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土壤节肢动物的生态指示作用及其在城市生态系统中的应用综述

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摘　要

随着城市化的不断发展，城市土壤生态环境不断恶化，需要得到进一步的指示预警。本研究基于土壤节肢动物的生态指示作用，介绍了土壤节肢动物群落特征和功能特征的特点、影响因素和在自然/半自然生态系统的应用优势和不确定性，探讨了其指示城市土壤生态系统健康的潜力和可能存在的问题，并提出建议，为同类研究和城市土壤生态治理提供参考。

关键词

土壤节肢动物，生态指示作用，城市生态系统

Review of the Ecological Indication of Soil Arthropods and Its Application in Urban Ecosystems

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Abstract

With the continuous development of urbanization, urban soil ecosystems are deteriorating and need to be further indicated for early warning. Based on the ecological indication of soil arthropods, this study introduces the characteristics and influencing factors of soil arthropod community features and functional characteristics, and the advantages and uncertainties of their applica-

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tion in natural/semi-natural ecosystems, explores their potential and possible problems in indicating the health of urban soil ecosystems, and makes recommendations to provide reference for similar studies and urban soil ecological management.

Keywords

Soil Arthropod, Ecological Indication, Urban Ecosystem

1. 引言

据联合国估计，到 2050 年，全球人口将达到 98 亿，其中 68%的人口将在城市生活[1]。人口的大量集中将进一步加速城市扩张和大规模城市建设。城市居民的生产与生活活动等导致城市土壤生态系统发生了巨大的改变，造成城市土壤生态系统景观格局特征改变[2] [3]，土壤理化性质发生变化(容重增加、pH 上升、有机质增加等) [4]，重金属[5] [6]及有机物污染[7] [8]，土壤生物群落结构中外来种及边缘种比例增加[9] [10] [11]等，引起城市土壤质量的退化，削弱其生态系统服务功能。城市土壤与城市居民福祉关系密切，承载着支持城市绿化与农业生产[12]，调节地表径流，污染物汇集与分解[13]，控制有害生物与调节人类免疫系统[14]等作用。城市土壤退化和土壤质量下降事关城郊农业生产安全及城市生态系统服务的可持续性，直接或间接地影响城市居民的健康[15] [16] [17]。因此，城市土壤生态风险问题关系着人类社会的可持续发展，需得到有效的警示与管控。

生物的生态指示作用是指利用指示生物对生态系统环境变化的反映，对过去、现在和未来的生境质量或生态健康进行评价。具有指示作用的生物类群很多，既有以单个物种如蚂蚁等作为指示生物的[18]，也有如土壤节肢动物等利用整体群落特征或功能特征作为指示指标的生物类群。土壤节肢动物是土壤生态系统中的重要类群，在土壤生态系统物质循环和能量转换中发挥着积极作用[19] [20]。土壤节肢动物如跳虫和螨虫等因其体型较小，处于土壤食物链底层，相比于蚯蚓等大型土壤动物对土壤环境变化更敏感，能更早地指示城市土壤生态的变化，因此常作为监测城市土壤污染和土地利用变化等的良好指示生物[21]。

本文将根据土壤节肢动物群落特征和功能特征的特点，介绍其作为生物指标在指示土壤质量中的作用，综述其在当前城市土壤生态系统中的应用现状，分析当前其应用主要面临的挑战，探索未来可能的应用方向并提出相应建议推动其发展，以期为同类研究提供相关参考和经验借鉴。

2. 土壤节肢动物的生物指示功能

土壤节肢动物依赖土壤为其提供栖息场所、水热、碳水化合物、矿质养分等必要生存条件。植被改变、机械性扰动对土壤物理结构的破坏、农药与肥料的施用以及污染物排放都会影响土壤动物的生长繁殖，从而导致土壤节肢动物多样性特征的变化。将土壤节肢动物多样性特征作为评价土壤质量的指标，能够综合性地表征土壤质量，可以实现对土壤生态系统中长期趋势与历史状态的评估[22] [23] [24]。当前研究用于指示土壤质量的土壤节肢动物多样性特征指标主要包含两个维度，一个维度是土壤节肢动物群落特征，如丰度、丰富度、特有种和优势种等；另一个维度是土壤节肢动物功能特征，如活动能力、食性和生殖模式等。基于土壤节肢动物群落特征和功能特征的特异性反映，部分学者已经建立并发展出一

