

Review

Under Pressure: Environmental Stressors in Urban Ecosystems and Their Ecological and Social Consequences on Biodiversity and Human Well-Being

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Abstract

Urban ecosystems are increasingly shaped by multiple environmental stressors, which may threaten both biodiversity and human well-being. We summarised the current knowledge on the ecological and social consequences of seven major urban pressures: air pollution, freshwater degradation, biological invasions, noise pollution, habitat fragmentation, soil pollution and climate crisis. Air and soil pollution, largely driven by traffic and industrial activities, compromises vegetation functions, reduces ecosystem services, and affects human health. Urban freshwater systems face contamination from stormwater runoff, wastewater, and microplastics, leading to biodiversity loss, altered ecosystem processes, and reduced water availability. Biological invasions, facilitated by human activities and habitat disturbances, reshape ecological communities, outcompete native species, and impose socio-economic costs, while management requires integrated monitoring and citizen engagement. Noise pollution disrupts animal communication, alters species distributions, and poses significant risks to human physical and mental health. Simultaneously, habitat fragmentation and loss reduce ecological connectivity, impair pollination and dispersal processes, and heighten extinction risks for both plants and animals. Collectively, these stressors interact synergistically, amplifying ecological degradation and exacerbating health and social inequalities in urban populations. The cumulative impacts highlight the need for systemic and adaptive approaches to urban planning that integrate biodiversity conservation, public health, and social equity. Nature-based solutions, ecological restoration, technological innovation, and participatory governance emerge as promising strategies to enhance urban resilience. Furthermore, fostering citizen science initiatives can strengthen monitoring capacity and create community ownership of sustainable urban environments. Addressing the combined pressures of urban environmental stressors is thus pivotal for building cities that are ecologically robust, socially inclusive, and capable of coping with the challenges of the climate crisis and global urbanization.



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1. Introduction

For centuries, urbanization has been a critical global issue. As cities expand, they transform natural landscapes, altering ecological processes. Urban ecosystems are complex and dynamic environments characterised by a mix of natural and constructed elements, including buildings, transportation systems, and green spaces such as parks and gardens. The vegetation within these ecosystems can vary widely, from native plant communities to introduced species for urban greening use, and the animals present range from common urban adapters to more specialised species.

Urban ecosystems are increasingly subject to intense environmental stressors driven by rapid urban growth, such as air pollution, heat island, and resource scarcity. Air and soil pollution are recognised as deleterious factors to public health, with air pollutants, especially the key greenhouse gases, such as carbon dioxide (CO₂) and tropospheric ozone (O₃), considered the main drivers of the present global climate crisis [1,2]. To address this problem, the United Nations 2030 Agenda targets urban sustainability, requiring significant efforts to mitigate and adapt cities to the climate crisis. Accordingly, in December 2019, the European Commission presented the Green Deal, which aimed to achieve climate neutrality by 2050 and reduce greenhouse gas emissions by 55% compared to the 1990 scenario by 2030, highlighting the importance of air pollution removal by natural sinks to achieve the overall EU target.

Understanding the interplay between these stressors and their ecological and social consequences is critical. Ecologically, urban stressors can degrade biodiversity, alter ecosystem functions, and reduce the capacity of natural systems to provide essential ecosystem services such as carbon sequestration. Biodiversity underpins urban ecosystem functions that are essential for human health and well-being. Therefore, the European Union (EU) Biodiversity Strategy aims to prevent biodiversity loss and restore ecosystems across Europe by 2030. This ambitious plan emphasises the importance of urban green spaces in fostering biodiversity, including both insect and animal populations, which are vital for ecosystem services such as pollination, pest control, nutrient cycling, and maintaining food webs. Urban environments, however, may alter the behaviour of both insects and other animals, potentially leading to declines in their diversity and disrupting ecological balance [3,4].

Urban ecosystems also offer unique opportunities for adaptive resilience strategies. For example, the planting of ornamental tree species in urban areas offers an effective ecological approach to enhancing air quality in cities, recognised as nature-based solutions (NBSs) [5,6]. Trees act as natural air filters, absorbing gaseous pollutants through leaf stomata, while their canopies capture particulate matter (PM) by intercepting airborne particles [7,8]. In particular, urban greening plays a crucial role in mitigating the impacts of the climate crisis by absorbing and storing CO₂, the primary greenhouse gas, and by reducing the urban heat island effect through cooling during summer months. However, the positive capacity is highly variable among tree species, and it has been recognised that some plant species may even have negative effects on air quality due to emissions of volatile organic compounds (VOCs), which are precursors for O₃ production. Therefore, to ensure effective and sustainable urban greening efforts, optimal tree species selection is essential to achieve functional, ecologically rich urban landscapes [9].

This paper synthesises and critically discusses the current state of knowledge and explores the multifaceted impacts of environmental stressors on urban ecosystems (Figure 1),

emphasising their dual role as drivers of ecological degradation and contributors to social vulnerability. By integrating ecological theory with urban sustainability frameworks, the study focuses on the complex feedback loops between natural and human systems, aiming at highlighting pathways toward more resilient and equitable urban futures.

