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Perspective

The One Health approach in urban ecosystem rehabilitation: An evidence-based framework for designing sustainable cities

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SUMMARY

Rapid urbanization has led to negative, and sometimes unintended, consequences on biodiversity and human health. While cities offer numerous advantages in meeting the basic needs of a growing population, they also pose less apparent and longer-term health costs. To address the multifaceted impacts of urbanization, an evidence-based design framework for establishing mitigation and regeneration actions is essential. Via a "One Health" approach, this perspective provides recommendations and strategies for the urban ecosystem rehabilitation of future cities, placing biodiversity and ecosystem services at the core of designing healthy and sustainable urban spaces. The framework we propose is based on a Hub and Spoke model to integrate diverse perspectives from public and private sectors and declined in a six-building-blocks structure. This will ensure that efforts are sustainable, health-centered, socially inclusive, and grounded in high-quality data, reinforcing the essential connection between healthy environments and thriving communities.

INTRODUCTION

Urban environments are considered by most of us as our natural habitat. The past 50 years have witnessed exponential growth in built-up areas worldwide, which has more than doubled. More than half of the human population now lives in cities (The Sustainable Development Goals Report 2023).[1] This has triggered significant ecological, epidemiological, demographic, and socio-cultural shifts, affecting both humans and the environment. While cities offer numerous advantages in meeting the basic needs of a growing population, they also pose less apparent and longer-term health costs. To address the complexity of urbanization, evidence-based design (EBD)[2,3] emerges as a promising framework for urban regeneration. EBD was initially applied to healthcare facilities,[4] a design field more prone to collect insights from empirical data in light of the target populations affected by the built environment, such as patients, physicians, and other staff members. Over the years, this approach has been applied to diverse environments[5,6] and has been proposed as a unifying framework for different theoretical approaches bridging psychology and design sciences.[7] EBD emphasizes the importance of science-based theories and methods to inform proper design choices without prescribing the final design choices but rather inspiring creative decision-making processes.[8] While this approach represents a fruitful connection between design sciences and other disciplinary fields assessing the impact of the environment on several variables, it has been limited so far mainly to medical and psychological factors due to its origins. Yet, in recent years, such approach has been considered fruitful not only to inform the design of single buildings or facilities but rather to innovate the approach to planning and design even at larger scales. In this venue, it has been conceived as a broader reference for landscape design,[6] a conceptual framework for urban greenspaces[9] and even a model for evidence-based decision making supporting participatory urban design processes.[10] In consideration of its sound connection with theoretical literature and the professional field, we argue it is a valuable methodological framework to inform urban regeneration choices, effectively integrated by the One Health (OH) approach to identify a broader set of sources of information for the assessment variables. The resulting approach strives for collaboration across disciplines (ranging from architecture and

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engineering to psychology and biology/ecology) to identify and address health issues at the human-environment interface and to develop robust scientific knowledge for sustainable living.

In this perspective, we identify strategies and priorities for the urban regeneration of cities, placing biodiversity, ecological functions, and ecosystem services at the core of designing healthy and sustainable urban spaces. First, we highlight the importance of having a comprehensive picture of biodiversity, including its relationship with built environments and mediated services and its interdependence with abiotic factors. Second, we discuss the complexity, involving multiple pros and cons, of biodiversity rehabilitation in urban settings. Third, we elucidate the psychological and physiological effects of nature in urban ecosystems. Fourth, we provide examples of innovative architecture and design for urban ecosystem rehabilitation. Finally, we describe a conceptual framework enabling a shared decision-making strategy in which all the involved stakeholders cooperate aiming at urban solutions that harmonize human and environmental health preservation, psychological well-being, social equality, and sustainability.[11] Recognizing the intrinsic link between human health and environmental integrity, we underscore that the health of urban populations is inextricably tied to the integrity of urban ecosystems, in alignment with the One Health concept.

URBAN BIODIVERSITY: THE IMPORTANCE OF A BIGGER PICTURE

Biodiversity thrives not only in natural ecosystems but also in artificial environments and urban settings. Urban areas harbor a diverse array of living beings, including humans, creating unique ecosystems with their own biodiversity, dynamics and interactions. Understanding biodiversity within various types of built environments is therefore vital to understand their associated ecosystem services.

Within these ecosystems, macro and microorganisms are part of an intricate network of living organisms that rely on each other and on the abiotic environment. These interactions can have cascading effects, providing a multitude of ecosystem services that benefit not only the immediate participants but also ecosystems as a whole, including urban built environments. Many built environments are used as habitats by various plant, animal, and bacterial species, feature gardens, parks, and street trees. Trees within semi-natural ecosystems provide multiple ecosystem services including carbon sequestration, air quality improvement, and stormwater attenuation.[12–14] Commercial and industrial zones, although typically less green, still provide habitat and substrate for a significant number of animal and plant species.[15] Green rooftops, urban gardens, and green walls are examples of how we can better integrate biodiversity into these environments. These green infrastructures can host microbial communities and other species that help degrade pollutants and improve air quality. Additionally, these structures contribute to reducing the urban heat island effect and managing stormwater. Noteworthy, transportation networks, including roads, railways, and waterways, intersect various urban environments and can influence biodiversity. Vegetated buffers and corridors along these networks can serve as habitats for many species. Less intuitive is the role of transportation networks in shaping and spreading the microbial communities.[16] Often, transportation networks link urban parks. Public spaces and urban parks act as biodiversity hotspots and refuges for various species. The microbial communities in all these areas, such as those on the phyllosphere of trees, play a crucial role in reducing airborne pollutants and enhancing ecosystem resilience. The microbial communities that live in the phyllosphere are generally specific to individual plant species, suggesting that there is a system of communication and interaction between the host plant and the microbial community that exists to encourage a distinct assemblage. Furthermore, some microbes in the phyllosphere have been shown to degrade airborne pollutants that collect on leaf surfaces, reducing their concentrations in the urban environment.[17] Moreover, urban forests also contribute to microclimate regulation and the consequent reduction in annual energy consumption,[13] which gains significant relevance in light of the impacts of climate change.[18]

Greater biodiversity at all taxonomic levels increases both the complexity and resilience of these networks to confront natural or anthropogenic disturbances.

Increasing the knowledge of these complex networks is crucial, as the significance of the involved actors and their potential extinction is rarely assessed.[19] Indeed, in the previous decades, the mutualistic and antagonistic interactions occurring among species were often overlooked by conservation projects that instead focused on species-specific safeguarding efforts.[20,21] Nowadays, management approaches are changing, and it is clear that species interactions have to be preserved first, as these can be affected by anthropogenic stressors even before populations of potentially threatened species.[22] Furthermore, mutualistic and antagonistic species interactions often result in the provision of ecosystem services, as in the case of pollination and seed dispersion (plant-animal interactions) or pest control (predator-prey interactions). Ecosystem services also depend on the interaction between the biodiversity and the abiotic environment, both considering climatic factors and pollutants which may be dispersed in the urban context due to human activities. Thus, preserving species interactions is of primary importance in the self-maintenance of biodiversity and ecosystem functioning, especially in urban habitats where several anthropogenic stressors threaten biodiversity.[23] Nevertheless, it is important to note that several species thrive in urban environments, indicating that urbanization is not necessarily synonymous with biodiversity decline.[24]

Biodiversity and the dynamic interactions among organisms can significantly influence the emergence and spread of infectious diseases, illustrating the complexity of ecosystems. This complexity becomes particularly evident when considering the animal-human-environment interface, a critical aspect of the One Health approach. For instance, the early 2000s saw the emergence of several infections like avian flu, Lyme disease, and West Nile disease, each underscoring the intricate linkages between wildlife, human health, and environmental factors.[25,26] These cases highlighted the necessity of integrating ecological, veterinary, and medical sciences when designing and implementing public health programs to effectively manage and mitigate the risks associated with infectious diseases.

