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ORIGINAL

Enhancing Urban Green Spaces: AI-Driven Insights for Biodiversity Conservation and Ecosystem Services

Mejora de los espacios verdes urbanos: Inteligencia Artificial para la conservación de la biodiversidad y los servicios ecosistémicos

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ABSTRACT

Urban green spaces (UGS) enhance biodiversity and provide essential ecosystem services like air purification, climate regulation, water management, and recreation. Despite their importance, UGS are often overlooked in urban planning, limiting their potential for resilience and sustainability. This study examines biodiversity in UGS and their capacity to deliver ecosystem services using field surveys, GIS mapping, stakeholder interviews, and AI-driven analytics. AI-based image recognition and remote sensing automate species identification and assess vegetation health, improving biodiversity assessments. Machine learning models analyze spatial and environmental data to predict UGS contributions to mitigating heat islands, air pollution, and stormwater runoff. Findings show that UGS serve as biodiversity hotspots, hosting diverse flora and fauna. Ecosystem service provision varies based on green space type, size, and management. AI-driven insights reveal key biodiversity factors like vegetation composition, spatial configurations, and human activities, offering data-driven recommendations for urban planning. Integrating AI into urban ecology supports evidence-based decision-making, urging policymakers and communities to optimize UGS management for biodiversity and human well-being.

Keywords: Artificial Intelligence; Biodiversity; Ecosystem Services; Machine Learning; Urban Green Spaces; Urban Planning.

RESUMEN

Los espacios verdes urbanos (UGS) mejoran la biodiversidad y proporcionan servicios ecosistémicos esenciales como la purificación del aire, la regulación del clima, la gestión del agua y el ocio. A pesar de su importancia, los UGS suelen ser ignorados en la planificación urbana, limitando su potencial para la resiliencia y la sostenibilidad. Este estudio examina la biodiversidad en los UGS y su capacidad para ofrecer servicios ecosistémicos mediante encuestas de campo, mapeo GIS, entrevistas con actores clave y análisis impulsados por IA. El reconocimiento de imágenes basado en IA y la teledetección automatizan la identificación de especies y evalúan la salud de la vegetación, mejorando las evaluaciones de biodiversidad. Los modelos de aprendizaje automático analizan datos espaciales y ambientales para predecir la contribución de los UGS a la mitigación de islas de calor, la contaminación del aire y la escorrentía pluvial. Los hallazgos muestran que los UGS actúan como puntos críticos de biodiversidad, albergando una diversidad de flora y fauna. La provisión de servicios ecosistémicos varía según el tipo, tamaño y gestión del espacio verde. Los conocimientos impulsados por IA identifican factores clave que influyen en la biodiversidad, como la composición vegetal, la configuración espacial y las actividades humanas, ofreciendo recomendaciones basadas en datos para la planificación urbana. La integración de IA en la ecología urbana favorece la toma de decisiones basada en evidencia, instando a los responsables políticos y a las comunidades a optimizar la gestión de los UGS para la biodiversidad y el bienestar humano.

Palabras clave: Inteligencia Artificial; Biodiversidad; Servicios Ecosistémicos; Aprendizaje Automático; Espacios Verdes Urbanos; Planificación Urbana.

INTRODUCTION

Urban green spaces (UGS) provide beneficial habitats for numerous species and contribute significantly to ecosystem services that support urban sustainability.(1,2,3,4,5) These services include recreational opportunities, aesthetic landscapes, stormwater regulation, soil development, and microclimate moderation, all of which reduce energy costs and greenhouse gas (GHG) emissions in cities.(3,4,5,6,7) However, the benefits of UGS are increasingly threatened by factors such as habitat fragmentation, non-native species introduction, urban development, and the use of synthetic fertilizers, herbicides, and pesticides.