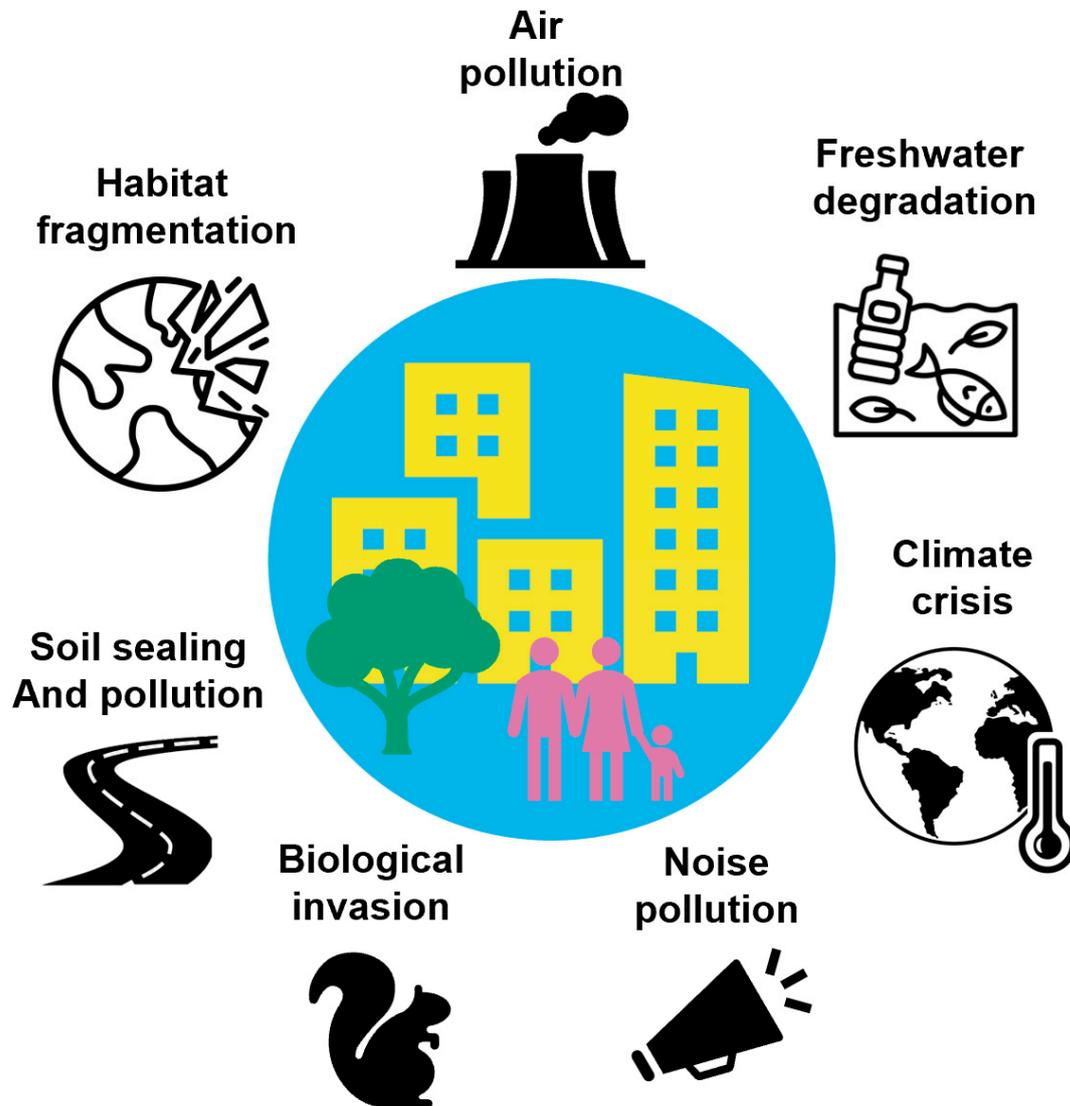


Figure 1. Main stressors of urban ecosystems, which may affect human well-being.

While multiple urban stressors have cumulative effects, their interactions are often mediated by underlying ecological and physiological mechanisms. For instance, noise pollution can exacerbate biological invasions by disrupting native species' acoustic communication, reducing their reproductive success and territorial defence, thereby opening ecological niches exploitable by invasive taxa that are more tolerant to acoustic disturbance. Similarly, air and soil pollution can weaken plant physiological defences and reduce ecosystem resilience, indirectly facilitating the establishment of opportunistic or invasive species. Habitat fragmentation and climate-induced heat stress further compound these effects by isolating populations and reducing genetic diversity, making communities less resistant to novel pressures. Understanding these mechanistic feedbacks is essential for predicting cascading impacts of urban stressors and designing integrated mitigation strategies (Figure 2).

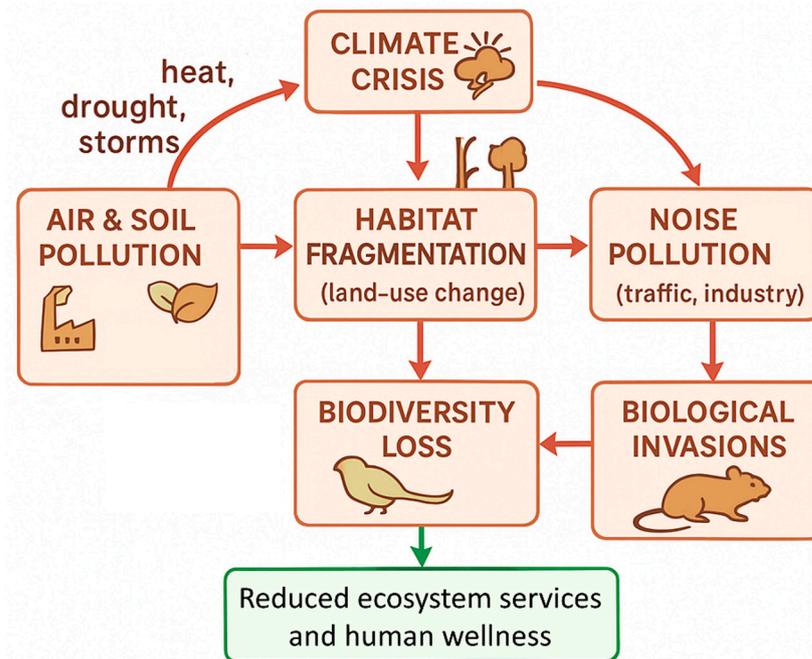


Figure 2. Conceptual framework illustrating the synergistic interactions and feedback loops among major urban stressors. Climate crisis amplifies air and soil pollution, noise, and habitat fragmentation. These stressors degrade vegetation and soils, reduce native biodiversity, and favour biological invasions. In turn, biodiversity loss and ecosystem degradation weaken urban ecosystem services, decreasing human well-being and resilience. Reduced resilience further exacerbates vulnerability to climatic and anthropogenic stressors, forming reinforcing feedback loops.

