Pharos Journal for Architecture and Planning
Vol. 1, No. 1, July, 2025, pp. 35-45
Journal homepage: https://www.pua.edu.eg/faculty-of-engineering/pharos-journal-for-architecture-and-planning-pjarchp/
PJARCHP
PHAROS JOURNAL For Architecture and Planning

The Role of Green Infrastructure in Providing Urban Ecosystem Services

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Received: 4 June 2025
Revised: 16 June 2025
Accepted: 1 July 2025
Available online: 20 July 2025

Keywords:
green infrastructure; urban ecosystems; ecosystem services; Urban Green Spaces; environment; Ecological Indicators.

ABSTRACT

Despite increasing urbanization, humanity still relies on the natural environment for its survival. This paper examines the vital environmental services provided by urban ecosystems, known as "ecosystem services," which significantly impact the quality of life for urban residents. Land-use planning must integrate these services by integrating natural processes into urban development strategies to address the increasing environmental challenges of urbanization.
Green infrastructure (GI) is essential for improving the functionality of urban ecosystems. It enhances a number of ecosystem services, including biodiversity enhancement, mitigating urban heat island effects, improving air quality, and managing stormwater. Through examples including urban forests, permeable pavements, green walls, and green roofs, this paper examines the various benefits of green infrastructure in urban environments. These components help local governments improve water quality, manage stormwater, and reduce flood risk. Furthermore, by reducing heat stress and storing carbon, green infrastructure helps regulate the climate and promote healthy living conditions.
By providing habitats for a variety of species, urban green spaces also enhance biodiversity and increase the resilience of ecosystems. Additionally, support mental health, foster social cohesion in urban communities, and offer vital recreational opportunities.
Cities are increasingly relying on green infrastructure as a sustainable urban planning approach to improve urban resilience, support ecological processes, and enhance the quality of life for residents. The strategic integration of environmental indicators becomes increasingly important as cities expand. Converting unused or abandoned urban areas, such as alleyways, into green infrastructure is becoming increasingly common as a means of increasing ecosystem service capacity.
As a case study, created and evaluated a methodology for assessing ecosystem service capacity available to practitioners and community members in Montreal, Canada, using a network of green alleyways, indicators were collected for four important ecosystem services—food provision, pollinator habitat, anthropogenic noise management, and air temperature regulation falong with information on vegetation cover and structural characteristics.
Vegetation cover may be a useful measure for determining ecosystem service capacity. However, there was little correlation between alley vegetation and indicators of temperature control and noise abatement. The complexity of urban ecosystems is highlighted by the lack of clear links between ecosystem services and explanatory factors, further underscoring the need for further research.
This paper lays the foundation for establishing ecosystem service capacity indices, essential tools for measuring the success of green infrastructure and promoting sustainable urban growth.

1. INTRODUCTION

In the twenty-first century, most people on the planet are expected to live in urban areas. This urban population growth will surely increase the demand for public services, infrastructure, and housing! Urban environments are under greater strain. These pressures are caused by several factors, including:

The ageing of the population.

a. The growing need for resource and energy efficiency.

b. The incorporation of intelligent materials and technologies into city infrastructure.

c. A change in the values of society. In response to these issues, various forms of urban management and development are likely to appear. Emotional states, general life satisfaction, and human health and well-being are all improved when ecosystem services are delivered efficiently. The advantages that natural systems offer to humans, such as recreation, food, water, and climate regulation, are referred to as ecosystem services. The elements of the natural environment that directly or indirectly benefit humans are considered natural capital. It encompasses freshwater, land, minerals, air, oceans, species, and ecosystems. "Green infrastructure" refers to natural elements that offer ecosystem services in urban settings. Features like green walls and roofs, street trees, ponds, canals, rivers, private gardens, and community allotments are examples of this. A strategically planned network of natural and semi-natural areas, along with other environmental features, that are created and maintained to offer a variety of ecosystem services is known as "green infrastructure" according to the European Union. In both terrestrial and marine environments, urban green infrastructure encompasses the ecological services provided by green spaces and blue spaces linked to aquatic ecosystems. As of right now, there is no strategic planning in place for using green infrastructure to deliver ecosystem services. Supporting urban green infrastructure has been suggested as a cost-effective way to address public health concerns, and research indicates that this type of infrastructure can offer additional ecological services in urban areas. Demand for some of these services may rise as a result of climate change. Ecological services are divided into four primary categories by the Millennium Ecosystem Assessment: provisioning services (like food), regulating services (like pollination), supporting services (like nutrient cycling), and cultural services (like recreation). According to the European Environment Agency's Common International Classification of Ecosystem Services (CICES), various habitat types offer distinct ecological services, and supporting services are crucial for preserving ecosystem functions. For instance, forests are essential for storing and sequestering carbon. High concentrations of impermeable surfaces, crowded populations, and high levels of air pollution and noise are characteristics of urban ecosystems. Which ecological services are most crucial, however, will depend on the unique environmental, social, and economic features of each city. The ecological services provided by urban green infrastructure are highlighted in this overview, along with the difficulties in improving these services [1].