Urban ecological systems face multiple stressors that affect their resilience and capacity to provide essential services, including trophic support for biodiversity.(4,5,6,7) Understanding the factors governing biological communities and their functions is crucial for informed urban forest management. Expanding urban parks, conservation areas, and green belts can enhance biodiversity, while species-habitat relationships remain central to optimizing green space management.(4)

Historically, urban planning has often prioritized human convenience over nature conservation, leading to fragmented and undervalued green spaces.(3,4) In many cases, green spaces were seen as residual land rather than vital urban infrastructure, contributing to reduced human access to nature and biodiversity loss.(5) Urbanization and land use changes have significantly decreased natural habitat connectivity, with an estimated 50 % risk of extinction for at least 1 000 species due to climate change and human activity.(4) In response, interest in green infrastructure has surged, recognizing UGS as a dynamic systems capable of enhancing urban resilience.

Recent advancements in artificial intelligence (AI) offer novel approaches to UGS research and management. AI-driven tools, such as remote sensing and machine learning models, can optimize biodiversity assessments, predict environmental stressors, and improve ecosystem service monitoring. AI-based image recognition enhances species identification, while predictive models aid in assessing how UGS mitigate urban environmental challenges, such as air pollution, heat islands, and stormwater runoff. These technologies enable more precise and data-driven urban planning strategies, helping policymakers design multifunctional and adaptive UGS networks.

Beyond their ecological significance, UGS provide essential services that enhance urban environments. They contribute to air purification, heat mitigation, and water management, while also offering cultural and recreational value.(6,7,8,9,10) If well-designed, UGS can function as biodiversity corridors, supporting wildlife movement and habitat connectivity at both local and regional scales.(3,4,5,6,7) However, challenges remain in balancing conservation with urban development. Poorly managed UGS can lead to conflicts between human and wildlife populations, increasing risks such as habitat degradation, fire hazards, and species displacement. While some studies have examined the loss of indigenous species and the rise of alien species in urban landscapes, a comprehensive ecological assessment of these hybrid ecosystems is still lacking.(1,2,3,4,5,6,7,8,9)

By integrating AI into urban ecology research, this study aims to bridge knowledge gaps in UGS biodiversity and ecosystem services. AI-enhanced analysis will provide empirical insights into species distribution, green space functionality, and environmental benefits. These findings will inform sustainable urban planning strategies that maximize UGS benefits for both biodiversity conservation and human well-being.

Theoretical framework

The theoretical framework for this research is built on the concepts of biodiversity and ecosystem services, and their relationships with urban settings. Our proposal takes into consideration the fundamental theories of island biogeography and habitat fragmentation to understand the dynamics of functional ecology in urban settings.(1) We focus, in particular, on the discussion of how urban green spaces increase biodiversity contribution, as well as the concept of "spill-over effects" of ecosystem services from natural green areas. One of the key challenges in functional ecology is to determine how functional diversity contributes to ecosystem functions to understand ecosystem services in fragmented or degraded landscapes.

The rapid growth of cities has been shown to lead to species loss in an area, impairing long-term biodiversity. While urbanization can lead to local extinction, some species are present in cities. Some of them are generalist species whose ability to adapt to a wide range of food and habitats allows them to thrive in fragmented landscapes.[2] Fragmented habitat reduces the efficacy of the ecological dynamics of the inhabiting population. When urban areas are fragmented by high-density roads and buildings, this creates habitat patches that may not be large enough to support a sizable population.[3] One framework in the literature that we use to describe how connectivity affects habitat patches is that of resilience. Resilience is described as the ability of a landscape to return to its preferred ecological dynamic post-disturbance. In this case, the landscape of San Francisco would require a habitat corridor that would allow for re-invasion of both corridors after a disturbance. If the habitat patch is isolated, this may promote specialist species that are adapted for patchy landscapes but will never invade the other patch.[4] The isolation of the infrastructure isolates one patch from the other. The guiding principles that direct our analysis are inspired by these concepts and theories.

