. and Cooper, E.J. (2019). When spring ephemerals fail to meet pollinators: mechanism of phenological mismatch and its impact on plant reproduction. *Proceedings of the Royal Society B: Biological Sciences 286*(1904), 20190573. https://doi.org/10.1098/rspb.2019.0573

昆虫

Konvicka, M., Benes, J., Cízek, O., Kuras, T. and Kleckova, I. (2016). Has the currently warming climate affected populations of the mountain ringlet butterfly, *Erebia epiphron* (Lepidoptera: Nymphalidae), in low-elevation mountains? *European Journal of Entomology* 113, 295. https://doi.org/10.14411/eje.2016.036

Macgregor, C.J., Thomas, C.D., Roy, D.B., Beaumont, M.A., Bell, J.R., Brereton, T. *et al*. (2019). Climate-induced phenology shifts linked to range expansions in species with multiple reproductive cycles per year. *Nature Communications* 10(1), 1-10. https://doi.org/10.1038/s41467-019-12479-w

蹄类动物

Froy, H., Martin, J., Stopher, K.V., Morris, A., Morris, S., Clutton-Brock, T.H. *et al*. (2019). Consistent within-individual plasticity is sufficient to explain temperature responses in red deer reproductive traits. *Journal of Evolutionary Biology* 32(11), 1194-1206. https://doi.org/10.1111/jeb.13521

Plard, F., Gaillard, J-M., Coulson, T., Hewison, A.J.M., Delorme, D., Warnant, C. *et al*. (2014). Mismatch between birth date and vegetation phenology slows the demography of roe deer. *PLOS Biology* 12, e1001828. https://doi.org/10.1371/journal.pbio.1001828

Renaud, L.A., Pigeon, G., Festa-Bianchet, M. and Pelletier, F. (2019). Phenotypic plasticity in bighorn sheep reproductive phenology: from individual to population. *Behavioral Ecology and Sociobiology* 73(4), 1-13. https://doi.org/10.1007/s00265-019-2656-1

Stopher, K.V., Bento, A.I., Clutton-Brock, T.H., Pemberton, J.M. and Kruuk, L.E. (2014). Multiple pathways mediate the effects of climate change on maternal reproductive traits in a red deer population. *Ecology 95*(11), 3124-3138. https://doi.org/10.1890/13-0967.1

鱼类

Friedland, K.D., Reddin, D.G., McMenemy, J.R. and Drinkwater, K.F. (2003). Multidecadal trends in North American Atlantic salmon (*Salmo* salar) stocks and climate trends relevant to juvenile survival. *Canadian Journal of Fisheries and Aquatic Sciences* 60(5), 563-583. https://doi.org/10.1139/f03-047

Kennedy, R.J. and Crozier, W.W. (2010). Evidence of changing migratory patterns of wild Atlantic salmon *Salmo salar* smolts in the River Bush, Northern Ireland, and possible associations with climate change. *Journal of Fish Biology* 76(7), 1786-1805. https://doi.org/10.1111/j.1095-8649.2010.02617.x

Kovach, R.P., Joyce, J.E., Echave, J.D., Lindberg, M.S. and Tallmon, D.A. (2013). Earlier migration timing, decreasing phenotypic variation, and biocomplexity in multiple salmonid species. *PloS one* 8(1), e53807. https://doi.org/10.1371/journal.pone.0053807

Ohlberger, J., Thackeray, S.J., Winfield, I.J., Maberly, S.C. and Vøllestad, L.A. (2014). When phenology matters: age–size truncation alters population response to trophic mismatch. *Proceedings of the Royal Society B: Biological Sciences* 281(1793), 20140938. https://doi.org/10.1098/rspb.2014.0938

鸟类

Arlt, D. and Pärt, T. (2017). Marked reduction in demographic rates and reduced fitness advantage for early breeding is not linked to reduced thermal matching of breeding time. *Ecology and Evolution* 7(24), 10782-10796. https://doi.org/10.1002/ece3.3603

Both, C. and Visser, M.E. (2005). The effect of climate change on the correlation between avian life-history traits. *Global Change Biology* 11(10), 1606-1613. https://doi.org/10.1111/j.1365-2486.2005.01038.x

D'Alba, L., Monaghan, P. and Nager, R.G. (2010). Advances in laying date and increasing population size suggest positive responses to climate change in common eiders *Somateria mollissima* in Iceland. *Ibis* 152(1), 19-28. https://doi.org/10.1111/j.1474-919X.2009.00978.x

de Villemereuil, P., Rutschmann, A., Ewen, J.G., Santure, A.W. and Brekke, P. (2019). Can threatened species adapt in a restored habitat? No expected evolutionary response in lay date for the New Zealand hihi. *Evolutionary Applications* 12(3), 482-497. https://doi.org/10.1111/eva.12727

Fletcher, K., Howarth, D., Kirby, A., Dunn, R. and Smith, A. (2013). Effect of climate change on breeding phenology, clutch size and chick survival of an upland bird. *Ibis* 155(3), 456-463. https://doi.org/10.1111/ibi.12055

Gaston, A.J., Gilchrist, H.G., Mallory, M.L. and Smith, P.A. (2009). Changes in seasonal events, peak food availability, and consequent breeding adjustment in a marine bird: a case of progressive mismatching. *The Condor* 111(1), 111-119. https://doi.org/10.1525/cond.2009.080077