2. Air Pollution in Urban Ecosystems

Air pollution in urban ecosystems represents not only a major driver of ecological degradation but also a fundamental challenge for social well-being.

Urban air pollution results from a complex interplay of multiple anthropogenic sources, including traffic, residential burning, and industrial point sources. Importantly, emissions from road traffic are released close to ground level, thus having an immediate impact on local air quality and human exposure. Beyond the well-recognised exhaust emissions of nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HCs), increasing attention has been paid to so-called non-exhaust sources such as brake, tire, and road wear, as well as road dust resuspension. These non-exhaust emissions have been demonstrated to contribute as much as, and in some cases more than, tailpipe exhaust to ambient PM concentrations in cities, and their relative importance is expected to rise in the coming decades [10]. Studies have confirmed that heavy-duty vehicles and long-distance car journeys are particularly relevant emitters of NO_x, while buses and motorcycles represent smaller but still significant contributions to urban pollution burdens [11]. Furthermore, pollutants include both primary emissions, which are directly released into the atmosphere, and secondary pollutants, such as tropospheric O₃ and secondary inorganic aerosols, which form through complex atmospheric reactions involving VOCs.

Green infrastructure (e.g., urban forests, green roofs, vegetative barriers) provides multiple benefits, such as reducing noise and creating spaces for recreation and mental well-being, thereby significantly influencing local atmospheric conditions by mitigating urban microclimate and air quality [12,13]. Urban forests—comprising street trees, parklands, and peri-urban woodlands—are especially effective at filtering air pollutants through dry deposition, absorbing gaseous compounds via stomata, and intercepting PM on leaf surfaces,

while simultaneously enhancing carbon sequestration and biodiversity [7]. Figure 3 brings a simple summary of how urban trees act in reducing air pollution in urban environments.

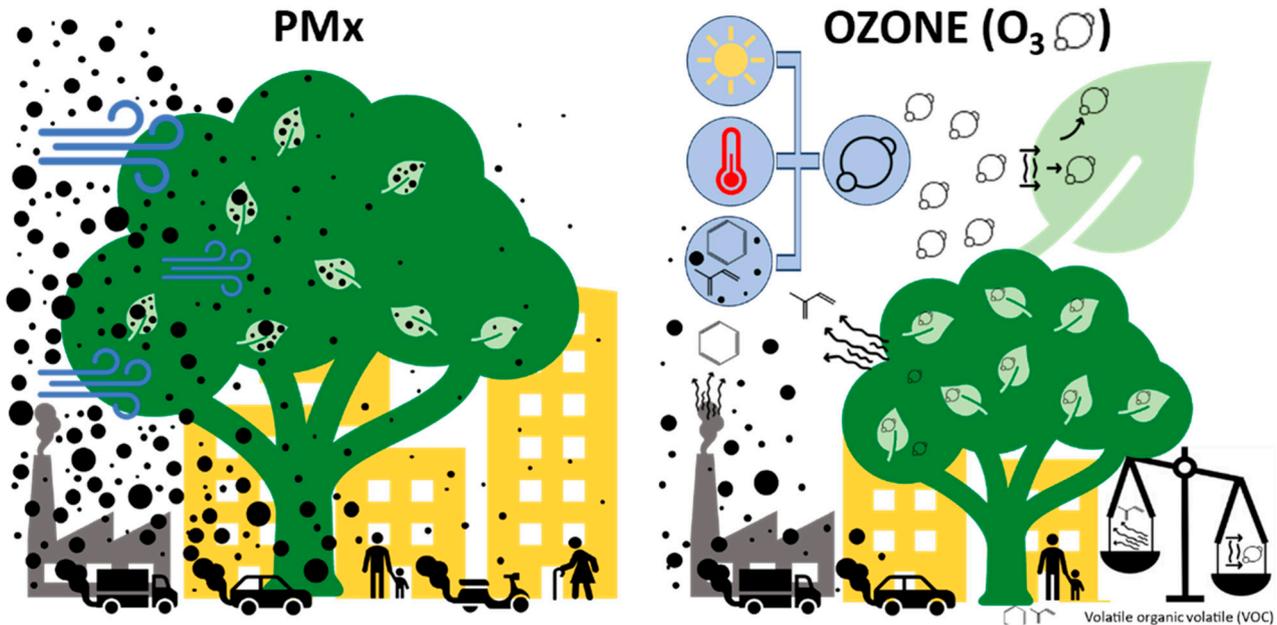


Figure 3. Scheme of how urban trees help to remove particulate and uptake ozone (O_3), improving air quality in the urban environment.

Furthermore, green roofs contribute by creating additional green surfaces in densely built environments; not only retaining and filtering airborne particles but also reducing building energy demand through insulation, mitigating stormwater runoff, and lowering roof surface temperatures, thereby attenuating the urban heat island effect. The vegetation can also work as a pollutant barrier, such as hedgerows, green walls, and linear tree plantings along roadsides, has been shown to reduce pedestrian exposure to traffic-related air pollution by altering local airflow dynamics and enhancing near-road pollutant deposition [14].