Importantly, also the change of climate and hydromorphological abiotic factors can have a major impact on organisms and living networks in the urban environment. Many studies highlighted the influence of climate change on invasive and autochthonous species distribution,[27] including that of vectors of arthropod-borne diseases[28] which are progressively adapting to live in densely populated urban areas.[29] Given the complexity of ecological systems and the multitude of biotic and abiotic factors involved, a multidisciplinary and multisectoral approach to public health is needed to tackle the spread and/or emergence of infections that can be achieved by relying on the wider approach of OH.

Thus, while biodiversity is an important aspect of urban rehabilitation, our focus is on creating ecologically healthy, balanced, and functional urban environments through the integration of biotic and abiotic elements.

A zoom-in at the microscale: We are living in a microbial world

When discussing biodiversity and its decline, our minds often evoke images of majestic macro-organisms like wild mammals and trees. However, a new understanding has emerged, acknowledging that biodiversity encompasses multiple scales, from macro-to micro-scale. Often the unseen majority of microbial organisms is still neglected in estimates of biodiversity[30]: there are approximately 10^{12} microbial species on Earth,[31] and a total biomass of microorganisms nearly 50 times greater than that of all animals on Earth, including humans.[32] Furthermore, microorganisms are essential to the functioning and well-being of virtually every ecosystem on our planet, making them indispensable in numerous aspects that affect our society.

Microbes are part of a wide and deep ecosystem service, contributing to the well-being of the Earth and its inhabitants, humans included. Humans are essentially holobionts,[33] "mega-organisms" composed of the host and the interacting viruses, bacteria, fungi, and other (micro) organisms, which together form a discrete ecological unit. This collection of microorganisms is not merely a random assembly of microbes emerging from the environment and/or selected by chance; rather, specific host–microbiota interactions are maintained over time by selection and, together, they (we) coevolved, developing tight relationships. Less obvious, every urban settlement has its own microbiome. In fact, urban landscapes are home to resident and transient microbial communities that populate everything from the soil and air to wastewater and building exteriors and interiors. Importantly, city-dwelling microbes play numerous, largely unexplored, roles in the structure and function of urban spaces and the health of those who inhabit them.

For millennia, environmental microorganisms have played a pivotal role in the training of immune responses during the first years of life, thus influencing the future functioning of the adult human immune system.[34] Human immune regulation evolved within natural environments vastly different from the anthropogenic urban settings that have become increasingly prevalent. Indeed, the expeditious changes in human lifestyle and urbanized environments have led to evolutionary mismatches between our "outdated" immune system, trained in times of higher microbial biodiversity, and the reduced microbial exposure in today's anthropogenic settings, driving the emergence of the so-called "diseases of civilization". Biodiversity loss is one of the main guilty parties of this phenomenon and, accordingly, this theme has become popularized and politicized as a metric for quality.[35,36] Building sustainable cities implies the guarantee of an accessible health-promoting environment for everyone, allowing our "Old Friends",[37] with whom we have co-evolved, to drive future interventions. Furthermore, the novel awareness of social microbiome transmission highlights the potential for microorganism exchange among individuals (going beyond the concept of pathogen transmission) and from the environment where they socialize as an important factor that could shape human well-being.[38,39] The interconnectivity of microbiomes across diverse environments should assist in urban planning, construction, mass transit systems, and school and work activities.[26] Additionally, it is crucial to recognize that the interplay of microorganisms within urban ecosystems is not only a matter of environmental preservation but also a fundamental element in the well-being of urban landscapes.[40]

THE PUSH TOWARD BIODIVERSITY: IS IT ALWAYS GOOD?

Urban environment is responsible for approximately 38% of greenhouse gases emissions and its expansion causes deforestation and change in land use, increasing climate change and contributing to biodiversity loss by altering habitats and ecosystems. In turn, biodiversity loss reduces the resilience of urban habitats to climate change, for instance by intensifying urban heat island effect and decreasing air quality.[41] Due to this interconnection, urban ecosystem rehabilitation can be accomplished by acting on both environment and biodiversity, as the result of an integrated approach on biotic and abiotic factors, that translate into ecological functions and ecosystem services. In this context, biodiversity regeneration represents a powerful tool to improve urban settings.

According to the International Principles and Standards for the Practice of Ecological Restoration,[42] restoration aims to assist the recovery of a native ecosystem that has been degraded, damaged, or destroyed. In this context, biodiversity restoration is usually intended as the adoption of policies and/or practical interventions to enhance species diversity and their mediated biological interactions improving the stability and functionality of degraded ecosystems.[43,44] However, returning an ecosystem to its original state is often not feasible nor the real goal in urban environments, due to extensive and irreversible changes occurred and needed. An approach to restoration is assisted regeneration, that focuses on actively triggering any natural regeneration capacity of biota remaining on site or nearby as distinct from reintroducing the biota to the site or leaving a site to regenerate. On the other hand, rehabilitation involves improving the existing conditions to support human and ecological needs, which is more applicable to urban settings.

Challenges in urban ecosystem rehabilitation

Nonetheless, the planning and realization of effective rehabilitation efforts are challenging given their intrinsic multifaceted impact on different trophic ecosystem levels. For this reason, ecosystem rehabilitation should be based on the monitoring of abiotic factors before, during and after the interventions and on the understanding of their influence on the biotic communities. Additionally, biotic communities should be comprehensively studied in order to predict the long-term effect of regeneration on their colonization dynamics, and interactions.

Predictions must take into account the change of climate and human-related factors, such as urbanization and socio-economic development. Modeling the impact of urban regeneration in various scenarios can help in the management of these interventions.

Balancing benefits and risks: Unintended consequences of new species introduction in cities

Indeed, disadvantages exist if interventions are not managed wisely: introducing or removing species and altering habitats can disrupt existing ecosystems, potentially leading to unpredictable and sometimes negative cascading effects that impact the well-being of both humans and wildlife.[45] The awareness about the risks of species introduction and removal from urban environments arises from the numerous cases of invasive species introduced into cities for practical or aesthetic reasons, and thus independently from restoration attempts, with consequent negative effects on the autochthone population. Flora and fauna introductions are highly frequent within cities: many species co-habit in artificial or modified environments due to habitat heterogeneity related to multiple land uses and high concentration of people, industries and infrastructures, increases the probability of accidental introduction and provides resources exploitable by a wide range of species.[46] In particular, the introduction of species like Gambusia fish, initially intended as biological control agents, has demonstrated how well-intentioned interventions can backfire, turning the introduced species into a new pest and further destabilizing urban ecosystems.[47]

Dealing with rehabilitation, the creation of new habitats (e.g., woodland, grassland, wetland) and the introduction/removal of some species can lead to changes in the availability of habitat and resources, thus modifying the abundance of key species. These alterations directly influence the dynamics of biological systems (such as predation and herbivory patterns), can lead to "pathogen pollution" (i.e., the anthropogenic import of pathogens into new geographic locations or toward novel host species), or conversely, the high trophic availability can attract new "undesirable" species like pests, pathogens, disease vectors or alien invasive species.[26] This, in turn, can diminish habitat quality when viewed from a One Health perspective.