2. Methodology

To examine how green infrastructure contributes to the provision of urban ecosystem services, this study combines two components: a preliminary study and a comprehensive case study, utilizing a range of tools.

1. Literature Review: To provide a useful empirical basis for the social and climate benefits of green infrastructure, a comprehensive literature review was conducted. The objective of this review was to list the various ecosystem services, such as food production, pollinator habitat provision, noise reduction, and air temperature, that depend on green infrastructure.

2. Case Study: Montreal's green alleys, Canada, were chosen as the central case study due to several factors that make them an ideal model for analyzing the role of green infrastructure in urban environments, including:

a. Easy access to data, good documentation, and ease of conducting detailed analysis.

b. The project offers a range of environmental services.

c. The project reflects a modern approach to urban planning by reimagining neglected small spaces to address environmental challenges and meet the needs of residents. The "Green Alleys" model offers a flexible and scalable solution for other cities facing similar urban and ecological challenges, By combining existing research with an in-depth case study, this paper aims to provide a comprehensive understanding of the green network as a vital component of urban ecosystems and to illustrate how small-scale, community-led projects, such as "Green Alleys," can deliver broad environmental and social benefits [2].

3. GREEN INFRASTRUCTURE

Green infrastructure plays a vital role in enhancing urban quality of life by providing essential ecosystem services, including air purification, temperature regulation, stormwater management, and biodiversity conservation. Many countries have integrated this concept into their urban planning strategies. In the **United States**, New York City launched the “Million Trees NYC” initiative to plant one million trees, aiming to expand green cover and mitigate climate change. In **China**, cities like **Shenzhen** have implemented vast urban parks and green roofs to combat pollution and improve air quality. **Stockholm**, **Sweden**, utilizes green infrastructure, including rain gardens and ecological corridors, to manage stormwater naturally and reduce stress on its sewage systems. In **the Netherlands**, **Rotterdam** is recognized for its “blue-green roofs,” which temporarily store rainwater and help mitigate flood risks. In **Australia**, **Melbourne** has adopted a green infrastructure plan that includes extensive tree planting and the creation of “cool corridors” to combat the urban heat island effect. Even in the **Arab world**, cities like **Abu Dhabi** and **Riyadh** have begun incorporating green infrastructure principles in urban development projects to enhance sustainability and reduce dependence on traditional grey infrastructure. These global examples illustrate the transformative potential of green infrastructure in creating resilient and sustainable cities [3] [4].

3.1. Definitions of Green Infrastructure (GI)

The definition of green infrastructure (GI) varies depending on the context and the field of study. Urban planners may focus on policy implementation, while ecologists and conservationists emphasize biodiversity and environmental health. Recreation and landscape experts may highlight the social and developmental benefits [5] [6] . A widely accepted definition describes GI as a network of interconnected green and open spaces—such as parks, forests, rivers, urban nature reserves, and tree-lined streets—that provide multiple functions [7] [8] :

- Support for biodiversity and ecosystems
- Climate regulation and environmental improvement
- Recreation and social interaction
- Enhanced urban livability and well-being

Modern definitions stress connectivity, multifunctionality, and the integration of ecological, social, and economic benefits. GI is now seen as essential for creating sustainable, resilient cities that respond to climate change, preserve natural habitats, and improve access to green spaces for all [9] [10].

3.2. Urban Green Space Strategies

The UK House of Commons Communities and Local Government Committee recommended that local authorities collaborate with health and wellness organizations to develop joint strategies for parks and green spaces. Despite the recognized importance of such spaces, only 48% of local authorities currently have green space strategies, a decline from 76% in 2014. New areas like Birmingham lack dedicated green infrastructure plans. In Scotland, local councils were instructed in 2011 to map urban green spaces, and in 2017, the government released an updated public Urban Green Space Map based on official classifications [11] [12]. The UK also supports the UN Sustainable Development Goals, aiming to ensure equitable access to safe, inclusive green spaces by 2030. However, only half of urban residents live within 300 meters of green areas, and there is significant inequality in the distribution; wealthier neighborhoods have five times more green space than the most deprived. Studies show that only a third of urban residents interact with nature in truly natural settings. Planning frameworks emphasize the need for up-to-date assessments of local recreational and open space needs. Internationally, cities like Berlin implement tools such as the “biotope area factor,” which mandates a minimum level of vegetation in developments, while Japan’s Urban Green Space Conservation Act allows local governments to designate private or public land as protected green areas, offering incentives to owners. Singapore developed the Urban Biodiversity Index to measure ecological performance. In the UK, most urban green spaces are privately managed, limiting local governments’ control and planning capacity. [13]. For example, 80% of Leicester’s green space is privately maintained, with 40% managed by households. Household landscaping decisions significantly impact green infrastructure, with trends like paving front gardens increasing strain on drainage systems. A notable model is Milton Keynes, where The Parks Trust—an independent, self-funded charity manages over 2,000 hectares of green space, including 80 miles of landscaped roadways, covering around 25% of the city in partnership with local authorities and developers [14] [15].