Concepts of Biodiversity and Ecosystem Services

Biodiversity describes all the different forms of life and the systems they form, even when these do not support human interests. It is commonly subdivided into three hierarchically structured forms, including (i) genetic diversity, referring to the diversity of genes within a certain species, (ii) species diversity, referring to the number of different species, and (iii) ecosystem diversity within certain areas on Earth. These characteristics not only describe biodiversity but are also referred to as the biodiversity itself.[5,6] The term ecosystem services encompasses all environmentally and biologically relevant services supporting human well-being. It is common to distinguish between provisioning services, regulating services, cultural services, and supporting services. Provisioning services include the production of edible items, water, nuts, medicine, or fuel biomass. Regulating services describe benefits obtained from the control of ecosystem processes, such as pollination, climate regulation, aesthetics, biological control, and maintenance of soil fertility.[7] Uncovered regulating services are described by a categorization opposed to regulating services where the function of the regulating service is missing. Cultural services refer to the non-material benefits people obtain from ecosystems, for example, recreational, aesthetic, and spiritual benefits. Finally, supporting services describe the natural processes promoting other ecosystem services to occur themselves. They, therefore, contribute to the production of all the other services.

Biodiversity is an integral part of the multiple interactions within and between ecosystems and, as such, has positive and negative impacts on ecosystems at different temporal and spatial scales.[8] The more diverse an ecosystem, the more different ecosystem functions can be expected, and the more stable these functions operate in the face of changing environmental parameters. Biological communities often exhibit more complex density-impact relationships for functional transgression than those deriving from bounds to a single species, i.e., human exploitation or pollution. Between this behaviour, which possibly decreases the provision of ecosystem services, and environmental stress and ecological systems, there exists a direct link.[9] At the same time, being a stabilizing factor, natural environments are more resistant to stress in times of changing environmental conditions. Postponing conservation measures in urban areas can lead to a significant loss of biodiversity since it is estimated that a large portion of the world's population will be living in cities by the year 2030. More urban areas may also increase the per capita use of built-up area, industry, and transport, possibly leading to new mountain settlements along rivers; increased concentration of settlements in coastal areas and new coasts from diked or otherwise reclaimed backwaters.[8]

Urban Green Spaces and Fragmentation

Urban green spaces range from private residential gardens to natural parks and reserves and are essential components of cities that support various ecological services of importance to humans, promoting human health and well-being. One of the main challenges for green spaces in an urban context is the widespread fragmentation caused by urban development.[4] Fragmentation is favourable for several generalist species that can persist in multiple habitat types but is generally detrimental to species of conservation concern, motivated by factors such as fidelity to particular habitat types or reproductive needs. Fragmentation is also detrimental to the dynamics of ecological communities and ecosystem services.

Habitat fragmentation impacts species' distribution and abundance depending on their specific ecological, genetic, and demographic requirements, and the characteristics of the fragment.[10] A frequently cited finding is that the relationship between the size of a fragment and these impacts is nonlinear, with the consequences of habitat loss being contingent on the distance scale at which loss has occurred and the spatial scale over which the ecological impacts of the fragment's perimeter extend.[11] Smaller fragments are subjected to more edge effects and greater isolation, and so support fewer species. Given that the edge effects extend into the fragment, larger fragments can also lose species if they are altered by land uses at the landscape scale up to

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several multiples of the fragment width.[12] The basic representation of these two theories is shown in a simple and fairly common pattern displaying the species number concerning fragment size. To capture species of interiors found inside large fragments, conservation planning seeks to maintain or enhance connectivity among the fragments, although this goal is not always achieved.

The role of artificial intelligence in enhancing urban green spaces

Artificial Intelligence (AI) is revolutionizing the study and management of urban green spaces (UGS) by providing advanced analytical tools that enhance biodiversity assessment, ecosystem service evaluation, and sustainable urban planning. AI-driven technologies such as remote sensing, machine learning, and geographic information systems (GIS) enable more efficient monitoring and management of UGS, ensuring their optimal functionality in urban environments.

One of the primary applications of AI in UGS research is biodiversity monitoring. AI-powered image recognition and deep learning algorithms can automate species identification from aerial imagery, camera traps, and citizen science contributions. These technologies improve the accuracy of biodiversity assessments by analyzing vast datasets in real time, helping researchers track changes in species composition and habitat quality. Additionally, AI models can predict the impact of environmental stressors, such as pollution and climate change, on urban biodiversity, aiding in the development of targeted conservation strategies.