Noteworthy, in recent decades, we have witnessed an increase in the emergence or re-emergence of infectious diseases, of which zoonoses (diseases that can be transmitted to humans from animals) account for the majority. Among them, wildlife-borne infections play a greater role. As a consequence, interventions on the biodiversity of cities may convert cities into more suitable habitats for parasite life cycles or alter pathogen transmission by increasing animal abundance or contact rates, resulting in the possible emergence of new infections. Approximately 40% of zoonotic viruses are transmitted to humans by the bite of arthropod vectors, in particular mosquitoes and ticks, which show an increasing adaptation to urban habitats thanks to greening efforts both in urban parks and city expiation to surrounding woodlands.[48,49] Particularly, arthropod vectors, such as mosquitoes, are able to exploit artificial containers within public and private gardens as breeding sites for aquatic larvae.[50] Highly populated areas are also more affected by globalization-driven effects, such as the high movement of people and goods. This can lead to an increase in the return of infected travelers from areas where arboviruses such as dengue are endemic. As a result, the number of cases of several vector-borne infections (e.g., borreliosis, West Nile, and dengue) is increasing in cities, particularly in southern Europe.[51] Indeed, the impact of climate change must be taken into account when considering the spread of vectors and pathogens within urban environments. Furthermore, the high animal and population densities in cities and the high contact rates between them not only increase the probability of spillover but may even lead to a growth in opportunities for pathogens to evolve and take advantage of human-to-human transmission.[52]

Moreover, the size and dynamics of arthropod populations are heavily affected by available resources and predator densities. Human-dominated landscapes are often characterized by abundance of resources and scarcity of predators, thus in urban areas many animal species can attain population densities higher than what is observed in wildlands.[53] The abundance of available hosts (e.g., mice and squirrels in cities) can influence the success of several problematic arthropod species. An example of this is ticks: in green areas of big cities, there is an increasing prevalence and emergence of tick-borne diseases, as well as an increasing risk these diseases pose to humans, domestic animals, and wildlife.[51]

Balancing benefits and risks: New habitats in cities

Wetlands are another key example of the complexity of environmental management and rehabilitation in urban environments, where there are advantages and disadvantages. The presence of wetlands can be extremely important in urban ecosystems, as they regulate water flow, limit the risk of flooding under extreme meteorological events, buffer temperature during heat waves and, of course, host significant biodiversity.[54] Urban wetlands also have great aesthetic values and have been built to beautify the landscape in multiple cities across the world.[55] Nevertheless, wetlands can increase the occurrence of noxious insects such as mosquitoes, which can also be vectors of several pathogens. In an attempt to control mosquitoes, predators such as the mosquitofish have been extensively introduced worldwide. Still, controversies exist on the effectiveness of predators introduced for biological control, particularly because many of them are invasive species that impact native biodiversity.[56] In some habitats, introduced fish have drastically reduced the abundance of mosquitoes and the transmission of pathogens.[56,57] At the same time, in other environments, they have heavily impacted native predators (e.g., amphibians) that feed on mosquito larvae, and can even result in increased mosquito abundance.[56] As a consequence, the type of wetlands created in urban areas is crucial. Properly designed and maintained wetlands can provide significant ecological benefits without increasing the risk of vector-borne diseases. By ensuring wetlands have well-oxygenated, heterogeneous habitats, we can promote a balanced ecosystem that supports a variety of organisms and reduces the dominance of mosquito populations.

Thus, detailed information on local biotic communities, their habitats, and interactions is essential to identify the appropriate management strategies and avoid unwanted side effects.

Balancing benefits and risks: Human health considerations in urban green space design

With specific regard to human wellbeing, urban green spaces provide recreational opportunities and psychological benefits, reducing stress and mental illness. Furthermore, green infrastructures, such as green roofs and walls, help mitigate the urban heat island effect and reduce energy consumption. However, poorly designed interventions and the re-creation of natural conditions in urban contexts may increase the risk of zoonotic disease transmission and exposure to allergens[58] and remobilized contaminants. There is a growing awareness of the need for more ecologically sound approaches to urban greening: recent research and best practices in urban ecology emphasize the benefits of incorporating native species and diverse vegetation strata to enhance not only ecological functions, resilience, and long-term sustainability of urban green spaces, but also human health. For example, the regeneration of urban spaces with vegetation does require to take into consideration several aspects that may elevate risks to human health. The selection of plant material introduced is important as many species carry with them the potential increased risk of exacerbating respiratory issues in vulnerable individuals, particularly those with pollen sensitivity and asthma. However, this risk can be reduced or potentially eliminated altogether by choosing plants that produce low amounts of wind-borne and allergy-inducing pollen or planting only the seed-producing female individuals of dioecious plant species.[59] Phytoextraction itself may also disperse or remobilize pollutants into the topsoil through the biological cycling of decomposing root[60] and leaf biomass[61] or in the atmosphere through the production of volatile compounds.[62,63] These concerns require careful consideration of the physiology of the plant species being used for regeneration as well as a thorough evaluation of the soil targeted for phytoremediation efforts.

Given the complexity of ecosystem rehabilitation in urban regions, should we give up trying for biodiversity-inspired urban regeneration? This thought-provoking question prompts us to consider the importance of designing urban rehabilitation with an understanding of its multidisciplinary nature and complexity. Here, we support the idea that a well-designed rehabilitation plan should consider an exhaustive knowledge of the actors of an ecosystem that also involves long-term monitoring both before and after the rehabilitation efforts.