3.3. The principles of green infrastructure planning

The literature contains several conceptually sound green infrastructure planning criteria, the majority of which are grounded in geography, ecology, and the ecology of landscapes [5] , By integrating environmental, social, and economic considerations into the process of making decisions and implementing green spaces, these suggested principles seek to facilitate the planning and development of advantageous green infrastructure [6] The question of what green infrastructure planning principles are has remained since the term was coined in the 1990s, even though the literature has addressed a wide range of them. In an attempt to answer this query, Monteiro and associates assert that "the fundamental principles that help guide and facilitate green infrastructure planning processes, to ensure that contribute to a network of superior and beneficial green spaces, capable of meeting the requirements of a given urban area, and contributing in the best way to the sustainability of a given area or local area, depending on its size" This definition gives practitioners and decision-makers a foundation for comprehending and choosing how to develop and manage landscapes by emphasising the promotion of sustainability as an integrated approach to green infrastructure planning. A set of guidelines for designing green infrastructure has been put forth by academics. Hansen and associates suggested four fundamental ideas: ecological and functional multiplicity [Table 1]. As part of the Green Surge project, green infrastructure planning should incorporate social inclusion, network and interconnectedness, and green-grey integration. [3]. Also offered other suggestions, such as the significance of scale, evidence-based strategy, and long-term approach, to name a few. Coordination, functional multiplicity, interconnectedness, multi-scale planning, diversity, and identity are the six design principles for green infrastructure that Gradinaru and Hersberger identified [6] .

Table 1. Components of the GI Network and Their Associated Characteristics**, [7].**

Component	Description Of Attributes	Corridors Component	Description Of Attributes
Reserves	Large protected areas, including national parks.	Landscape Linkages	Large protected natural areas that link parks or reserves, providing ample space for native plants and animals.
Managed Native Landscapes	Large publicly owned lands, such as national forests, are managed for the purpose of resource extraction.	Conservation Corridors	The groom's lining is not half as impressive as Susa AS River in Stream Criders.
Working Lands	Private farms, forests, and pastures are managed to produce various goods and commodities..	Greenways	Designated areas of land that are managed to conserve natural resources or provide recreational opportunities.
Regional Parks and Preserves	Less extensive hubs that are ecologically significant on a regional scale..	Greenbelts	Protected natural areas provide a foundation for development while safeguarding native ecosystems.
Community Parks and Natural Areas	Local parks and other community-based locations.	Eco-belts	Linear timber barriers can help reduce the conflict between urban and rural land uses while offering environmental and social benefits.

3.4. GI Networks

By linking existing green resources, geographic regions enhance connectivity and ecological value. These interconnected networks—including wetlands, forests, parks, greenways, wildlife habitats, and other open spaces—form the nation’s natural life support system that helps sustain native species, protect essential ecological processes, safeguard air and water quality, and improve both community health and quality of life. Large-scale ecological networks, known as georegions, consist of lakes, natural vegetation, and areas of known or potential biological significance. Rooted in over a century of planning and conservation theory, this concept is based on two key principles:

a) connecting parks and green spaces for public use and benefit, and

b) preserving and linking natural habitats to reduce fragmentation and support biodiversity.

When the core elements—ecological hubs and connecting links—are proactively identified, planned, and protected before development, the entire geographic network can guide land use decisions in favor of long-term conservation. This is especially important in urban environments where green space has been heavily altered or diminished by development [16].

4. Global Perspectives

The idea of ecosystem services, which can be used at both local and global scales, is essential to comprehending GIs. The benefits that people obtain from the conversion of natural resources, sometimes referred to as environmental assets, into necessities like food, clean water, and air are referred to as ecosystem services. The idea of ecosystem services has progressively changed over the last century to emphasise how reliant human societies are on systems found in nature [8].

"The conditions and processes by which natural ecosystems and the species that comprise human life support and sustain them" is the definition of ecosystem services. Growing awareness of the benefits that healthy ecosystems offer to both humans and other living forms emerged in the 1990s. Prominent academics like Ehrlich, Daily, Kennedy, Mattson, and Costanza contributed to this awareness [9][Fig. 1].