Nowak et al. [7] estimated that trees and shrubs in the United States remove approximately 711,000 tonnes of air pollutants annually (including O_3 , NO_2 , CO , and PM_{10}), generating health benefits valued at more than USD3.8 billion per year. Complementarily, Beckett et al. [15] demonstrated species-specific differences in PM capture efficiency, with rough-leaved species retaining substantially more particles than smooth-leaved ones, confirming that urban greening can substantially mitigate air pollution levels and human exposure, with its capacity particularly varying across seasons and urban zones [16].

Nonetheless, plant species selection is a critical determinant of whether urban greening contributes positively or negatively to air quality regulation. The overall benefits of vegetation may be partly limited by the release of BVOCs from certain species, which, in the presence of NO_x and sunlight, can promote the formation of ground-level O_3 and secondary organic aerosols, thereby deteriorating local air quality [12,16]. The efficiency of green spaces further depends on context-specific variables, including species composition, canopy structure, and local atmospheric conditions, underscoring the importance of thoughtful design and adaptive management to maximise benefits while minimising unintended consequences such as secondary pollutant formation [9].

Although urban vegetation plays a positive role in cities, it could also be highly vulnerable to these environmental stressors. Plants exposed to acute or chronic pollution stress often exhibit decreased photosynthetic efficiency, altered gas exchange, impaired

growth, and premature leaf senescence [17–20], thereby reducing their capacity to regulate microclimates and support ecosystem services. Moreover, eco-physiological impairments in urban vegetation can have secondary effects on both human physical and mental health, as the degradation or absence of healthy green spaces compromises opportunities for psychological restoration and stress recovery [21].

3. Urban Freshwater Ecosystems

The Blue Habitats of Urban & Suburban Areas refer to the freshwater components found in cities, encompassing both natural freshwater ecosystems (such as lakes, rivers, ponds, hyporheic zones, and groundwater) and the human-made infrastructure designed to provide drinking water and manage wastewater [22]. Together, they provide essential ecosystem services to urban populations, including water supply, temperature regulation, flood mitigation, and recreational and aesthetic value [23].

Urban water contamination is closely linked to city activities and development, with key drivers identified in stormwater runoff, atmospheric washout, and wastewater sources. Among non-point sources of contamination, urban stormwater runoff carries a variety of pollutants, including nutrients, pathogens, metals, microplastics, organic contaminants, road wear, tire wear particles, brake pad linings, and vehicle exhaust, along with their associated chemicals [24,25]. In contrast, wastewater is widely recognised as a significant point-source driver of the “urban stream syndrome” [26]. Besides contamination, urban waters are also impaired by the climate crisis. In many cities worldwide, such as Berlin, Paris, Milan, and Vienna, groundwater temperatures are increasing, contributing to the formation of shallow subsurface Urban Heat Islands [27]. This trend is largely influenced by urban infrastructure, including surface sealing.

The degradation of urban waters, particularly evident in the “urban stream syndrome,” is caused by a combination of high contaminant concentrations, altered channel morphology, loss and fragmentation of freshwater habitats, and over-exploitation from recreational activities [28]. Urban water contamination harms a wide range of aquatic life, including vegetation, birds, mammals, insects, reptiles, amphibians, invertebrates, and fish (e.g., [29]). For example, contaminated urban water from traffic-related rainstorms, such as tire rubber-derived pollutants, poses risks to fish [30]. The expansion of impervious surfaces further exacerbates this issue by facilitating the transport of nutrients into adjacent rivers and lakes, leading to eutrophication and harmful algae blooms [31]. Contaminated urban waters also affect the functionality of urban aquatic ecosystems (e.g., [32]), while rising groundwater temperatures due to the climate crisis and urban cementation negatively impact groundwater communities that have adapted to stable climatic conditions [33]. Additionally, solid, man-made, and long-lasting waste—such as plastics, rubber, glass, and metals—presents considerable dangers to aquatic organisms through risks of ingestion, entanglement, trapping, and inhalation (e.g., [34]). These effects can lead to death, drowning, physical damage, diminished ability to avoid predators, reduced food intake, and lower reproductive success in aquatic species [34]. Despite the growing focus on ecological issues, biodiversity in blue habitats remains underexplored in urban planning [22], with groundwater biodiversity in urban areas largely neglected [35].

4. Biological Invasions in Urban Landscapes

Biological invasions have become a defining threat of human-modified landscapes, particularly within urban ecosystems, where environmental conditions are often suitable for the establishment and expansion of non-native species [36,37]. The mechanisms promoting the success of biological invasions in urban areas are diverse and deeply linked to human activities [38]. Urban areas function as both gateways and hubs for species introductions

due to intense global trade, human travel, and cultural exchanges [39]. These movements may facilitate both intentional and unintentional introductions, including through horticulture, the pet trade, transportation networks, and contaminated goods [40]. Cities also often exhibit highly fragmented and disturbed habitats, e.g., abandoned buildings, roadside verges, managed parks, and artificial water bodies, offering ecological niches with reduced predation risk and biotic resistance [41]. Accordingly, these fragmented landscapes frequently lack the predators, pathogens, or competitive pressures found in more intact ecosystems, giving invasive species a considerable advantage [42]. Moreover, urban heat islands create microclimates that may favour thermophilic invasive species previously limited by climatic constraints, thereby expanding their potential invasion range [37]. The increased availability of anthropogenic resources, such as food provisioning and artificial nesting sites, further supports the success of urban invaders [43,44].

The impacts of invasive species on urban ecosystems can be irreversible [45]. Many invasive plants, animals, fungi, and microorganisms alter ecological dynamics by competing with native species for resources such as space, light, nutrients, and prey [46]. These competitive advantages often lead to the local decline or extinction of native flora and fauna, thereby reducing biodiversity [47–52].