Multidisciplinary and collaborative approaches in urban ecosystem rehabilitation

This is the reason why we propose a multidisciplinary and collaborative approach to effectively address the complexity of urban rehabilitation. This framework involves the integration of research methods and comprehensive monitoring. Emerging methods, such as coupling field monitoring with molecular analysis of environmental DNA (eDNA), can facilitate the monitoring of species diversity and interactions, while also allowing surveillance of pathogens and undesirable species.[64,65] Additionally, innovative approaches such as multi-omics analysis (e.g., genomics, transcriptomics, metabolomics) should be integrated into the evaluation of stress exposure and health conditions of wildlife, as these new tools may facilitate the evaluation of rehabilitation efforts efficiency in terms of improving health conditions.[66] In particular, metabolomic and transcriptomic analyses have already been conducted on people living in urbanized areas, highlighting the impact of abiotic factors on different metabolisms.[67] On the other hand, genomics has recently been applied to urban wildlife ecology studies to understand how populations are being shaped by anthropization.[68] Therefore, as some studies are already highlighting,[69–71] adopting a multi-omics approach could help in understanding how urbanization is affecting species health and wellbeing and consequently driving population decline. It is noteworthy that in the last decades, ecology, biology, and epidemiology have taken advantage of more advanced mathematical and statistical techniques to develop tools and methods to investigate mechanisms underlying ecological and infectious progress. The idea of the existence of a critical community size was conceptualized and the basic reproduction number (R_0) was transposed from ecology to infectious disease modeling, proving the importance of modeling in investigating the efficacy of intervention strategies to limit the spread of infectious diseases,[72] in showing the contribution of different mechanisms to infection spread, or in investigating pathogen variability among environments.[73] Indeed, this strategy has been successfully employed by Lélu et al.[73] to decipher the transmission dynamics of *Toxoplasma gondii*, the protozoan parasite responsible for toxoplasmosis, an infection that concerns public health. The risk factors and the routes of transmission are influenced by environmental conditions and the inhabitants' lifestyles demonstrating the importance of these approaches in managing disease spread in rural and urban contexts.

There are daily advancements in ecological knowledge and in the development of new practical tools for ecological investigation. In our opinion, these aspects should be involved in the development of biodiversity monitoring, in order to fill the existing gaps. However, the integration of research methods and comprehensive monitoring alone are not enough to effectively address the challenges of the push toward ecosystem rehabilitation. To date, for example, there is a lack of agreement on the approaches that can be applied to evaluate the efficiency of ecological rehabilitation projects. Furthermore, there is a need for the creation of ecological rehabilitation guidelines that should consider local (e.g., urban, periurban) and regional (e.g., ecoregion) contexts, since species interactions vary in a context-dependent manner.[74] Thus, a collaborative model that involves academic and industrial research, local institutions, civil associations, companies, the service industry, and the population is an essential element of the framework: while science-based tools have been and are constantly being developed, there is a need to enhance the transfer of knowledge from academia to policymakers through effective communication strategies, fostering the application of Evidence-Based Design in urban ecosystem rehabilitation (Figure 1).

PSYCHOLOGICAL AND PHYSIOLOGICAL EFFECTS OF NATURE IN URBAN ECOSYSTEMS

Previous research has demonstrated the relevance of including in the OH approach the role of mental health, especially when investigating the quality of urban green spaces.[75] Indeed, the natural elements of urban settings significantly impact people's physiological, cognitive, emotional, and behavioral responses, and a large number of theoretical models has described the interaction of one or more variables with environmental factors. Among them, the biophilia hypothesis[76] presents a general evolutionary framework, suggesting an inherent

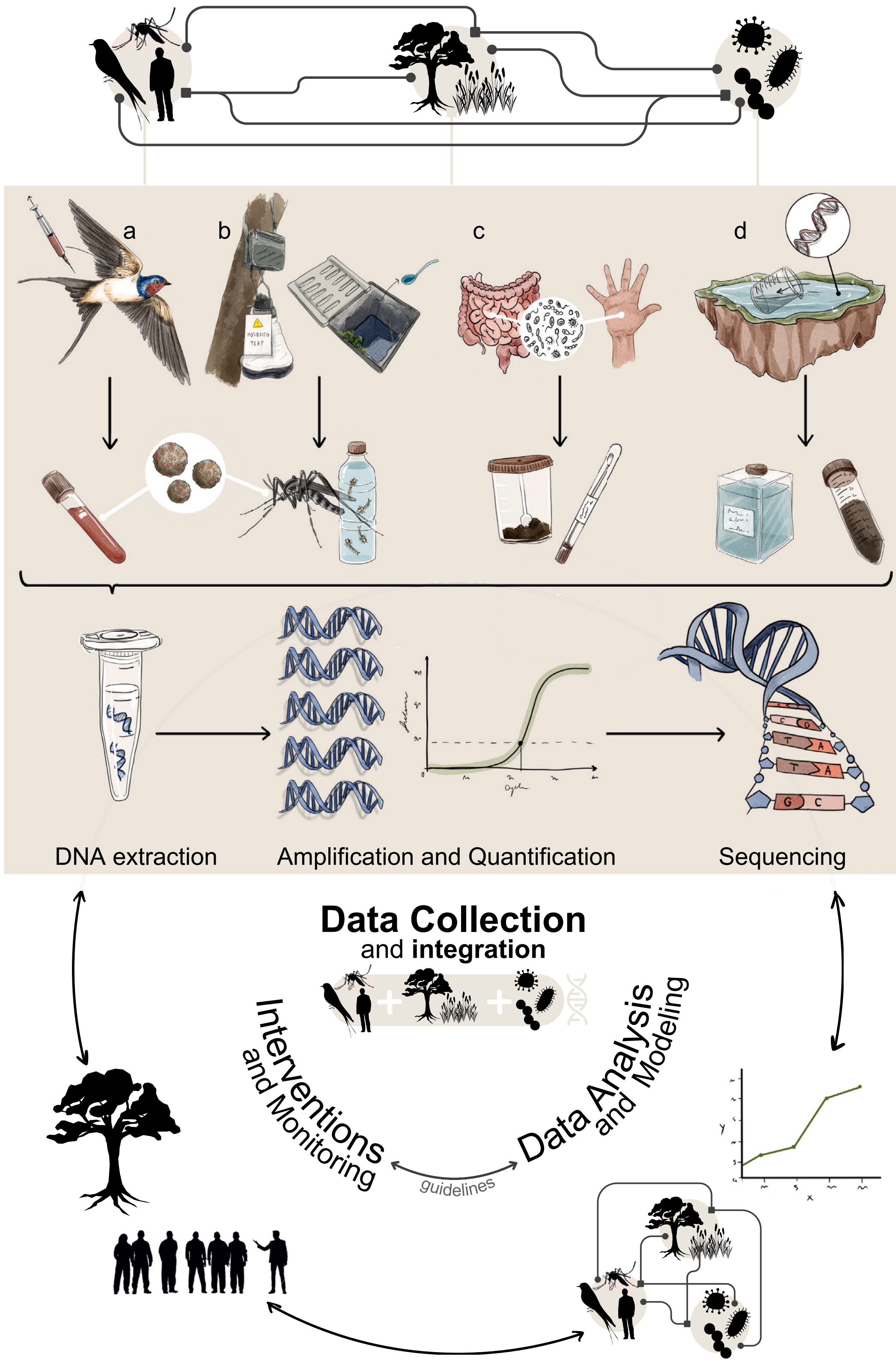
a
b
c
d
DNA extraction
Amplification and Quantification
Sequencing
Data Collection
and integration
Interventions
and Monitoring
guidelines
Data Analysis
and Modeling