Over the past 50 years, environmentalists, economists, and social scientists have been debating the social and economic factors that contribute to the deterioration of ecosystems. A comprehensive study known as the Millennium Ecosystem Assessment was carried out by an international consortium of governments, non-profits, universities, and corporations in response to a request from the UN. The idea of ecosystem services, which can be used at both local and global scales, is essential to comprehending GIs. The benefits that people obtain from the conversion of natural resources, sometimes referred to as environmental assets, into necessities like food, clean water, and air are referred to as ecosystem services. The idea of ecosystem services has progressively changed over the last century to emphasise how reliant human societies are on systems found in nature ."The conditions and processes by which natural ecosystems and the species that comprise human life support and sustain them" is the definition of ecosystem services. Growing awareness of the benefits that healthy ecosystems offer to both humans and other living forms emerged in the 1990s. Prominent academics like Ehrlich, Daily, Kennedy, Mattson, and Costanza contributed to this awareness. Over the past 50 years, environmentalists, economists, and social scientists have been debating the social and economic factors that contribute to the deterioration of ecosystems. A comprehensive study known as the Millennium Ecosystem Assessment was carried out by an international consortium of governments, non-profits, universities, and corporations in response to a request from the UN [13].

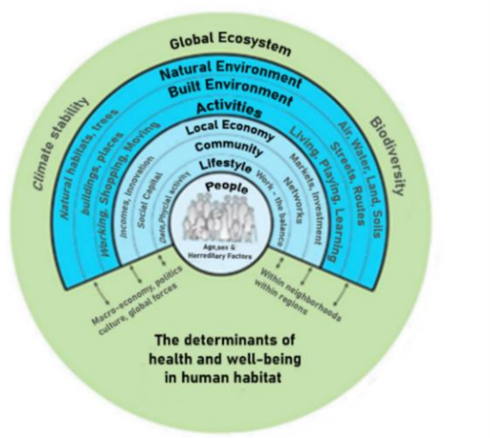

Fig.1. An Ecological Model of Health **, [16].**

4.1. Green Infrastructure and Ecosystem Services

Green infrastructure refers to an interconnected network of natural and semi-natural elements that provide vital ecological and societal benefits. This includes features such as forests, parks (both local and national), wetlands, greenways, green roofs, street trees, and preserved landscape areas—collectively known as "green spaces." These elements may occupy limited urban space but offer significant environmental and public health benefits.

At its core, green infrastructure focuses on the symbiotic relationship between people and nature. While it emphasizes the services and well-being derived by humans, it also reinforces the environmental value of preserving natural systems. Green infrastructure functions as a “natural life support system,” offering combined environmental, social, and economic benefits that are essential for sustainable urban living [3] **[Fig. 2].**

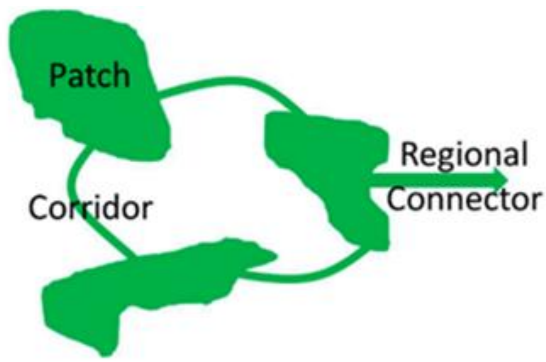

Fig.2. eco-friendly infrastructure**, [3].**

The green infrastructure matrix consists of interconnected ecological patches and corridors that ideally link to larger regional or national networks. This forms the ecological backbone of urban and peri-urban areas, essential for:

Maintaining ecosystem functions, supporting biodiversity,

And ensuring the sustainability of built environments.

Green infrastructure supports a wide array of ecosystem services, categorized into four main types:

Provisioning services: Supplying food, freshwater, and other resources.

Regulating services: Controlling climate, air quality, water purification, carbon sequestration, flood mitigation, and disease regulation.

Cultural services: Providing recreational, aesthetic, educational, and spiritual value.

Supporting services: Enabling vital natural cycles such as pollination, nutrient cycling, and soil formation, which underpin all other services [17].
In addition to these ecological services, green infrastructure delivers significant health benefits:
Presence-based benefits (e.g., reducing urban heat islands and improving air quality), Accessibility-based benefits (e.g., encouraging physical activity and community cohesion), Exposure-based benefits (e.g., reducing stress and enhancing mental health through contact with nature)