Imlay, T.L., Mills, J., Saldanha, S., Wheelwright, N.T. and Leonard, M.L. (2018). Breeding phenology and performance for four swallows over 57 years: relationships with temperature and precipitation. *Ecosphere* 9(4), e02166. https://doi.org/10.1002/ecs2.2166

Kentie, R., Coulson, T., Hooijmeijer, J.C., Howison, R.A., Loonstra, A.J., Verhoeven, M.A. *et al*. (2018). Warming springs and habitat alteration interact to impact timing of breeding and population dynamics in a migratory bird. *Global Change Biology* 24(11), 5292-5303. https://doi.org/10.1111/gcb.14406

Ludwig, G.X., Alatalo, R.V., Helle, P., Lindén, H., Lindström, J. and Siitari, H. (2006). Short-and long-term population dynamical consequences of asymmetric climate change in black grouse. *Proceedings of the Royal Society B: Biological Sciences* 273(1597), 2009-2016. https://doi.org/10.1098/rspb.2006.3538

McDermott, M.E. and DeGroote, L.W. (2016). Long-term climate impacts on breeding bird phenology in Pennsylvania, USA. *Global Change Biology* 22(10), 3304-3319. https://doi.org/10.1111/gcb.13363

McDermott, M.E. and DeGroote, L.W. (2017). Linking phenological events in migratory passerines with a changing climate: 50 years in the Laurel Highlands of Pennsylvania. *PLoS One* 12(4), e0174247. https://doi.org/10.1371/journal.pone.0174247

Moe, B., Stempniewicz, L., Jakubas, D., Angelier, F., Chastel, O., Dinessen, F. *et al*. (2009). Climate change and phenological responses of two seabird species breeding in the high-Arctic. *Marine Ecology Progress Series* 393, 235-246. https://doi.org/10.3354/meps08222

Møller, A.P. (2008). Climate change and micro-geographic variation in laying date. *Oecologia* 155(4), 845-857. https://doi.org/10.1007/s00442-007-0944-3

Nilsson, A.L.K., Slagsvold, T., Røstad, O.W., Knudsen, E., Jerstad, K., Cadahia, L. *et al*. (2019). Territory location and quality, together with climate, affect the timing of breeding in the white-throated dipper. *Scientific Reports* 9(1), 1-11. https://doi.org/10.1038/s41598-019-43792-5

Rosenfield, R.N., Hardin, M.G., Bielefeldt, J. and Keyel, E.R. (2017). Are life history events of a northern breeding population of Cooper’s Hawks influenced by changing climate? *Ecology and Evolution* 7(1), 399-408. https://doi.org/10.1002/ece3.2619

Sanz, J.J., Potti, J., Moreno, J., Merino, S. and Frias, O. (2003). Climate change and fitness components of a migratory bird breeding in the Mediterranean region. *Global Change Biology* 9(3), 461-472. https://doi.org/10.1046/j.1365-2486.2003.00575.x

Sauve, D., Divoky, G. and Friesen, V.L. (2019). Phenotypic plasticity or evolutionary change? An examination of the phenological response of an arctic seabird to climate change. *Functional Ecology* 33(11), 2180-2190. https://doi.org/10.1111/1365-2435.13406

Schaefer, T., Ledebur, G., Beier, J. and Leisler, B. (2006). Reproductive responses of two related coexisting songbird species to environmental changes: global warming, competition, and population sizes. *Journal of Ornithology* 147(1), 47-56. https://doi.org/10.1007/s10336-005-0011-y

Vatka, E., Orell, M. and Rytkönen, S. (2011). Warming climate advances breeding and improves synchrony of food demand and food availability in a boreal passerine. *Global Change Biology* 17(9), 3002-3009. https://doi.org/10.1111/j.1365-2486.2011.02430.x

Visser, M.E., Gienapp, P., Husby, A., Morrisey, M., de la Hera, I., Pulido, F. *et al*. (2015). Effects of spring temperatures on the strength of selection on timing of reproduction in a long-distance migratory bird. *PLoS Biology* 13(4), e1002120. https://doi.org/10.1371/journal.pbio.1002120

Watanuki, Y., Ito, M., Deguchi, T. and Minobe, S. (2009). Climate-forced seasonal mismatch between the hatching of rhinoceros auklets and the availability of anchovy. *Marine Ecology Progress Series* 393, 259-271. https://doi.org/10.3354/meps08264

Weatherhead, P.J. (2005). Effects of climate variation on timing of nesting, reproductive success, and offspring sex ratios of red-winged blackbirds. *Oecologia* 144(1), 168-175. https://doi.org/10.1007/s00442-005-0009-4

Wegge, P. and Rolstad, J. (2017). Climate change and bird reproduction: warmer springs benefit breeding success in boreal forest grouse. *Proceedings of the Royal Society B: Biological Sciences* 284(1866), 20171528. https://doi.org/10.1098/rspb.2017.1528

蝙蝠

Linton, D.M. and Macdonald, D.W. (2018). Spring weather conditions influence breeding phenology and reproductive success in sympatric bat populations. *Journal of Animal Ecology* 87(4), 1080-1090. https://doi.org/10.1111/1365-2656.12832

海洋物种

31. Poloczanska *et al*. (2013)

32. Poloczanska *et al*. (2016)

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