Figure 1. The push toward urban ecosystem rehabilitation

To be effective in deciphering, reconstructing and protecting the intricate relationships between animals (including humans), plants, and microorganisms in local contexts, urban ecosystem rehabilitation must be sustained by cycles of data collection, analysis and modeling, and monitoring interventions. Molecular approaches, such as DNA analysis, combine multidisciplinary fields allowing the integration of samples obtained from the environment, humans and other key animal species. In the depicted example, blood samples collection from birds and the evaluation of the prevalence of vector species can be used to assess West Nile Virus infections (a, b) and can be integrated into human microbiome (c) and environmental DNA studies (d). Data analysis and mathematical modeling guide the application of Nature-Based Solutions (NBS) and future interventions aiming at sustaining the animals-plants-microorganisms network and defining new targeted guidelines to be followed by policymakers. Continuing the cycle, interventions must be validated through systematic monitoring and novel data collection.

emotional affinity of humans toward other living beings, a result of bio-cultural selection for human species preservation. Although criticized by some for its inaccuracy,[77] it has become a crucial reference as a bridge between design and psychological sciences. In the psychological field two pivotal theories, the Stress Reduction Theory,[78] and the Attention Restoration Theory,[79] expound on the favorable impacts of natural exposure on an individual's psychological well-being. They both emphasize the intrinsic and immediate effects resulting from human interaction with natural surroundings. The former concentrates on diminishing stress-related markers, while the latter focuses on revitalizing cognitive functions, including heightened attention, improved memory, mental clarity, and fostering positive mood shifts, reducing anxiety and depression. Moreover, the environmental self-regulation hypothesis[80] posits that humans consciously and purposefully utilize natural environments to facilitate cognitive restoration and enhance their emotional state. These positive psychological outcomes have also been found responsible for significant mediating effects, such as the promotion of physical activity, the stimulation of pro-social and sustainable behaviors, and the reduction of aggression and crime rates in inner cities. However, not all natural environments yield identical outcomes.[81] Settings characterized by savannah-like vegetation have shown a higher preference, as well as those offering a blend of comprehensibility (ease of mapping) and novelty (potential for new discoveries). Additionally, factors interlinked with these include biodiversity, contextual positioning, historical value, perceived extent, and distance from the ordinary norm (''being away''). Looking at the human side,[82] some individuals' socio-demographic characteristics have been identified as moderators influencing the potential impact of exposure to natural surroundings. Factors such as age, gender, economic status, cultural affiliation, and personality have surfaced as elements moderating the strength of observed psychological effects. These encompass the subjective inclinations toward fostering a more or less profound connection with natural environments overall, whether through a heightened bond (*connectedness*) with nature or a more well-defined *ecological identity*.[83] Some built environments have also been found to have a high regenerative potential, in particular those that present a significant interaction between the natural and historical-artistic dimensions (monasteries, cloisters, museums). Such a wealth of literature has given rise to many quantitative psychometric scales to assess those constructs[84] as well as qualitative tools (e.g., Boffi et al., 2021; Nordh et al., 2017; Johansson et al., 2024; Sonntag-Öström et al., 2015).[85–88] Urban planning can certainly benefit from these findings by incorporating green spaces and natural areas to create healthier and more sustainable cities that are a source of well-being for urban residents. Concurrently, the literature emphasizes the essential need for Nature-Based Solutions (NBS) design practices to be blended with data-driven and evidence-based approaches. They should holistically consider the geographical, social, and cultural variations within specific urban landscapes and the nuanced attributes of their residents, devoting specific efforts to better comprehend how local communities define their own health within specific contexts. This is part of a broader effort to effectively include social sciences in the OH framework along with STEM disciplines,[89] that in its more proactive conception may take form of participatory design. This approach ensures a more comprehensive understanding of the diverse urban environments and enhances the effectiveness of NBS in addressing their unique requirements.

To complete the picture, the assessment of subjective, physiological responses in urban spaces measured by biomedical signals (such as EEG, ECG, and PPG) has emerged as a powerful tool to provide novel, objective measurements of how citizens perceive and represent spaces in the city. These measurements, made available by non-intrusive, wearable devices, offer unique information, especially when combined with Machine Learning methods,[90] on a pedestrian's emotional interactions with the built environment[91] and/or experienced environmental distress.[92] The theory of physiological pattern recognition can derive significant evidence about human perception: for example, level of arousal (high and low arousal) can be quantified by measuring changes in the skin conductance signal (or in the electrodermal activity - EDA) and related to both positive and negative biological reactions; additionally, Heart Rate Variability measures (derived from linear and non-linear analysis of R-R inter-beat changes measured on the ECG) can be interpreted in terms of sympathetic and parasympathetic action of the autonomic nervous system and related to quantification of stress, discomfort or relaxation in the subjects. These measurements can be also complemented by other physiological measurements like systolic (SBP) and diastolic (DBP) blood pressure changes or respiration patterns. Two factors have promoted the use of quantitative physiological measurement in different contexts than health applications including the human-urban experience: the availability of wearable sensors and the advent of machine learning tools. The former made it possible to move those technologies, originally confined in controlled laboratory settings, to the outdoors. The latter has contributed by providing methods for robust, multiparametric and more precise analysis of physiological responses (Figure 2).

The two have definitely enlarged the field of applications of those technologies to the still unexplored areas of quantitative, objective evaluation of the human-environment interactions in outdoor settings.

THE IMPORTANCE OF PLANNING AND DESIGNING URBAN ECOSYSTEM REHABILITATION

Taking into account the complex scenario resulting from previous reflections, creating harmonious urban environments that balance human needs with ecosystems' health is a critical challenge for urban planners and designers. As urban populations increase, biodiversity