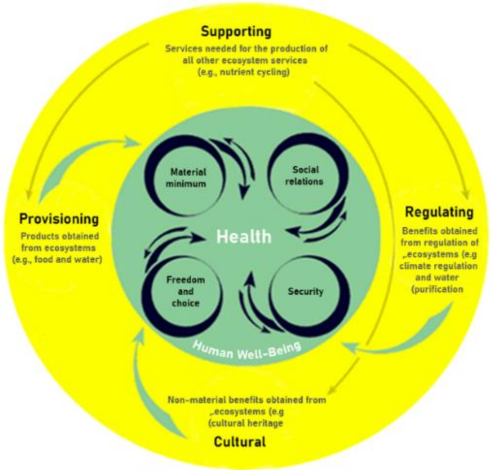

Fig.3. Ecosystem Services and Human Health, **[16].**

Global Examples of Cities Implementing Green Infrastructure
Singapore: A global leader in urban greening, Singapore's “City in a Garden” policy integrates green roofs, sky gardens, and park connectors throughout the city to improve biodiversity, reduce urban heat, and support citizen well-being [18].

Copenhagen, Denmark: Incorporates green infrastructure in its climate adaptation strategy, using green roofs, permeable pavements, and blue-green corridors to manage stormwater and enhance urban livability [8].

Portland, USA: Utilizes green streets, bioswales, and urban tree canopy programs to manage runoff, improve water quality, and increase green space accessibility in dense neighborhoods [19].

Rotterdam, Netherlands: Implements multifunctional green infrastructure such as "water squares" that combine public recreation with stormwater storage, adapting to rising rainfall from climate change [18].

Melbourne, Australia: Developed an “Urban Forest Strategy” that aims to increase canopy cover, reduce temperatures, and improve air quality as part of a broader climate resilience initiative [18].

Green infrastructure is not merely an environmental concept but a strategic planning tool essential for the future of urban life. It delivers key ecosystem services, improves human health, supports biodiversity, and strengthens cities' resilience to climate and environmental challenges. Integrating green infrastructure into urban planning ensures sustainable, livable, and healthier cities for generations to come [20].

4.2. Ecosystem Services

This method makes use of ecosystem services and natural cycles to assess urban infrastructure globally. [8]. By preserving, re-establishing, and improving these natural cycles, communities can gain local benefits. The evolution of concepts related to urban ecology and sustainable development has long been intimately associated with this viewpoint. Urban infrastructure in urban areas can provide a variety of advantages, including enjoyment, biodiversity, cultural identity, environmental quality, and biological solutions to technological problems [12].Any natural, semi-natural, and man-made networks of multipurpose ecosystems that are found inside, outside, and between urban areas can also be referred to as urban infrastructure [15]It's crucial to keep in mind that, in contrast to conventional single-purpose engineering infrastructure, urban infrastructure can produce numerous advantages from the priceless urban space it takes up [18].

a. Water

Green infrastructure is also essential for water quantity because of its ability to control runoff amounts and support groundwater recharge. By filtering pollutants that fall with rain and those that build up in runoff, green infrastructure improves water quality. Trees in particular, which allow water to enter the soil, store it there, and then release it back into the atmosphere through transpiration, are essential to the hydrological cycle [Fig. 4]. Water is taken from the soil and released into the atmosphere by plants through a process called transpiration, or "respiration". Green infrastructure is also essential for water quantity because of its ability to control runoff amounts and support groundwater recharge. By filtering pollutants that fall with rain and those that build up in runoff, green infrastructure improves water quality. Trees in particular, which allow water to enter the soil, store it there, and then release it back into the atmosphere through transpiration, are essential to the hydrological cycle. Water is taken from the soil and released into the atmosphere by plants through a process called transpiration, or "respiration" [19].

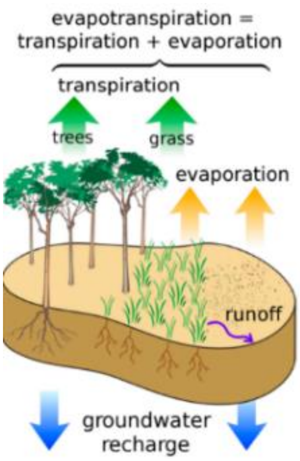

Fig.4. Evapotranspiration, **[1].**

b. Food

Three ecological processes, of which the digestive system is an essential component, are necessary for food production. Primary production, pollination, and nutrient cycling are these processes. As photosynthetic organisms grow and reproduce, "the synthesis and storage of organic molecules" is known as primary production. About 25% to 15% of the energy that all plants on Earth gather is used by humans [21] [22] Using photosynthesis, autotrophs consume every other living thing on the planet; humans can only get energy by consuming other living things. Another ecological service that is necessary for food production is pollination; green infrastructure also offers habitats for biological control agents that feed on agricultural pests [16].