The introduction of the Eastern grey squirrel *Sciurus carolinensis* in Italy has led to the widespread displacement of the native Eurasian red squirrel *Sciurus vulgaris*, primarily through competition for food [50]. Similarly, aquatic invaders such as the red swamp crayfish *Procambarus clarkii* disrupt nutrient cycles, reduce native invertebrate populations, and degrade water quality [51]. In Mediterranean cities, the ring-necked parakeet *Psittacula krameri*, originally introduced as a pet, has established large breeding populations with thousands of individuals in urban parks [53]. These parrots compete with native cavity-nesting birds such as hoopoes and nuthatches, as well as with protected bats, and may displace them by monopolising nesting sites [54]. Additionally, they can damage ornamental trees and agricultural crops in peri-urban areas [54]. Urban populations of Northern raccoons, *Procyon lotor*, introduced to Europe in the mid-20th century, have become firmly established in several countries [54]. Their omnivorous diet and adaptability have allowed them to rapidly expand in residential areas, but their presence poses a threat to native species and public health due to the potential transmission of diseases such as leptospirosis and raccoon roundworm [55,56].

Invasive plants like Japanese knotweed *Reynoutria japonica* Houtt. not only displace native vegetation but also cause physical damage to urban infrastructure, undermining pavements, building foundations, and flood defences [52]. The cumulative effects of such invasions often lead to altered ecosystem functions, reduced ecosystem services, and increased costs for urban management and restoration efforts.

In response to the growing threat of urban biological invasions, cities and governments are implementing a range of monitoring, management, and prevention strategies [57]. Early detection and rapid response are widely recognised as one of the most cost-effective approaches [57]. This involves routine surveys, risk assessments, and real-time reporting mechanisms to identify new incursions before they become unmanageable. Citizen science initiatives have become increasingly important in this regard, empowering residents to report sightings of invasive species through mobile applications or online platforms, thereby extending the reach of professional monitoring networks [58,59]. On a broader scale, regulatory frameworks, such as the European Union Regulation on Invasive Alien Species 1143/2014, aim to prevent the introduction and spread of high-risk species through trade restrictions, quarantine protocols, and coordinated cross-border efforts [60].

In addition to invasive species introduced through natural or accidental pathways, synanthropic species, i.e., those closely associated with human settlements, represent a

major but often underappreciated component of biological invasions [41,43]. Species such as the black rat *Rattus rattus*, brown rat *Rattus norvegicus*, and house mouse *Mus musculus/Mus domesticus* have achieved global distributions through their commensal relationship with humans, causing extensive impacts on native biodiversity, agriculture, and public health. Likewise, the house sparrow *Passer domesticus* and feral pigeon *Columba livia domestica* exemplify avian synanthropes that thrive in urban and agricultural environments, often outcompeting native bird species and contributing to the homogenisation of urban ecosystems.

Control and management of established invasive populations require a multifaceted approach that balances ecological goals with socio-economic and ethical considerations [61]. Mechanical removal, chemical treatment, and biological control are among the primary strategies employed, although each comes with trade-offs [62]. For instance, herbicides may be effective against invasive plants, but their use in densely populated urban areas is often restricted due to health and environmental concerns [63]. Biological control, i.e., introducing natural enemies from the native range of the invaders, has shown promise in urban contexts, such as controlling the spread of invasive scale insects [64]. However, these interventions must be carefully tested to avoid unintended consequences for native species. Habitat restoration efforts help native species improve ecological resilience and reduce resource availability for invasive species, as the best long-term solutions [65]. Community engagement is also vital, as public attitudes and behaviours significantly influence the success of management programmes [44]. Education campaigns informing residents about the risks of releasing pets into the wild or planting invasive ornamentals in gardens can reduce inadvertent introductions and trigger a sense of stewardship [66,67].

5. Noise Pollution

Noise pollution is a significant environmental issue in urbanised societies, characterised by the presence of unwanted or harmful sound levels that interfere with normal activities and health [68,69]. In contemporary cities, the primary sources of noise pollution are related to transportation systems, industrial activities, construction work, and densely populated residential and commercial areas [70]. Road traffic is widely recognised as the most consistent and impactful contributor [70]. The combination of engine sounds, braking systems, tire-road friction, and frequent use of horns contributes to elevated ambient noise levels, especially during peak hours. Construction sites introduce intermittent yet intense acoustic disturbances, often operating over extended periods with equipment such as jackhammers, bulldozers, and cranes [71]. Furthermore, airports and railway stations generate high-decibel sound events affecting the surrounding neighborhoods [72]. Industrial zones contribute continuous mechanical noise, particularly when factories are not acoustically insulated [73]. In urban areas with poor planning or regulation, this multifaceted noise landscape creates chronic exposure for human and urban animal populations [69,73]. Some invasive bird species in urban environments also contribute to noise pollution (e.g., the ring-necked parakeet *Psittacula krameri* [74]).

The impact of noise pollution on wildlife is substantial and often underestimated. Acoustic communication plays a critical role in many animal species, especially in birds, amphibians, and marine mammals [75,76]. Urban noise interferes with the transmission of vocal signals, disrupting mating, territory defense, and predator avoidance [77]. Birds exposed to chronic noise may shift their vocalizations to higher frequencies, a phenomenon known as the Lombard effect, but such adaptations are not always effective [78,79]. Furthermore, species less capable of acoustic flexibility may abandon urban habitats altogether, leading to reduced biodiversity [78]. These interferences can cause behavioural changes, stress, and even strandings, with potential long-term consequences for population viability.