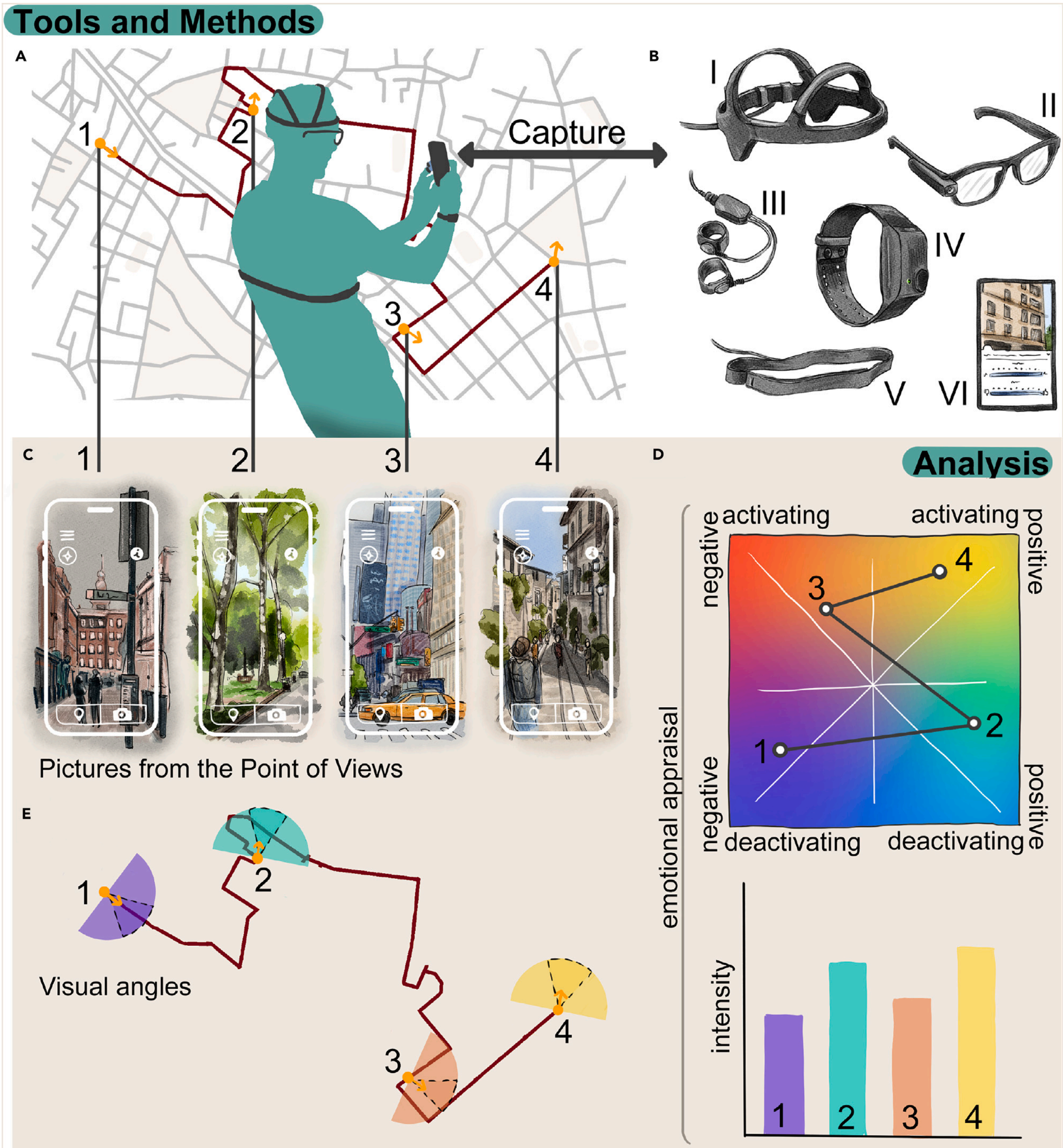

Figure 2. Assessment of psychological and physiological responses to urban experience

(A) An urban walk, whose path and points of interest are defined according to research objectives, enables psychological and physiological data collection. (B) Wearable (for objective quantitative data) and smart mobile devices (for subjective quali-quantitative data) enable measurement of citizens' response to the built environment as it changes across different types of urban areas. Tools can include I) EEG headset, II) eye-tracking glasses, III) electrodermal activity (EDA) sensors, IV) wristband measuring photoplethysmogram (PPG) and accelerometer (ACC) signals, and V) electrocardiogram (ECG) monitor. Using a mobile device (VI) citizens can capture pictures from specific Points of View (POV) and answer surveys including psychometric scales on relevant constructs (e.g., emotions). Georeferenced data acquisition leads to the analysis on (C) pictures' content, (D) emotional appraisal of the intensity and the type of emotions according to Russell's circumplex model,[93] and (E) their cartographic representation.[94] Further psychological constructs can be included in the analysis.

becomes crucial for fostering urban resilience and people's well-being toward a better quality of life. The OH concept, originating in the veterinary discipline,[95] carries significant potential in the realm of urban planning and design. Indeed, embracing the OH approach in these fields can enhance human-nature interaction, creating inclusive urban spaces by recognizing the interconnectedness of humans, animals, and environmental health, and emphasizing that the health of one impacts the others. This perspective also aligns and contributes to achieving Sustainable Development Goals (SDGs), with specific attention to the broader concept of urban health and well-being.[96] The World Health Organization (WHO) underscores the importance of integrating health in urban and territorial planning, providing guidance through their sourcebook[97] to assist national governments, local authorities, planning professionals, and civil society organizations in improving planning frameworks and practices. This incorporation of health considerations spans all levels of governance and across the spatial-planning continuum. However, the practical application of this approach is complex, and achieving the ambitious targets of OH requires an integrated, interdisciplinary, and holistic approach,[98] extending beyond design disciplines, and encompassing urban policies, procedures, and ideally legislation. The duty of urban planning is to assess the existing condition of the complex urban environment system and provide strategies and guidelines for proper urban growth. Considering the complexity of spatial environments, urban planning should ideally act holistically to govern and plan the many interrelated aspects of urban environments. Yet, the global adoption of the OH perspective in the field is still in its early stages and challenging to implement in practice. Traditional methods and procedures may fall short in addressing the multifaceted aspects of urban environments, necessitating innovative public procedures, legislation, and design perspectives.[99] For a proper integration of the OH approach in the field of spatial design, it should ideally be applied across all phases of urban planning and design, i.e., from the analyses of the current condition to the definition of design briefs that lead to plans, urban designs, and architectural solutions. In this perspective the OH concept should act as a guiding principle that drives innovative urban transformations and development from the outset, as each design phase influences and shapes the other ones. As with all complex and innovative approaches, this are hard to become current practices, this interdisciplinary OH perspective in the urban transformation is challenging to implement both in professional practice and in educational university programs of urban planning and design.[100] Not surprisingly, as the OH concept is relatively new and is even newer in the context of spatial design.[95] A more familiar approach that considers the person-environment connection is Biophilic Design, typically related to architecture rather than urban planning. Nevertheless, this shift in perspective at the urban and territorial scale is crucial,[101] and contributes to moving toward the OH direction in a more systematic way.

To manage the complexity of urban issues and address their challenges in the OH perspective, digital tools, and techniques can support interdisciplinary collaborations that provide valuable insights for advancing urban environments.[102] This aligns with the evidence-based design approach, which is crucial for effectively translating interdisciplinary collaboration into practice. This is especially true when considering the inclusion of disciplines such as biology and microbiology, veterinary and entomology, psychology, and neuroscience, which do not typically contribute directly to urban plans and design solutions. In this context, Decision Support Systems (DDS),[102] that facilitate data analysis and simulation of future scenarios for cross-disciplinary reading of the urban system can leverage interdisciplinary understanding. This fosters design approaches and solutions that favor the creation of livable, healthy, and biodiverse cities. By connecting various types of data, these systems should enable the analyses and support the evaluation of urban transformation from different disciplinary perspectives before construction. Furthermore, they can enhance transparency in decision-making processes and proper transdisciplinary representation and communication of outcomes, fostering inclusive collaboration among a wide range of stakeholders, including citizens and researchers from different disciplines, beyond the traditional private and public sectors. This ambitious interdisciplinary synergy aims to facilitate collaboration and coordinate conscious actions at various levels and scales of operationalization, ultimately shaping urban spaces that promote a sustainable and thriving coexistence between humans and the environment. While connecting and relating various types of data can support interdisciplinary collaboration, it does not absolve urban planners and designers from the challenging task of making informed decisions and finding optimal solutions. Despite the potential limitations of DSS in integrating diverse data types, this interdisciplinary and evidence-based approach represents a significant advancement in framing urban issues from a holistic perspective and fostering OH solutions.