c. Medicine

At least half of all prescription drugs in the US are either directly or indirectly derived from natural sources, and "thirty percent of drugs sold worldwide contain compounds derived from plant materials." The body of research on the benefits of bioactive chemicals for health has exploded. Polyphenols, the most common antioxidants in the human diet, protect against degenerative diseases like cancer and heart disease. Phytoestrogens, primarily found in soybeans, have been associated with a decreased risk of osteoporosis, breast cancer, heart disease, and menopausal symptoms [15].

d. Air

Airborne gaseous and particulate pollutants can be absorbed by some plant species, especially trees [15][16]. One of the three methods by which gases are drawn from the atmosphere is by absorption by plant surfaces through stomata. Particulate debris is eliminated by deposition on leaves and other plant surfaces. Chemical adsorption or adhesion upon impact holds particulate matter in place on these surfaces [18]. Trees remove tonnes of air pollution annually. In the southern U.S. cities of Atlanta and Houston, which have comparable tree cover, the amount of particulate matter removed by trees was 3.2 and 4.7 tonnes per square mile, respectively [8]. It is challenging to connect trees' intrinsic worth to observable health advantages. According to a recent study that focused on health benefits, trees and forests prevented $6.8 billion worth of acute respiratory illnesses and human deaths in the US in 2010 as a result of their ability to capture air pollutants [15].

4.3. Infectious Disease Modulation

The goal of the quickly developing field of infectious disease ecology is to comprehend how pathogens, hosts, vectors, and their environments interact and change over time to affect the spread of disease. Green infrastructure (GI) and the landscape are becoming more widely acknowledged as important obstacles or pathways for the spread and amplification of disease in populations of people, domestic animals, and wildlife. The effects of green infrastructure modifications are

Part of a dynamic process that involves feedback loops and cascading effects of ecosystem disturbances, which may not become apparent for years, according to researchers in disease ecology and related fields. The different ways that patterns of green infrastructure can affect the spread of infectious diseases have been demonstrated by numerous studies in these fields. For example, by giving vector and zoonotic reservoir populations appropriate habitat, green infrastructure can have a direct impact on disease risk. Altering an ecosystem's biodiversity in ways that either restrict or promote the spread of pathogens among reservoir communities could have more indirect effects :

1. Zoonotic Disease: Zoonotic diseases are caused by animal pathogens that have infected humans, accounting for about two-thirds of all human infections. The term used to characterise the long-term host of pathogens is the reservoir of disease. Changes in the landscape can affect the frequency and closeness of human-zoonotic disease reservoir interactions and the spread of pathogen transmission between species, according to studies from a range of ecological contexts. Hunters can effectively introduce new zoonotic infectious agents into human populations through the close contact of blood and bodily fluids [14].

2. Vector-Borne Disease: Humans can contract vector-borne diseases from arthropods like fleas, ticks, mosquitoes, and other bloodsucking insects. In the past decade, approximately 30% of newly identified infections have been vector-borne, and this proportion has increased since the 1940s. Changes in the landscape can have a significant effect on vector survival, biting frequency, and larval development rates by influencing local climates and vector breeding sites [23].

4.4. Climate Regulation

Experts believe that as climate parameters change, the severity of health issues will change in all countries and places, possibly in unexpected ways. Ongoing climate change will also affect the digestive system and the environmental services that promote health. The digestive system is once again playing a critical role in improving human well-being, as evidenced by our expanding understanding of how climate change is affecting and will continue to affect global health. [24]. Green infrastructure is essential for both mitigating the effects of climate change and preparing for its aftermath. Human-induced landscape changes must be considered when assessing how climate change may affect health [8] [Table 2].

Table 2: The Health Effects of Climate Change**, [2].**

Climatic Event	Intermediary	Health Outcome
Heat waves	direct to → Increased ground-level ozone, pollen	Heat stress and heat stroke can exacerbate respiratory diseases.
Increased mean temperature	direct to → More hospitable to disease vectors (e.g., mosquitoes, ticks) More hospitable to infectious disease agents (e.g., bacteria)	Reduced risk of hypothermia and increased prevalence of vector-borne diseases (e.g., Lyme disease, malaria, dengue) and foodborne illnesses such as cholera.)
Ozone depletion	UV radiation	Skin and eye maladies
Drought	Water/food shortage Lack of water safety	Dehydration, malnutrition Water-borne disease
Extreme weather events (e.g., flooding, tornado, hurricane)	direct to → Population movement Lack of food/water safety	Injuries, drowning Conflicts Water-borne disease, malnutrition
Sea-level rise	direct to → Population movement Water/soil salinization	Injuries, drowning Conflicts Dehydration, malnutrition
Climate change generally	Stress	Mental health