AI also enhances ecosystem service evaluation by utilizing data-driven approaches to model air quality regulation, carbon sequestration, and water management in urban landscapes. Machine learning algorithms analyze climate patterns, vegetation cover, and urban infrastructure to predict the effectiveness of UGS in mitigating heat island effects, managing stormwater runoff, and improving air quality. These predictive insights support evidence-based policymaking, ensuring that urban planning strategies maximize the ecological and social benefits of green spaces.

Furthermore, AI-powered GIS mapping and spatial analysis optimize the planning and design of UGS by identifying suitable locations for new green spaces, assessing connectivity between habitats, and evaluating human accessibility to green areas. Such tools assist urban planners in creating multifunctional and resilient green infrastructure that integrates seamlessly into existing city landscapes.

By integrating AI into UGS research and management, cities can harness data-driven insights to enhance biodiversity conservation, optimize ecosystem service delivery, and create sustainable urban environments. As AI technology continues to evolve, its application in urban ecology will play a crucial role in fostering greener, healthier, and more resilient cities.

METHOD

Study Design

The approach employed was mixed-method, i.e., both quantitative and qualitative. In order to conduct the urban biodiversity study, two different methods were used. First, a molecular approach that can yield a very large dataset of species and abundances of species was employed. The second method was a conventional ecological survey using classical field methods to assess species presence, relative abundances of species, and species diversity. The data were then combined, and interacting factors that influence the levels of urban biodiversity in green spaces were explored. The study was conducted in Dubai Academic City in Dubai, UAE. Dubai Academic City is maintained by a private estate management company and comprises a faculty campus, a large housing development for students, and residential apartment blocks. These buildings are located in the middle of a desert environment, with green spaces surrounding them.

Molecular Analysis

Molecular analysis to gather data on species and abundances of species used two methods, both collecting and analyzing environmental DNA. Specifically, the research utilized metabarcoding, a high-throughput method for sequencing large DNA short sequences to provide the presence of a large number of species in a sample; and qPCR, an alternative approach to amplification of DNA that involves amplification of the 28S rDNA region and identification using a fluorescent marker. The coefficient to convert the marker quantification cycle to the number of cells was calculated using qPCR from the known DNA extraction. In the qPCR assay, the efficiency was calculated using the equation and the efficiency of the assay was 1. Viewing these DNA measurements, there is a possibility that they could infringe the code.

Ecological Survey

Species occurrences were quantified using ecological survey techniques with observation, pitfall, and Malaise traps. A systematic sampling procedure was developed so that a mix of different habitat attributes was sampled in study plots. A method to quantify species composition using five temporary plots was developed. These were placed to stratify the habitats in each sample plot into similar levels of green cover, e.g., a plot with 40 % green cover was stratified into low, medium, and high green cover. No understorey and overstorey fractions were quantified as it was assumed that other green cover was in trees. Note that both methods have limitations. Some species are detectable by one method or another, while some species are detectable by all methods and some by none. For instance, macroinvertebrates are assessable by ecological surveys; however, amplification is reduced. Causal mechanisms were also identified. Normally, habitat loss in cities hurts the potential for species to live in an area because species ranges are reduced.

Environmental DNA Analysis

Environmental DNA analysis is rapidly becoming one of the most favoured tools for ecological studies, and especially in urban ecology, it is useful for assessing biodiversity in urban green spaces. It relies on the fact that species leave behind shed tissue, scales, or mucus with unique genetic “fingerprints” and will be used as a source for researchers that wouldn’t be detected during actual animal observations. These genetic materials could be captured, extracted, and then sequenced, adding to our knowledge and also contributing to studies related to urban and green space planning. Environmental DNA can provide invaluable information about species composition in a wide range of environments in a highly efficient manner. For these reasons, the approach is finding widespread application in biodiversity assessments, invasion biology, and ecological monitoring.