In conclusion, the integration of the OH perspective into urban regeneration processes, fostering biophilic and biodiverse design approaches, requires a shift in traditional urban planning practices. This is not a straightforward process and implementing it globally is even more challenging. However, the urgency imposed by climate change hazards demands a decisive reaction that cannot follow the traditional routes of evolution. In the field of urban planning and design, this urgency requires innovation in public procedures, related legislation, and even planners' and decision-makers' perspectives with an interdisciplinary approach; this should lead to innovative strategies, and effective decision-support systems based on evidence-based design approaches, methods, and tools. The goal is the creation of urban spaces that are not only sustainable and resilient but also promote the well-being of all inhabitants, human and non-human alike.

A CONCEPTUAL FRAMEWORK FOR A SHARED DECISION-MAKING STRATEGY

To effectively address the complex challenges of urban ecosystem rehabilitation, we propose a comprehensive and systematic framework rooted in the One Health approach, which recognizes the interconnectedness of health on the whole, beyond a rigid distinction among environment, human and animal (being *Homo sapiens* an animal) health. Our framework hinges on the Hub and Spoke model,[103] a collaborative public-private partnership designed to integrate diverse perspectives and expertise across sectors. This model is essential for harmonizing research, data production, technological transfer, and policymaking, ensuring that urban regeneration efforts are both sustainable,

Box 1. A concrete EBD framework for urban regeneration: the MUSA project

The above-described framework requires in-depth synchrony of multiple gears in order to keep the engine of evidence-based urban regeneration running. As a demonstration of the actual feasibility of this multidisciplinary approach, we briefly describe a project tailored to be an ecosystem model for urban regeneration and sustainability. The MUSA (Multilayered Urban Sustainability Action - Urban Regeneration, City of Tomorrow) project[107] has been conceived to lead the transition of the metropolis of Milan, Italy, toward environmental, economic, and social sustainability. This structured project was launched in September 2022, is funded by the European Union – NextGenerationEU, under the National Recovery and Resilience Plan (NRRP) and promotes a science-based approach to the multidisciplinary engagement of citizens, scientists, industries, and public administrations, reflecting an unprecedented effort for urban ecosystem health. It involves six thematic nodes concerning urban regeneration, big open data, technology transfer, sustainable economic impact, fashion and luxury design, and sustainable inclusive societies. This ambitious applied research effort involves more than 970 people belonging to four different universities, local authorities, research institutions, and private parties and aims to establish the groundwork to transform multidisciplinary urban policymaking from idea to practice.

health-centered, socially inclusive, and grounded in high-quality data. Indeed, to reconcile the plurality of themes mentioned above with a systematic and cohesive approach to urban regeneration, we must adopt a broad perspective while maintaining inter-scalar viewpoints. We envision a consortium-like extended partnership among these parties, to support the development and application of innovation strategies. The Hub and Spoke model, originally used in airline distribution networks to optimize transportation, features radial routes connected to a central hub. This model has since been applied in various fields such as healthcare service delivery,[104] sustainable marketing, and supply chain management.[105]

One practical example is precisely the structure of the NextGeneration EU NRRP projects, where the hub manages the overall direction while the spokes - composed of experts in specific thematic areas - focus on specific aspects. Among them, the MUSA project example is described in Box 1: here, the collaborative expertise evaluating urban design, micro- and macro-biodiversity, and effects on human psychology and physiology is one of the spokes branching off a central hub that acts as the actuator subject that oversees monitoring research activities and actualizing the related interventions. The executor parties (spokes) have thematic identities and represent the specialized scientific expertise in charge of the effective execution of the project[106] (Figure 3A).

Applying the framework: Leadership and coordination

The success of this framework requires strong leadership and coordination, facilitated by the central hub. This leadership body, composed of project directors, managers, auditors, coordinators, scientific committee, belonging to government, academia, industry, and civil society, plays a pivotal role in mobilizing resources, securing funding, and providing consistent support to all stakeholders. Centralizing these activities is crucial to ensure mindset integration, information sharing, inclusive changes, and health prioritization. The defined hub should not be merely a cooperation between high-profile roles, but rather a true collaboration between mutually informed fields. The spokes branching off the hub cluster together expertise referring to the same thematic (e.g., urban regeneration, big and open data management, technological transfer, economic impacts, societal inclusion, and processes sustainability) and provide science-based feedback to the hub.

Drawing inspiration from the "International Principles and Standards for the Practice of Ecological Restoration",[42] we have developed our framework based on a six-building-block structure (Figure 3B).

Stakeholder engagement and participation

Effective urban regeneration requires robust stakeholder engagement and active participation. Our framework incorporates mechanisms to ensure that all relevant stakeholders—government bodies, academia, industry, civil society, and local communities—are involved in every stage of the process.

For instance, the EU Horizon2020 project "Sharing Cities"[108] exemplifies this approach by bringing together multiple stakeholders to co-create smart and sustainable urban solutions. The project's governance model, which includes a central coordination team and thematic working groups, has successfully integrated various perspectives and expertise, leading to the implementation of energy-efficient buildings, sustainable mobility solutions, and community-led digital platforms in three cities: Milan, Lisbon and London.

Interdisciplinary investigation of urban areas

A key element of our framework is the interdisciplinary investigation of urban areas before, during, and after the implementation of urban rehabilitation plans.

Standards and protocols from various fields, including architecture, engineering, psychology, medicine, epidemiology, microbiology, and ecology, are integrated into a health-centered action plan. For example, in the design of public spaces, integrating green infrastructure like trees and water features can reduce urban heat islands, improve air quality, and provide habitats for local wildlife, which in turn benefits human health. The "High Line" in New York City, a park built on a former railway line, is a prime example of how urban regeneration can enhance biodiversity while also providing a recreational space that improves mental health and social interaction.[109]