5. Royal Verts Program

Montreal's Ruelles Vertes (Green Alleys) are vegetated alleyways primarily located in densely populated areas of the city. Initiated in 1995, the program was a response to growing concerns about urban sustainability challenges, such as the urban heat island effect and declining social cohesion. Many of the city's alleys were neglected and underutilized, presenting an opportunity to convert them into green infrastructure that promotes environmental benefits and fosters community engagement. The Ruelles Vertes Program is considered an exemplary case for evaluating how vegetation influences ecosystem service capacity in urban settings, due to its longevity and widespread implementation. This study focused on Ruelles Vertes in the Rosemont–La Petite-Patrie borough (Fig. 5), while accounting for influencing variables such as municipal funding, which can significantly affect green infrastructure performance. As of March 2021, Rosemont–La Petite-Patrie hosted 130 Ruelles Vertes, comprising 29% of all such alleys in Montreal. Spatial data on alley locations within the study area were provided by the City of Montreal (2019) [25].

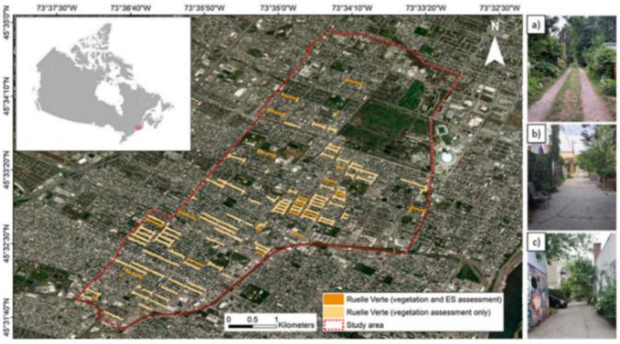

Fig.5. Map showing the locations of the assessed green alleys in the Rosemont-La Petite-Patrie borough of Montreal, Canada, **[25].**

5.1. Explanatory variables

a. Vegetation and structural variables within alleys

Using a rapid assessment method, vegetation factor data were collected for each 130 green alleys in the study area. At three equally spaced points in each alley, the percentage of ground cover, the middle layer/shrub, and the tree cover were calculated (Table 3). These three vegetation variables were chosen because previous studies have demonstrated links between them and the four relevant ecosystem services (Cameron and Planosa, 2016). The average of the three assessment points for each alley and the values of the different criteria were summed to obtain an overall greenness score for each alley. Next, to conduct a more comprehensive assessment, we selected 24 alleys with a range of vegetation, divided all 130 alleys into eight equal levels based on greenness scores, and selected three alleys from each layer. When a layer contained more than three alleys, three alleys with different dominant vegetation were selected, and the structural form variables were then combined into the alley subset. The area of each alley was measured because it may affect the type of vegetation [25].

b. Surrounding land cover

To ascertain whether the surrounding landscape or the alleys themselves have a greater impact on ecosystem service capacity, the proportion of different land cover types surrounding alleys was used as an explanatory variable. This study helped validate the importance of alley features as indicators of ecosystem service capacity. Three land cover variables were chosen for the study because previous studies have demonstrated links between these variables and cityscape-scale urban ecosystem services. Land cover metrics were calculated at 50 circular buffer zones around each alley to calculate the percentage of each land cover variable inside each zone [15].

Table 3. The following is a list of the explanatory variables assessed in this study, **[25].**

Variable Category	Variable	Definition	Indicator(s)	Data Sources	Number of Alleys Data Collected Within	Number of Sampling Points in Alley
Vegetation within the alley	Canopy cover	Vegetative cover > 3 m in height within a 5 m² area around the sampling points in each alley	% canopy cover	Field data	130	3
	Shrub/midstory cover	Vegetative cover within 0.3–3 m in height was measured for a 5 m² area around the sampling points in each alley	% shrub and midstory cover		130	3
	Ground cover	Vegetative cover with < 0.3 m height measured within a 5 m² area around the sampling points in each alley	% vegetative ground cover		130	3
Structural form of an alley Surrounding land cover	Area of Alley	The total area of the alley	Metres²	Field data	24	
	Canopy cover buffer	The proportion of canopy cover (vegetation > 3 m high) within a 50 m buffer of the alley	% Canopy cover within 50 m of the alley	Communauté métropolitaine de Montréal (2019)	24	
	Vegetation cover buffer	The proportion of vegetation cover (< 3 m in height) within a 50 m buffer of the alley	% Vegetation cover within 50 m of the alley		24	
	Density of main roads buffer	Length of main roads within a 50 m buffer of the alley. Main roads are classified as "Freeway", "Expressway/highway", or "Arterial" in the Canadian National Road Dataset (GC 2022)	Length (m) of main roads within 50 m of the alley	GC (2022)	24	

5.2. Ecosystem service assessments

Indicators of ecosystem service capacity for each of the four services were measured for the subset of 24 alleys in the field between August and September 2021.