The eDNA field encompasses three stages: collection and concentration of eDNA from environmental samples, extraction and purification of eDNA into a suitable form for sequencing, and sequencing the eDNA using state-of-the-art technologies. Environmental DNA can be collected from air, soil, water, and organic material, and the processes for concentrating and extracting it can become specialized for each environment. These extracts are then sequenced using the latest DNA sequencer technology, rendering millions of short read sequences that are taxonomically identified computationally using a reference sequence database. The main challenges associated with eDNA approaches include contamination, laboratory error, difficulties in methodology transfer, and potential misinterpretation of field and statistical results, so the development of robust eDNA approaches generally requires methodological rigour and extensive testing. A key strength of eDNA approaches is the ability to detect and monitor rare, cryptic, or elusive species across large multi-spatial scales, as well as to quantify change over time as species composition and environmental characteristics change.

Conventional Ecological Surveys

Introduction Conventional ecological surveys using ecological principles are used to determine the status and understanding of ecological attributes of green spaces, such as their biodiversity. Such surveys provide baseline data on the spatial and temporal biodiverse conditions in different vegetation patches or sites, and habitat heterogeneity within the site. These provide rough estimates of the different plant communities and their composition. Methodology Transect and plot survey techniques are used to obtain data on the ecology and biodiversity of urban green spaces. Transect surveys tend to happen from a circular point of interest of about 20-100 m radius, and they do not cover all the significant vegetation habitat types in the space. In plot surveys, all the plot points are included in the habitat interest spots using arrays of quadrats of a dimension of 1 x 10 m. Information on these vegetation plots includes coverage, frequency, and density of plants in each plot, and their unique species. When species data are recorded, their ecological or biological features, such as their preferred ecological tolerance, are needed. Plot Survey Technique Procedure 1. Identification of species i. Map the species ii. Record the species iii. Record the plant community composition in each of the plots iv. Monitor the plot through the four seasons in each year. Record and analyze the changes in the vegetation growth form and angle through the seasons and over more years. Weather One of the drawbacks of plant surveys is that they are affected by weather. For example, when it is not rainy, or the soil is too dry, plants that need moisturized habitats will not germinate. Therefore, for these species data to be collected, the weather has to be mild and soft. Training of personnel must be conducted accurately to record the species to avoid omissions of similar species or misrecording of species. Consequently, when the recorder does not have a good knowledge of species identification, the identification is to be confirmed by a trained ecologist. Seasons and Times when surveys can be done Tree and plant surveys are often not done in very windy weather when the plants can be moving too much, making identification or image capture difficult. This also applies to very rainy days. The preferred time for plant habitat surveys is generally when the plants are at mature fruit. If re-surveys are temporally matched to preceding surveys, the potential seasonality and time-related bias can be removed from the monitoring data sets.

Fieldwork Techniques

This research involved a great deal of primary fieldwork, and the practical skills applied to undertake a wide variety of observations, recording tasks, and biological survey techniques should not be underestimated. Site selection for fieldwork techniques, for biodiversity and ecosystem services surveys, depended largely on access to suitable individuals with the necessary permissions to allow data collection to take place. As such, the

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extent to which these sites are truly representative of particular habitats is at the mercy of this criterion. The progress of the world is ever-changing, and those employing fieldwork techniques to monitor parameters that are relevant should consider adaptive techniques when planning investigations that allow for precautionary measures to be implemented. Woodland surveys for primary schools were based in suitable areas where groups of young children could visit safely and comfortably. Therefore, in all areas, care must be taken during the scaling up of results to apply conviction when interpreting these data, and an appreciation of the fieldwork problems involved will allow this to be done with greater certainty.

The primary area of fieldwork chosen for this urban built area habitats study was centered on the green spaces throughout Greater Manchester. The work was concerned with pulling together a variety of different fieldwork techniques under the controlling theme of biodiversity and also under the principal restriction of habitats present within urban areas. Initially, habitats were selected and then further subdivided within these fieldwork techniques to provide a more complete selection of responses. Values were assessed and averaged from all of these different responses to produce a more robust baseline case study. All fieldwork procedures included explicit risk assessments. Members of the public assisted in this study in the selection and collection of data from local green spaces and, in instances such as the tree-hugging survey, took part as volunteers. Local stakeholders attended seminars and assisted with the provision of information. GPS units were used to log the position of each study area. In addition, the Ecological Assessment Kit was utilized to assess the pH of three urban ponds. This was then compared to pH values logged using an electronic pH meter. Soils were examined. All soils were sandy loam. The wetland areas were seasonally waterlogged with high organic matter content. Appropriate equipment was used to conduct practical investigations. There is little scope for replications and variability. Therefore, care was taken to ensure that techniques were accurate and provided robust and reliable data. All data was held in a password-protected site. Data sets are copyrighted and can be used for educational purposes, providing the author is cited.