Humans are also vulnerable to both the psychological and physiological consequences of prolonged noise exposure [80]. Several studies have suggested that chronic noise, especially in residential areas, contributes to sleep disturbances, increased stress levels, and reduced cognitive performance [81]. Children exposed to high levels of environmental noise have shown deficits in memory, attention, and reading skills [82]. On a physiological level, noise pollution is associated with elevated cortisol and adrenaline levels, hypertension, and cardiovascular disease [83]. The World Health Organization (WHO) classifies environmental noise as a public health risk and recommends exposure limits for day and night-time noise, typically below 55 dB (A) for general outdoor environments [84]. However, in many urban centers, these thresholds are regularly exceeded, particularly near major roads, airports, and industrial sites [85].

To mitigate the negative effects of urban noise pollution, several technological and planning-based solutions have been proposed and implemented [86]. One effective strategy is the use of green infrastructure, such as tree belts, green roofs, and vegetative barriers, which not only reduce noise through absorption and diffusion but also offer additional ecological benefits [87]. Advances in building materials have led to the widespread use of double-glazed windows, soundproof insulation, and acoustic panels that significantly reduce indoor exposure [88]. At the infrastructural level, noise-reducing asphalt and silent road surfaces have shown promise in lowering traffic-related sound emissions [89]. The increased adoption of electric vehicles further contributes to noise reduction, especially at lower speeds [90]. Moreover, some cities have integrated real-time noise monitoring systems to identify critical noise hotspots and apply targeted interventions, such as traffic regulation or urban redesign [91]. While the complete elimination of urban noise is not feasible, the combination of policy measures, technological innovation, and public awareness can contribute to significantly reducing noise levels and improving the quality of life [92].

6. Habitat Fragmentation and Loss

Habitat fragmentation in cities poses one of the greatest threats to both biodiversity and the health of urban environments [93]. As urbanization expands, natural areas in cities are reduced to smaller, isolated patches by roads, housing developments, and commercial infrastructure [94]. While green spaces such as parks, gardens, and remnant woodlands may still exist, their ecological value is diminished when they are cut off from one another [95]. This loss of connectivity makes it hard for wildlife to move among different habitats, find food, and reproduce, often resulting in declining populations, thus requiring reforestation policies [96]. Animals that once roamed across large continuous landscapes are forced into smaller areas where competition for resources intensifies, and many species face increased risks such as road collisions, human conflict, and further habitat loss, leading to local extinctions [47,97,98]. Plants are similarly affected by fragmentation, even if the impacts of this threat are less immediately visible with respect to animals [99]. Angiosperms rely on pollinators and seed dispersers to reproduce and spread, and when green areas are divided into isolated patches, these natural processes are disrupted [100]. Pollinators such as bees and butterflies may be unable to move between fragmented patches, thus reducing pollination success [100,101]. Over time, fragmented habitats favor fast-growing, highly adaptable species, while rare or specialised plants decline, leading to a reduction in overall plant diversity [102]. This loss matters not only for its own sake but also because diverse plant communities sustain entire ecosystems, providing food, shelter, and regulating services for other organisms [103,104]. Another key issue linked to fragmentation is the loss of ecosystem resilience [105]. Small, isolated patches of vegetation are more vulnerable to edge effects, such as changes in light, wind, and temperature, which make conditions harsher for many sensitive species [106,107]. As to plants, this can mean lower survival

rates, less successful regeneration, and in some cases, the invasion of non-native species that thrive in disturbed environments [108]. The decline in native vegetation further weakens ecosystems and diminishes the ability of urban green spaces to provide essential services such as air purification, stormwater absorption, and temperature regulation [109,110].

To address these threats, cities must adopt strategies to restore ecological connectivity and strengthen fragmented habitats [111,112]. One approach is the creation of ecological corridors, linear stretches of vegetation such as greenways, riparian buffers, and hedgerows with flowering native plants, allowing wildlife and plants to move between isolated patches [113]. These corridors help pollinators and seed dispersers carry out their roles while enabling animals to migrate more safely across urban landscapes [114]. Furthermore, restoring degraded patches through the planting of native trees (e.g., native *Quercus* spp. in Mediterranean countries), shrubs (e.g., native *Cystus* spp. in Mediterranean countries), and wildflowers can expand available habitat and increase resilience against invasive species [115,116]. Urban planners and communities can also design multifunctional green spaces that combine recreational uses with ecological functions, ensuring that human activity does not completely displace wildlife [117]. Green roofs, living walls, and roadside plantings add further layers of habitat within the urban fabric, providing stepping stones for several wild species, including bats, dormice, and pollinators [118].

Connectivity can also be enhanced by reducing barriers that fragment habitats. For instance, wildlife crossings such as green bridges and underpasses help animals safely navigate across busy roads, while urban forestry initiatives can create shaded corridors linking parks and natural areas [119]. At a smaller scale, community initiatives like pollinator gardens and tree-planting programs can contribute to broader networks of habitat [96]. Together, these strategies not only restore biodiversity but also improve the delivery of ecosystem services, strengthening climate resilience, reducing heat islands, and enhancing urban wellness [120]. The long-term consequences of habitat fragmentation in cities are difficult to reverse once buildings and infrastructures have been built over, but proactive strategies show that it is possible to weave nature back into urban systems [121]. Efforts like wildlife corridors, green roofs, and urban tree planting can help to reconnect some areas and support biodiversity, but they rarely match the ecological function of intact habitats [122]. This reality highlights the importance of protecting larger patches of natural land within cities and designing urban growth with ecological connectivity in mind. Habitat loss threatens not only wildlife and plant life but also the quality of life for people, as the health of urban ecosystems directly influences human well-being, climate resilience, and the sustainability of urban environments [123,124]. Protecting large natural patches, reconnecting fragmented landscapes, and encouraging nature-sensitive urban design are essential steps for sustainable cities [125].