系列定量化参数，用以评估土壤生态环境质量[25]。

2.1. 土壤节肢动物群落特征的指示作用

土壤节肢动物栖息在土壤环境中，依赖土壤环境生存，受生态环境变化影响而发生群落结构转变，可以综合体现土壤环境特征[26]。国内外许多研究已证明土壤群落特征与土壤环境变化存在紧密的联系[27] [28]。

2.1.1. 丰度，丰富度

丰度是指一个物种在特定区域范围内的个体数量之和，丰富度是指一个生态系统中物种的多样性即物种数量的多寡。丰度会随环境变化而出现波动，影响群落结构进而导致群落内物种数量的变化，造成丰富度的转变。在局部尺度下，受干扰的、不稳定的生态系统，由于受各种直接干扰多，水热条件不稳定，通常具有较低的土壤节肢动物丰度和丰富度。N'Dri 等发现与未被破坏的热带次生林相比，具有 7 年种植历史的橡胶种植园土壤中螨虫的丰度下降了 60%，丰富度下降了 48%；种植 25 年后，螨虫丰度恢复至正常水平，但丰富度仍比未被破坏的热带次生林低 15% [29]。Rodgers 等的研究中将农业机械运行轨迹限定在一定范围后，在 0~190 mm 的土壤中，土壤节肢动物的整体丰度及丰富度都显著上升，跳虫的丰度也在春季出现显著上升[30]。在澳大利亚，Nkem 等发现土壤节肢动物在没有农业活动的草地中具有最高的丰度和丰富度，而放牧草地的土壤节肢动物比耕作的草地丰度多 30% [31]。Elo 和 Sorvari 发现皆伐减少了人工林土壤中甲螨的丰富度[32]。在北欧云杉林，红橡的引入减少了包括土壤节肢动物在内的次级分解者的丰度[33]。在巴西几个牧场，放牧强度最低的农场跳虫的丰度最高[34]。Machado 等对不同用地类型的土壤跳虫多样性的研究表明，自然林中跳虫的香农－维纳多样性指数在冬季时比其他用地类型高[35]。

2.1.2. 特有种，优势种

由于干扰对原有生境，特别是内生生境的破坏，一些特有种可能会随之消失。通过分子生物学手段，Dopheide 等发现，特有种数量指标是一个比物种多样性指数更能区分土地利用类型的指标[36]。在非洲南部一系列退化的草原上，自然形成的低地平原生态系统相比受到干扰(人工修复)的生态系统具有更多的特有种[37]。在大西洋东部的特塞拉岛，受人类高度干扰地区的土壤节肢动物特有种仅为低干扰地区的约 20% [38]。在意大利全国范围内，在 10 × 10 km 的空间粒度(grain)下，步甲特有种的数量与人口密度呈负相关性[39]。

某些土壤节肢动物物种对环境变化相对其他种类敏感，可单独作为生物指标指示土壤生态系统的状态和变化。例如缺弹跳属(*Anurophorus*)被认为是抗干旱能力较强的一类跳虫[40]，在受到干扰的生境更能够取得竞争优势。在受风灾影响从而出现倒木的云杉林中，缺弹跳属跳虫丰度上升，成为跳虫群落的优势种[41]。柴特北绥螨(*Arctoseius cetratus*)具有较高的繁殖速率，常随其它物体一起迁移，从而开拓新生境，被认为是演替早期生境的代表性螨虫[42] [43]。在荷兰，5 年间，一种平懒甲螨属螨虫(*Platynothrus peltifer*)丰度随着松林的恢复上升[44]。也有研究发现在科、目水平上，土壤节肢动物具有一定特异性的响应。Rousseau 等发现，将砍伐后的针叶林中木质残落物移除后，甲螨在物种多样性和功能形态上的响应要强于跳虫[45]。一个欧洲山地云杉林在发生林火两年后，其土壤跳虫群落显著与对照组不同，其中等节跳科和棘跳科仅出现在发生过林火的区域中，研究者因此认为这两个科的跳虫具有指示火烧干扰的潜力[46]。Reis 等通过对比发现，虽然将跳虫鉴定至属的解释度更高，但鉴定到科也能很好地区别五种不同林型的跳虫群落多样性[47]。Meehan 等用中气门螨虫和甲螨从科、属、种三个物种级别，均成功揭示了林火、森林砍伐和道路建设三种不同干扰对森林生态系统的影响[48]。然而，土壤节肢动物群落的空间异质性很大，而且由于土壤节肢动物种间高度的功能冗余性，以单一物种作为生物指标的应用容易受到一定的限制。