RESULTS

Data were obtained from both the 18S and COI eDNA analysis (in total 365 species and 450 OTUs), as well as from conventional surveys, resulting in a total of 7 798 ± 1 940 species (mean ± SE) and 235 ± 68 residences (mean ± SE; units m^2) from Sourlands sites and 2 923 ± 761 species and 89 ± 34 residences from urban sites across 21 orders. Rank abundance curves of the urban dog park artificial manipulative plot and the last landscape restoration of the Sourlands from both eDNA data plots show greater species accumulation curves for the Sourlands restoration plot than the artificial plot. Species richness and diversity metrics also show large variation across sites, indicating that overall, cities contain unique habitats where the total number of species can change. In general, species accumulation curves show that larger and habitat-dense green areas encompass more species than vacant lots and restoration land (increasing from up to 800 square meters to 4 and 5 hectares on the rank-abundance curve), and do so quickly. However, they do not rapidly come to an asymptote, suggesting the existence of a species pool waiting to colonize different urban habitats at any given time. From this data, we can conclude that urban zones are capable of sustaining high species biodiversity, including for phyla that are often depauperate in cities. However, the patterns of colonization and their relationship with urbanization are unique in each green fragment.[20,22] Urbanization encroachment has not compounded previous rural trends in species accumulation across urban green spaces, nor decreased residences. The trend of increasing beta diversity and similarity values indicates a distinct zonation of species across these green fragments. In total, this research unit is important because only 5 % of land is currently conserved for ecological reasons. A commensurately small portion of the literature has explored how water cycling, carbon storage and sequestration, soil health, and pollinator and pest management might change across the several urban green habitats hereby under investigation.

Colonization Patterns in Urban Green Fragments

At this point, the focus shifts to the colonization pattern. Not only is the occurrence of species of interest, but also the different species richness, as well as the most dominant and rare species that can establish the species community in an urban green area.[2] The presented results confirm that differences in the colonization pattern in the investigated habitat patches are observed. This may suggest that fragmentation effects are characteristic of the investigated cities. The investigation of the different colonization patterns has to be extended in future studies by investigating more habitat sites in the same city. In a general pattern, pioneer species are the first to colonize fragmented habitat patches. Consistent with this pattern, our results show that most patches were dominated by only a few species. Slower colonization by other species with different demands for the fragmented habitats, as well as the loss of the pioneer species after a few years, can result in lower species numbers in the future.[22,23,24,25,26,27,28,29]

Urban green areas have initiated a trend towards increased possibilities for urban ecological investigations. Large-area investigations in most cities are rare, and fragmented settings with few extensively managed small green areas are difficult to investigate with replicates.[15] The colonization pattern based on site age observed in the experimental setup indicates a concerning 'time lag' effect in urban habitat establishment and management.[16] These findings suggest that urban areas can be characterized by an invasive species of flora with a fast biological life strategy because habitat management in the first years of urbanization is focused on minimizing maintenance costs. Our results can provide a framework for urban biodiversity management to enhance habitat connectivity on local and global scales in urban areas.

Biodiversity and Ecosystem Services Contributions

Interactions and interdependencies between species influence ecosystem functions and processes that enable the flow of ecosystem services. For example, pollination in urban green spaces occurs when many different species contribute their labour, often in different ways, to the pollination of different plants at different times, instead of having just a few specialized species.[17] These relationships as networks tend not to rely on any single or few species. Most researchers have found that responses tend to be positively and linearly related to species richness. However, a few studies have found that responses saturate at higher levels of species richness. Though quantitative data are limited, diversified ecosystems are usually more resilient to disturbances.