7. Soil Pollution and Soil Sealing

Soil pollution in urban areas represents one of the most pervasive yet under-recognised environmental challenges of modern cities [126]. As urbanization accelerates, the expansion of impervious surfaces, industrial emissions, waste disposal, and traffic-related pollutants severely degrades soil health and function. Urban soils often act as sinks for contaminants, including heavy metals such as lead (Pb), cadmium (Cd), copper (Cu), zinc (Zn), and mercury (Hg), as well as persistent organic pollutants like polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and petroleum hydrocarbons [126]. These pollutants arise from diverse sources (e.g., vehicular exhaust, industrial processes, construction materials, and atmospheric deposition) and persist for decades due to limited microbial degradation and slow turnover rates [127].

According to Moura et al. [126], extensive research in Italian cities such as Turin, Milan, Naples, and Rome reveals that urban soils frequently exceed national and European safety thresholds for toxic elements and organic contaminants. The highest metal concentrations often occur along major roads and in older urban districts, where historic emissions and traffic dust accumulate. In addition to direct human exposure risks, polluted soils impair plant nutrient uptake, alter microbial community structure, and disrupt biogeochemical cycles, ultimately reducing soil fertility and ecosystem resilience.

A major aggravating factor in urban soil degradation is soil sealing, i.e., the covering of land with impermeable materials like asphalt and concrete. Soil sealing is one of the most permanent forms of land degradation, as it prevents infiltration, gas exchange, and biological activity. The European Environment Agency estimates that over 2.4% of EU territory is sealed, mostly in cities [128]. Sealing amplifies urban heat, increases flood risk, and eliminates natural pollutant filtration and carbon sequestration functions. Furthermore, it restricts the rooting space for urban trees and limits the potential of green infrastructure to improve air and soil quality. Unsealed urban soils are essential for sustaining vegetation capable of intercepting atmospheric pollutants and remediating contaminated substrates [126].

Addressing soil pollution and sealing requires integrated, nature-based approaches. Phytoremediation, i.e., the use of plants to remove, immobilise, or degrade contaminants, has emerged as an effective and low-cost strategy [129]. Field studies across Europe have shown that several plant species (e.g., *Phyllirea angustifolia* L., *Rhamnus alaternus* L., *Myrtus communis* L., *Quercus ilex* L.) can improve soil quality, enhance biodiversity, and increase carbon storage, while providing additional benefits such as reduced runoff, microclimate regulation, and recreational opportunities [126].

At the policy level, the EU Soil Strategy for 2030 and the UN Sustainable Development Goals (SDG 11 and 15) emphasise restoring degraded soils, reducing land sealing, and promoting urban greening as key pathways toward sustainable cities. De-sealing projects, where paved surfaces are replaced with permeable or vegetated materials, are increasingly adopted to restore soil ecological functions and reduce pollution [126].

Therefore, soil pollution and soil sealing jointly threaten the ecological foundation of urban environments. Restoring soil health through integrated green planning, pollution control, and de-sealing initiatives is vital for resilient, climate-adapted cities.

8. Climatic Crisis

Climate crisis is amplifying multiple stressors in urban ecosystems with cascading effects on biodiversity, ecosystem functioning, and human well-being. Cities already concentrate vulnerable populations and anthropogenic pressures (land-use change, biological invasions, air and soil pollution, sealing) which interact synergistically with rising temperatures, altered precipitation regimes, and increased extreme events, producing novel risks for both biota and people [130].

Ecologically, warming and altered seasonality drive shifts in species distributions, phenology and community composition, favouring heat-tolerant and often non-native or opportunistic species, whereas disadvantaged specialists and cold-adapted taxa [130]. Long-term syntheses show coherent climate fingerprints (including range shifts, earlier breeding/flowering and altered abundances), which may occur within and around urban areas where microclimates accelerate change. These biological responses reduce native biodiversity and alter trophic interactions, pollination services and pest dynamics in urban green spaces [130].

Urban expansion and densification further compound climate impacts by amplifying the urban heat island. Sealed surfaces, sparse canopy cover, and waste heat increase

ambient temperatures, intensifying heat exposure and heat-related morbidity and mortality, particularly among the elderly, socio-economically disadvantaged groups, and outdoor workers [126]. Heat extremes also exacerbate air pollution episodes (O₃ formation and particulate stagnation), undermining respiratory and cardiovascular health and increasing hospitalizations. Health agencies identify heat and climate-sensitive disease burdens as urgent urban public-health priorities [131].

Hydrological extremes, e.g., more intense rainfall and longer dry spells, interact with soil sealing to degrade urban ecological functioning [126]. Sealed surfaces reduce infiltration and groundwater recharge, elevate surface runoff and pollutant transport, and impede the capacity of urban soils and vegetation to buffer contaminants. Sealed and degraded soils reduce the capacity of urban forests and green infrastructure to provide remediation services (pollutant retention, carbon sequestration, microclimate regulation), weakening nature-based adaptation options precisely when they are most needed [126].

From a governance perspective, the climate crisis exposes inequalities in adaptive capacity: neighbourhoods with less green cover and higher sealing experience stronger urban heat island effects, poorer air and soil quality, and reduced access to ecosystem services, producing environmental justice concerns [132]. Integrated responses, expanding urban tree canopy, de-sealing and permeable surfacing, restoring soils, and prioritising vulnerable communities, can simultaneously mitigate heat, enhance biodiversity, and reduce pollution exposure [132].