2.2. 土壤节肢动物功能特征的指示作用

土壤节肢动物的功能特征与其形态、生理和物候特征紧密联系[49] [50]，反映了生物具体的生态位选择及环境耐受性[51] [52]。因此土壤节肢动物功能特征也常作为生物指标用于评价土壤质量。

2.2.1. 活动能力

与活动能力相关的土壤节肢动物形态特征，如体型(大小、性状等)和运动器官等是受关注较多的功能特征。一般来说，干扰及不稳定的生境有利于体型小、运动能力强的物种生存。例如，Birkhofer 等研究了草原和森林两个生态系统的大型土壤节肢动物的功能特征对土地利用强度的响应，发现草原生态系统中所有物种的土壤节肢动物的体型大小平均值都随利用强度提高而减小，同时发现蛛型纲和异翅目中迁移能力弱的物种丰度比例下降[53]。Barber 等长期观察植被恢复 0~28 年后的一系列草地，发现处于恢复早期的草地中的步甲体型更小，具有更大的翅膀，而恢复时间较长的草地中体型更大，飞行能力较差的物种成为优势种；如果在植被恢复之前进行火烧，将进一步减少体型大的物种的出现[54]。另外，林火[55]，皆伐[56]和种植园管理[57]通过改变地表有机质的质与量以及随之发生的土壤理化性质改变，也能够减少体型较大、体色鲜艳的表栖跳虫。

2.2.2. 食性

土壤节肢动物的食性也是指示生境变化的重要功能特征。土壤节肢动物的食性随着生境的资源种类和丰富度而变化。在原有植被被破坏后的早期恢复阶段，群落以速生的草本为主，此时的土壤节肢动物食性以植食性(包括食真菌)为主。随着植物群落的演替，生态系统可利用的资源发生改变，土壤节肢动物的食性也会发生变化。例如，在林龄分别为 5、25、45 和 95 年的云杉林中，食真菌甲螨的丰度在 25 年林龄中显著上升，而杂食性甲螨下降，其它食性的甲螨则没有显著变化[58]。在 2~160 年的针叶林演替系列的 4 个演替阶段中，腐食性甲虫的物种多样性随着演替的进行而增加[59]。林业生产活动也强烈影响土壤节肢动物可利用的资源的质与量。例如，Birkhofer 在草原和森林两个生态系统中发现，随着土地利用强度的增长，都有部分类群的食肉性大型节肢动物的个体比例出现上升[53]。另外，食物资源的改变还会影响土壤节肢动物群落的口器构造特征。例如，在凋落物积累较厚的凋落物层，具有更强壮上下颚的跳虫会成为跳虫群落中的优势种[60]。农药的使用会使具有紧凑/小型螯肢的甲螨在群里中比例上升以适应食物来源的变化[61]。

2.2.3. 生殖模式

有性生殖能产生变异的后代，在群落个体密度较大的情况下，有利于抵抗捕食与疾病[62] [63]。无性生殖则能高效地产生更多个体，能更大概率地占领新生境成为优势种[64] [65]。因此，在群落充分发展的阶段，有性生殖将成为优势的生殖模式；反之，无性生殖在受到干扰的不稳定的生境中较容易成为主导的生殖模式[66]。例如有研究发现在引入红橡树后受到破坏的波兰本地森林生境中，土壤甲螨群落中有性生殖的种类和丰度显著下降[33]。这种对生殖模式的影响在森林生态系统中尤其明显，研究表明林火及林业经营活动显著减少了有性生殖的跳虫[67]与甲螨[68] [69]在森林土壤生物群落中的数量比例。林火使几个样地中有性生殖的跳虫丰度平均下降了 40%，并且这种下降幅度与林火的强度正相关，与土壤表层凋落物的厚度及土壤的持水能力呈负相关[65]。

2.3. 定量化指数

特定物种或功能群落的节肢动物对生态环境变化具有专一性和忠实性，能够定向地反映出土壤生态系统内的环境变化。有研究提出利用这一特性，基于土壤节肢动物的群落特征和功能特征，建立定量化的指示指数[70]。