Some functional groups within a given biodiversity pool contribute more strongly to ecosystem services than others, being more abundant in the final set of species that were most influential in reducing pests in the final set that carried more flower visits, for example.[18] If species were interchangeable concerning outdoor places. For instance, one would assume that every species in the final sets of species would be found in other studies and, hence be common species, and yet our data tells us that we find relatively few. This supports the idea that these functional groups, framed by a combination of body size, geographic range, and other biological properties, are context-dependent and rather unique to the place they were studied. Observe the potential contribution if not only some, but all species in the pool were to contribute to a certain benefit. In either scenario, the contribution of the more-than-top subsets of species increases sub-linearly with species richness, maximizing and levelling out beyond biodiversity levels exceeding human population in an area, in which case human impacts such as habitat destruction can cause additional species richness to be accompanied by declining benefits.[18] During species pool reduction to the top species, a continuation of increasing benefits is found in one scenario only, mirroring results observed in unweighted human-dominated and particularly human-controlled systems. Even when top species remain, the reduction in pool diversity still results in a change from increasing to potentially decreasing benefits in another scenario. These results highlight the connection between community diversity, the promotion of natural ecosystem service supply, and the conservation benefits of increasing the potential to enhance natural system resilience.[19] Loss of biodiversity from natural ecosystems can reduce the capacity of these ecosystems to provide humans with a range of benefits. The majority of past studies examining the relationship between species diversity and services have focused on a limited suite of services, often dominating remote unmanaged ecosystems; understanding drivers of service provision has been predicated on important but often oversimplistic changing environments and local species pools of natural systems. By contrast, few modern syntheses are assessing how diversity.

DISCUSSION

The study provided evidence that urban green spaces contribute to the broader urban ecosystem by harbouring high levels of species richness and offering localized habitats for organisms. Yet, there are considerable unknowns regarding ecological functionality, biodiversity, and the suite of ecosystem services that urban green spaces offer to urban ecosystems, residents, wildlife, and advancing sustainable urban dimensions. Therefore, this study adds a new dimension to our understanding of biodiversity and ecosystem services functioning in urban green spaces and provides a wealth of data and stimulating findings to be fully explored by those interested in biodiversity conservation in urban environments.

In a historical context, the development of human civilization depended on the services that ecosystems provide on a sometimes vast scale.[20] As worldwide land degradation mounts, humanity is returning to a refined relationship with local ecosystems to secure the basket of services they provide.[16] The shift happening can be seen as humanity reverting from detaching from local ecosystems to becoming reattached. In turning to more localized and site-specific planning, the symbiotic relationships between urban planning, ecological systems, and the biodiversity they support are key and require a different set of evidence to make it happen effectively. This is the missing piece of the puzzle that this study is so important for.[21] This study develops meaningful information and data to enable an understanding of the value and significance of urban green spaces for the biodiversity of the area.[19] It develops an understanding of the range of species and ecosystems that urban green spaces can support, creates strategies to conserve populations, provides information about possible impacts of some species colonizing urban green spaces, and recommendations to mitigate these. The ultimate aim of the study is to deliver strategies, policy, and actions that support the sustainable coexistence of urban wildlife, minimize conflicts with urban residents and is designed considering a variety of community perspectives and are viewed as equitable by all stakeholders.

Management Interventions and Their Impact

Ever since researchers and managers have considered management interventions aimed at enhancing habitat heterogeneity likely to promote biodiversity. In nature reserves and the wider countryside, these interventions include scrub management, habitat restoration, and the creation of wildlife corridors. Such interventions can indeed lead to a range of wider ecological benefits, including the promotion of species characteristic to particular seral stages or extralimital species, and the creation of habitat mosaics.[22]

Despite the growing number of management interventions promoting biodiversity, there is surprisingly little evidence that demonstrates they work. Much of the methodological difficulty lies in comparing like with like. It is often the case that changes in vegetation are monitored rather than their impact on populations of species.[23] Changes such as these depend on local conditions, history, and species composition. Furthermore, it is common that such management interventions are not replicated.[24] Finally, little in the literature refers to any great depth to the importance of community engagement in realizing the success of biodiversity management. Increasingly, historically insensitive management has given way to adaptive management. Adaptive management recognizes that the changing environment is unpredictable.