9. Discussion and Conclusions

Urban ecosystems are subject to complex interactions among environmental stressors, and their cumulative effects are often more severe than the sum of individual pressures [1–3]. Air pollution, biological invasions, freshwater contamination, noise pollution, habitat fragmentation, soil pollution, and the climate crisis act simultaneously, compounding ecological degradation and undermining ecosystem services. For instance, noise and chemical pollutants can reduce the resilience of native flora and fauna, leaving them more susceptible to biological invasion attacks [1,3,80]. Similarly, fragmentation increases biodiversity's vulnerability to other pressures by isolating populations and reducing genetic exchange [101]. These interactions reveal that urban stressors are not isolated phenomena but interdependent processes that amplify one another, creating feedback loops that diminish the ecological stability of cities [3,4,8]. Recognising these synergies is pivotal, as addressing a single stressor in isolation will rarely yield sustainable outcomes. Thus, integrated approaches are required to manage urban environments as dynamic systems where multiple drivers interact.

The implications of these cumulative stresses for biodiversity conservation in urban areas are deep. Cities, once regarded as repulsive to wildlife, are increasingly acknowledged as sites of both refuge and feeding [3,44]. Green spaces, waterways, and remnants of semi-natural habitats provide vital resources for many species, yet these habitats are fragmented and heavily disturbed [47]. Biodiversity conservation in urban contexts, therefore, requires strategies to maintain ecological connectivity, promote species adaptation, and ensure the continuity of ecosystem services to support both human and non-human communities [41]. Furthermore, urban conservation efforts must be adaptive, recognising that species assemblages are shifting under the combined influence of climate crisis, pollution, and anthropogenic disturbance [47]. By incorporating biodiversity considerations into urban planning and infrastructure design, cities can become important sites for conservation rather than habitats of irreversible loss [93,95].

Environmental stressors in urban areas also exert substantial physical and mental effects on human health [83,84]. Chronic exposure to air pollution contributes to respi-

ratory and cardiovascular diseases, whereas persistent noise is linked to hypertension, sleep disturbance, and reduced cognitive performance [83]. Similarly, the degradation of green spaces limits opportunities for recreation, relaxation, and psychological restoration, contributing to elevated levels of stress, anxiety, and depression among urban residents [84]. The cumulative effects of these environmental hazards disproportionately affect vulnerable populations, including children, older people, and economically disadvantaged groups, thus exacerbating social inequalities. Urban environmental stress must therefore be understood not only as an ecological concern but also as a critical public health challenge which requires coordinated responses across different sectors [133]. Urban environmental stressors disproportionately affect marginalized or low-income communities, where exposure to air and noise pollution, limited green space, and poor housing conditions often coincide. Frameworks such as the “Environmental Justice paradigm” and the “triple inequity” model, which links social vulnerability, environmental exposure, and limited adaptive capacity, highlight how stressors exacerbate existing inequalities. For instance, studies in European and North American cities have shown that neighborhoods with lower socio-economic status typically have higher levels of particulate matter, reduced tree canopy cover, and greater heat island intensity, directly impacting public health and well-being. Integrating such frameworks into urban planning supports equitable access to ecosystem services and ensures that interventions, like urban greening or pollution mitigation, benefit the most affected populations, rather than reinforcing spatial disparities [133].

Mitigating the impacts of urban stress requires innovative, multi-level approaches. NBS solutions such as urban forests, green roofs, and restored waterways have proven effective in improving air and water quality, reducing heat stress, and supporting biodiversity. At the same time, technological innovations in urban infrastructure, ranging from noise-reducing materials to sustainable transport systems, offer further opportunities for alleviating threat pressures. Governance strategies should integrate environmental planning with social and economic objectives, ensuring that mitigation efforts deliver equitable benefits [134]. The challenge lies in addressing solutions to local contexts, recognising that the ecological, social, and cultural fabric of cities varies widely, and thus requires adaptive and participatory management [134].

Citizen science and community engagement play a pivotal role in enhancing urban resilience. Local residents are not only the primary beneficiaries of healthier environments but also vital contributors to data collection, monitoring, and conservation action [128]. Community-led initiatives, such as biodiversity surveys, pollution data, or invasive species monitoring, extend the reach of professional research and create a sense of stewardship that reinforces long-term sustainability [128]. Moreover, participatory approaches foster dialogue between citizens, policymakers, and scientists, ensuring that urban environmental strategies reflect diverse perspectives and priorities. By triggering communities to become active agents of change, cities can cultivate social capital, which strengthens ecological outcomes and enhances human well-being [135].

Looking forward, future research and practice must include interdisciplinary frameworks to link ecology, urban planning, public health, and social sciences. Investigations into the combined effects of stressors, particularly under climate crisis scenarios, are urgently needed to identify thresholds beyond which urban ecosystems may lose their capacity for recovery. Novel approaches, e.g., predictive spatially explicit modelling, long-term monitoring networks, and experimental urban greening projects, can provide valuable insights into resilience-building. At the same time, practical action should prioritise inclusive planning, ensuring that the benefits of healthy urban ecosystems are shared across all social sectors [133–135].

A comprehensive methodological framework for assessing urban environmental stressors should integrate ecological, technological, and social dimensions within a multiscale and multidisciplinary approach. From an ecological standpoint, spatially explicit models and geostatistical analyses can map the distribution and intensity of multiple stress factors (e.g., air and soil pollution, fragmentation, noise pollution) and identify cumulative impact zones. These quantitative tools can be complemented by long-term monitoring networks and remote-sensing data to track temporal changes and evaluate the effectiveness of mitigation actions. On the social side, public engagement through citizen science platforms, surveys, and community-based monitoring may enable the collection of fine-scale data while capturing local perceptions of environmental quality. Integrating biophysical indicators (e.g., pollutant loads, biodiversity indices) with social well-being metrics (e.g., perceived livability, mental health outcomes) can provide a comprehensive picture of how stressors influence urban life. Such a complete assessment frameworks not only support evidence-based urban planning but also promotes adaptive management and participatory governance, ultimately contributing to more resilient and health-promoting urban landscapes.

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