2.3.1. 成熟度指数

一些学者对不同土壤动物的适应性赋值后进行计算，从而能够量化土壤质量。成熟度指数(Maturity Index)利用土壤节肢动物，例如螨类的生活史策略(r 与 K)，对所研究群落内的所有种赋值，对土壤质量进行定量化表征[71]。成熟度指数能够指示土地利用类型[72] [73]、林业管理经营[74] [75]、农业耕作方式/强度[76] [77] [78]所引起的土壤质量变化。但在应用该指数时，某些种的赋值存在一定争议；若将其应用于种水平以上，也存在一定的问题，这在一定程度上限制了成熟度指数的应用[79]。

2.3.2. 土壤生物质量指数

土壤生物质量指数(Soil Biological Quality, QBS)是意大利学者 Parisi 等提出的一个利用土壤节肢动物的丰度及其对环境变化的适应程度来衡量土壤质量的指数[80]。QBS 能够对土壤质量进行定量化，对物种的鉴定精度要求不高，一般仅需要鉴定至目即可，在近十年得到了许多应用[81]。一般来说，随着土地利用强度的增加，土壤受到更多干扰，QBS 数值将降低，表示土壤质量正在变差。例如，受人类干扰的农田的 QBS 值要小于自然林[82]。Madej 和 Kozub 用基于小型土壤节肢动物的 QBS 监测了矿山修复后的土壤质量变化，认为它是一个简单有效且灵敏度高的指标[83]。Blas 等发现基于土壤节肢动物的 QBS 在硬木林中的值比灌木丛的高；林业经营活动通过影响土壤理化性状降低了 QBS [84]。传统耕作和有机耕作对土壤的不同影响也能够用 QBS 区别出来[85]。QBS 可以评估林火、土地利用方式等对土壤生态环境的干扰程度。Mantoni 等发现野火降低了自然桦林、人工松林和自然草地的 QBS [86]。通过野外控制试验，Yin 等证明不同的用地类型显著影响了基于跳虫的 QBS 值[87]。

3. 土壤节肢动物生物指标在城市生态系统的应用现状及挑战

3.1. 土壤节肢动物生物指标在城市生态系统的应用现状

土壤节肢动物的群落特征和功能特征对土壤生境条件改变的响应是其作为生物学指标衡量土壤质量的基础。一些研究表明，城市土壤节肢动物群落特征和功能特征与城市土壤生境环境因子，如用地方式、用地强度、土壤理化性质等的关系与自然/半自然生态系统类似[88] [89] [90]。例如，Toth 和 Hornung 在布达佩斯的研究发现，马陆的群落及功能多样性都随城市化程度而下降；城市化程度较低的样地中，体型较大的马陆较多，而城市化程度较高的样地，喜欢开阔生境的马陆种类较多[91]。Fiera 在罗马尼亚布加勒斯特的三个公园的取样结果显示，重金属污染最严重的公园的跳虫物种多样性最低；同一个公园内，污染程度更轻的中心地区比边缘拥有更多的跳虫物种[92]。Milano 等研究法国蒙彼利埃 14 个城市公园的景观组合，发现土地覆被减少、生境斑块破碎化和不透水表面的增加是影响城市公园跳虫生物多样性减少的主要原因[93]。

然而，另外一些研究却出现了不一样的结论，认为土壤节肢动物群落特征和功能特征无法完全反映城市土壤生态环境的变化[94]。例如，Joimel 等总结了不同研究的 758 份土壤节肢动物群落的数据后发现，工业区周边的土壤具有较低的土壤质量(以土壤理化性状衡量)，但却拥有比农田和种植园更高的土壤节肢动物多样性[95]。Sterzynska 等调查了波兰华沙 50 个生境斑块的土壤特征和跳虫群落特征，抽样结果显示跳虫物种丰度与土壤湿度、CEC、重金属污染等无关，反而与空气污染颗粒物存在强烈的负相关关系[96]。

现有研究表明，在不同的城市土壤环境条件和土地利用方式下，土壤节肢动物对城市土壤健康的预警能力强弱不一，这使得土壤节肢动物指示城市土壤生态系统健康的研究更加复杂。有关土壤节肢动物在不同土壤性质和土地利用条件下的城市土壤生态健康指示作用的研究仍然不足，需要得到更多讨论。