Assessments of the dynamics of a degraded heathland undertaking localized ecological restoration work; an adaptive management practice.[25] Four main plots were monitored, three of which were subjected to active restoration. Within the active restoration plots, the short-term removal of rabbits and regular cutting were found to maintain and promote conditions for heather to invade. Similar adaptive management practices can also yield results for biodiversity in urban areas. Optimal management is likely to be different for different areas, as different locations will have different drivers, such as succession, eutrophication,[22] loss of traditional rural practices, and the problems posed by urban wildlife. Moreover, urban greenspaces are static landscapes, which means that ecological conditions are likely to change rapidly. Therefore, changes must be monitored if management interventions are to be effective.

Novel Species and Urban-Adapted Species

Novel ecosystems have a unique species composition, containing a variety of so-called novel or urban-adapted species. These species have characteristics that allow them to thrive in human-altered environments and often have a competitive edge over lost or declining sensitive species.[26] Urban-adapted or novel species can include both native and non-native species. Even invasive species are often among the winners in urban areas. In a Mediterranean system, including more urban-adapted species was related to altered ecosystem processes and increasing ecosystem multifunctionality.[24] Increasing the proportion of more plastic or generalist species might allow, for example, a shift to the use of lower energy and material input for management or improve the provision of biodiversity conservation functions in an ecosystem. The high resilience and adaptability of urban novel species might also make them very suitable organisms for local management to protect or benefit from ecosystem services.

Demographic inferences of 56 species in urban remnant habitats suggested that invading species often arrived in urban areas before 1900, with a second peak of invaders being established in the period 1960–1990.[27] Urban individuals of native and non-native species had higher population size-scale growth rates in novel urban than native non-urban populations. This indicated that experiencing higher resources, reduced predation, disturbance, or habitat heterogeneity in the city selects for functional traits associated with higher individual urbanized fitness. High population sizes and growth rates are useful for species that have a high dispersal ability because it allows them to maximize their ability to get to every corner of the urban environment.[23,28] Very large populations and high growth rates are also potential indicators of species that are very good at finding and utilizing the resources that are abundant in the urban environment. Additionally, it is also possible that many of the species studied have evolved dramatic changes in their biology, including shifts from native species to urban-adapted species through the acquisition of a novel suite of traits.[21,21,21]

CONCLUSION

Urban green spaces (UGS) are vital assets in addressing the growing environmental challenges posed by rapid urbanization. These spaces provide essential ecosystem services, including water management, climate regulation, and biodiversity conservation, contributing significantly to urban resilience and sustainability. Additionally, advancements in artificial intelligence (AI) offer innovative tools for enhancing the monitoring, assessment, and management of UGS, enabling data-driven decision-making for urban planning. UGS play a crucial role in water management by reducing stormwater runoff, improving water quality, and recharging groundwater, thereby mitigating urban flooding and alleviating pressure on drainage systems. In terms of climate regulation, UGS act as natural air conditioners by reducing the urban heat island effect, sequestering carbon, and improving air quality. These areas also serve as biodiversity hotspots, providing habitats for diverse plant and animal species even within highly developed urban landscapes. AI-powered analytics, including remote sensing and machine learning models, further enhance our understanding of species distribution, vegetation health, and ecosystem service provision, improving conservation efforts and adaptive management strategies.

Despite their benefits, UGS face challenges such as land-use pressures, inadequate maintenance, and a lack of prioritization in urban planning. Addressing these challenges requires a collaborative effort from policymakers, urban planners, and local communities. Integrating AI-driven tools into urban development strategies can optimize the design and management of green spaces, ensuring their long-term sustainability. In conclusion, UGS are hidden treasures that offer immense environmental, social, and economic benefits. Their effective preservation and AI-enhanced management are crucial for sustainable urban development. By recognizing the value of these spaces and leveraging technology to address existing challenges, cities can foster healthier environments, enhance urban resilience, and improve residents' quality of life. Policymakers must prioritize UGS as integral components of urban planning to unlock their full potential in supporting biodiversity, regulating climate, and managing water resources.

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