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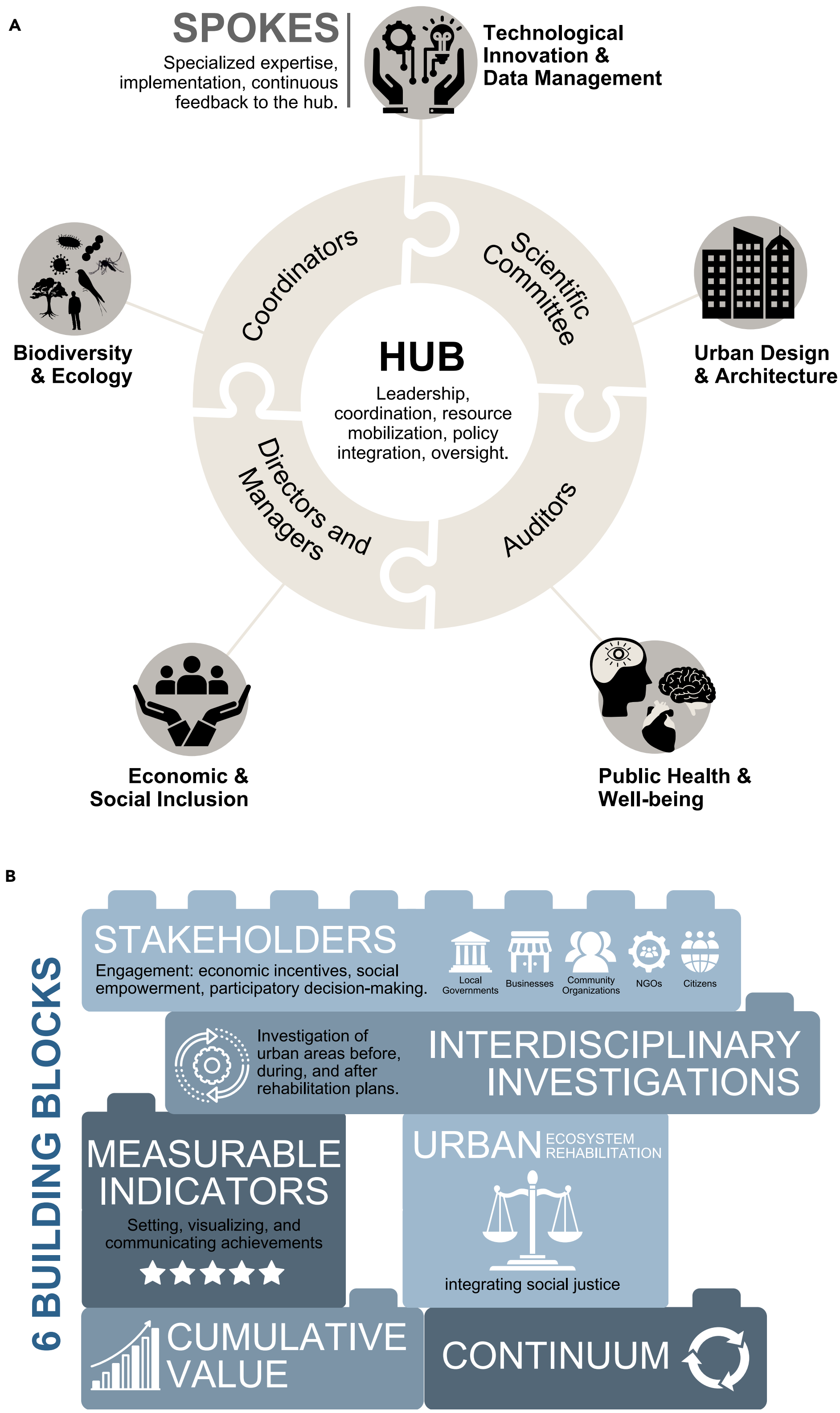

Figure 3. Structure of the conceptual framework

(A) Diagram of the proposed Hub and Spokes model.

(B) The six-block structure of our urban ecosystem rehabilitation framework.

Clear goals and objectives using measurable indicators

Establishing clear goals and objectives with measurable indicators is crucial for tracking progress and ensuring successful outcomes. Our framework recommends using tools that assist managers, practitioners, and regulatory authorities in setting, visualizing, and communicating achievements. For instance, the five-star rating system, or similar approaches, can be applied to define and evaluate targets for urban ecosystem rehabilitation. These tools possess desirable characteristics: they are simple yet effective, cumulative, and applicable to various attributes, ensuring that each project meets defined benchmarks for environmental, social, and health impacts. For instance, Copenhagen's green city initiatives,[110] which include measurable indicators such as reductions in carbon emissions and increases in green space, demonstrate how clear, data-driven objectives can guide successful urban planning. Digital platforms play a critical role here, providing the tools to collect, analyze, and share data transparently, thus enhancing accountability and enabling continuous improvement.

Seeking the highest level of urban ecosystem rehabilitation Attainable

Our framework strives to achieve the highest possible level of urban ecosystem rehabilitation, changes from the baseline condition in relation to the ideal level of recovery. This involves not only urban environment rehabilitation but also ensuring that all residents benefit from these improvements, integrating social justice into the process. The "Green Exchange" program in Curitiba, Brazil,[111] is an example of how urban regeneration can address both environmental concerns and social inequalities by allowing low-income residents to exchange recyclable waste for fresh produce. This initiative highlights how targeted, inclusive approaches can achieve high levels of rehabilitation while promoting equity and human dignity.

Gaining cumulative value at large scale

Applying our framework at large scales provides cumulative value and drives significant urban transformation. For instance, the "Decidim"[112] platform in Barcelona, Spain, enhances citizen engagement and transparency across numerous urban projects, resulting in widespread improvements in urban planning and community involvement. By scaling these efforts, cities can leverage collective insights and resources to achieve broader and more impactful results. Moreover, the open data practices guided by FAIR principles—ensuring that data are Findable, Accessible, Interoperable, and Reusable—allow for the accumulation and sharing of knowledge across different urban contexts, maximizing the scientific value of data and fostering collaboration.

Being part of a continuum of ecosystem rehabilitation activities

Urban ecosystem rehabilitation is not a one-time effort but part of a broader continuum of activities that must be sustained over time. Our framework promotes long-term engagement, integrating projects into ongoing urban planning and development strategies. For example, in Vienna, Austria, the city's social housing program, even with some criticisms, not only provides affordable housing but also integrates green spaces and public amenities, ensuring that regeneration efforts contribute to long-term social and environmental well-being. Also, The "Open Data Bristol"[113] initiative in the UK exemplifies how continuous access to urban data supports long-term innovation and problem-solving, fostering a dynamic and adaptive approach to urban regeneration.

Altogether, our perspective supports the concept that urban regeneration can and must rely on a cross-sectoral approach. The proposed framework, supported by real-world examples, demonstrates its feasibility and importance. "Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity".[114] We have the unique opportunity to build collaborative robust science, where theoretical and empirical advances will generate a sustainable human-nature relationship that reflect the intention to protect all the declensions of health, and that is not antithetical, but integrative. Indeed, humans are not detached from the rest of nature: they are instead a small part of the natural world with a disproportionate impact.

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AUTHOR CONTRIBUTIONS

Conceptualization: A.B. and M.L. Writing – Original Draft: "Urban biodiversity: the importance of a bigger picture": A.B. I.A., B.C., S.E., G.G., E.F., G.F.F., S.F., and N.T. "The Push Towards Biodiversity: Is it Always Good?": A.B., I.A., M.B., S.E., N.F., G.F.F., S.F., G.G., M.L., B.P., E.R.P., and N.R. "Psychological and Physiological Effects of Nature in Urban Ecosystems": M.B., L.M., and N.R. "The Importance of Planning and Designing Urban Ecosystem Rehabilitation": B.E.A.P. "A Conceptual Framework for a Shared Decision-Making Strategy": G.G., S.F., A.G., and M.L. Writing – Review and Editing: All authors. Visualization: G.G. designed and created all the figures, with significant input from I.A., S.E., and A.N., who contributed to the design of Figure 1, and B.P. and M.B. for Figure 2. Supervision and Funding acquisition: M.L. All authors approved the submission.

DECLARATION OF INTERESTS

M.B., B.P., and N.R. are inventors of exp-EIA© (experiential Environmental Impact Assessment) method (Patent 1: Italian Publication Number 102021000017168 - 30/06/2021; International Publication Number WO 2023/275679 A1 - 5.1.2023). M.B., L.M., B.P., and N.R. are inventors of exp-EIA© (experiential Environmental Impact Assessment) method (Patent 2: Italian Patent Publication filed Number 102024000011161 - 16.5.2024).

The other authors declare no competing interests.

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