3.2. 在城市生态系统中应用土壤节肢动物生物指标面临的挑战

城市生态系统具有自然/半自然生态系统不具有的独特环境因素及各种因素的特殊组合，这为解释土

壤节肢动物与城市土壤生态系统健康之间的关系提出了新的挑战。城市中，大多数土壤生态系统镶嵌于人工建筑的大背景下，周长面积比大，受城市活动的直接干扰强[97] [98]。Scharenbroch 等在美国爱达荷州和华盛顿州的研究发现，城市干扰导致土壤容重增加和有机质减少，需经过数十年时间才能缓慢自然恢复[99]。城市景观格局因素包括生境面积、连接度、景观多样性等对土壤节肢动物群落也都具有一定的影响。同时人类的一些活动对土壤节肢动物产生相互矛盾的影响。例如，Faeth 等整理了 92 篇关于城市影响生物多样性的研究文献，其中 49 篇显示在温带地区城市化减少了节肢动物的多样性，而另外 3 篇显示气候寒冷地区节肢动物多样性随城市化水平提升而增加[9]。在人类活动多的地方，一般土壤节肢动物会因土壤生境受人为干扰而受到抑制，但有时人类活动能增加土壤有机质反而为它们提供了更多可利用的资源。例如一些农田苗圃经营者会使用生活或工业废水进行灌溉，这一方面增加了土壤有机质，又会引入污染物抑制土壤节肢动物的生长繁殖。

此外，广受关注的土壤重金属污染及有机物污染对土壤节肢动物的影响的研究结果存在较大的矛盾。实验室条件下，许多重金属元素，如 Cd、Cu、Pb 等均会对土壤节肢动物的生存和繁殖产生抑制。但在野外/城市条件下，即使排除了污染严重程度不同的影响后，土壤节肢动物的丰度、丰富度和多样性指数等并不随土壤重金属含量增加而降低。相关土壤有机物污染物与土壤节肢动物群落关系的研究发现，土壤有机物污染在野外条件下鲜有直接对土壤节肢动物出现抑制作用的。Blakely 等研究了美国托莱多被杂酚油污染的土壤，发现杂酚油更多通过增加土壤容重，减少土壤孔隙而不是直接毒害来影响土壤节肢动物丰度[100]。Errington 等在亚南极地区麦考瑞岛的研究表明石油渗漏污染对跳虫群落没有明显直接影响，而土壤容重才是影响跳虫群落的最大因素[101]。Garcia-Segura 等对比分析了墨西哥韦拉克鲁斯州废弃油井周边受石油污染与未受污染土壤中的中型动物，发现中等污染土壤中的跳虫数量是其它土壤的三倍，且出现了部分优势种，这可能是由于跳虫拥有降解利用石油中有机碳的能力[102]。

在人类活动的影响下，城市土壤生态系统群落中包含许多外来种，广布种，机会种，其对城市化干扰的响应存在不确定性。例如，人为直接干扰会中断群落的自然组建或演替，使群落不能体现土壤理化性质等自然特征。园林绿化等会引入繁殖快，抗胁迫能力强的外来种，在污染大、强干扰条件下仍能达到非常高的丰度[103] [104] [105]。Fountain 和 Hopkin 在英格兰伍尔夫汉普顿的研究对比五个样地，发现几个跳虫物种仅在 Ladymoor 工业遗址(1920 年停用，现为自然保护区)出现，但无法明确其成为特有种是因为其更加耐受土壤重金属污染，还是因该地成为保护区受人为扰动更少而具有更稳定的良好生境条件[106]。

4. 结论与展望

综上所述，相比于自然/半自然生态系统，城市土壤生态系统具有独特的土壤节肢动物生境条件和物种组成，为土壤节肢动物的生态指示应用提出了新的挑战。为了更深入研究土壤节肢动物对城市土壤生态系统健康的指示作用，首先需完善节肢动物各类群的标准化抽样方法，建立科学统一的分析方法，以利于不同的城市土壤生态条件下的研究结果比较。其次需加强对城市土壤节肢动物多样性特征，特别是物种组成对不同的城市土壤生态环境条件下的响应与变化，以及城市特有种/广布种的识别及其环境响应的研究；此外对于土壤节肢动物对无机和有机污染物的响应，需要室内与野外/城市土壤条件的对比实验共同进行，利用非线性模型进行研究，分析造成不同条件下结果差异的影响因素和机制，以明确城市土壤生态系统环境变化与土壤节肢动物多样性的关系。

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