a. Air temperature regulation

Every day, note the lowest and highest temperatures that were recorded in each alley. With the use of these data, were able to determine whether vegetation cover and other alley characteristics were associated with temperature differences among the alleys that were the subject of the study, indicating the ability to regulate air temperature placed an Acurite radiation shield with a passive temperature sensor (Kestral DROP D2 sensor) in each alley over two weeks, taking readings every ten minutes. The temperature sensors were positioned in the middle of each lane, under the tree canopy, and at a height of roughly 1.5 metres above the ground calculated the day's maximum air temperature, which was between 12:00 and 18:00, as well as the average air temperature [25]**.**

b. Anthropogenic noise regulation

In order to determine whether alley characteristics were linked to differences in anthropogenic noise across alleys, in study collected acoustic data on each alley. This data suggests that anthropogenic noise could be controlled in each alley over two weeks. A temperature sensor and a passive acoustic monitor (Audio Moth) were installed. The audio monitor recorded sound waves every five minutes at one-minute intervals, extracted acoustic data for three time periods over seven days: morning (7:00–9:00), afternoon (12:00–14:00), and evening (17:00–19:00), per SensuLiu et al. (2013). Anthropogenic noise regulation is most necessary during these periods (Liu et al. 2013). Based on these data computed the Naturally Variable Soundscape Index (NDSI) was computed using the R statistical software's Seewave package [26].

c. Habitat provision for pollinators

Each alley's floral cover was evaluated as a gauge of the pollinators' capacity to find food there, excluded plants that bloom in spring and early summer because late blooming is most prevalent in Montreal during this time of year, Following a walk down the centre of each alley used a modified Lowenstein and Minor (2016) method to measure flower abundance at 5-meter intervals. One-meter squares were planted on either side of each 5-meter point on the alley fence, which was the area with the highest concentration of plants. All currently blooming plants in each square were photographed, geotagged, and identified using the iNaturalist app, down to the lowest taxonomic level, typically species [26].

d. Food provision

One indicator of adequate provision was the number of food-producing plants in each alley. The total above-ground coverage of the plant was measured after those was identified. The purpose of the field visit was to measure the coverage (m2) of plants that produced food [26].

5.3. Data analysis

As indicated in Table 3, we used general linear models to test the relationships between explanatory factors and ecosystem service capacity in alleys. Explanatory variables within the alley were included in one model, and buffer variables associated with land cover were included in another (Table 4). The study's sample size was small (n = 24), so it constructed distinct models for each ecosystem service, each with a different set of explanatory variables. Models for temperature regulation services and human noise regulation were run. The models were scaled and centred before any variables were added. After the models were fitted, we used residual plots to verify that the residuals met the assumptions of variance, independence, and normal distribution [23].

5.4. Analysis of Study Results: The Relationship Between Vegetation Cover and Ecosystem Services.

a. Providing Habitat for Pollinators:

- Researchers discovered a clear positive relationship between the amount of ground vegetation (i.e., vegetation close to the ground) in alleys and the alleys' ability to support bees and other pollinating insects.
- This indicates that a higher proportion of ground vegetation leads to a greater number of flowers available, which in turn supports the lives of these environmentally significant insects.
- This relationship was statistically significant (p-value = 0.01), confirming that the observed effect is not a coincidence. The explanatory model accounted for approximately 44% of the variation in the ability of alleys to support insects ($R^2$0.44).`This graph (Fig.6) shows a direct relationship between the percentage of trees, the National Noise Index (NDSI) value (which represents a classification of anthropogenic noise), and the increased sound level. This supports the study's findings, which partially demonstrated that vegetation positively impacts the acoustic quality of green alleys.

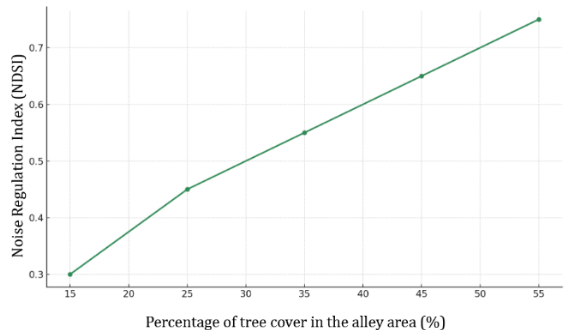

Fig.6. The updated graph shows the relationship between the percentage of tree cover in the alley's vicinity (within 50 meters) and the Noise Regulation Index (NDSI), **auther.**

b. Regulating Anthropogenic Noise:

- The Natural-Derived Sound Index (NDSI), which reflects the ratio of natural noise to anthropogenic noise, was measured.
- The results showed that noise levels decreased in alleys surrounded by large areas of vegetation, particularly trees, within a 50-meter radius.
- The presence of trees and dense vegetation around alleys significantly contributes to reducing noise nuisance.
- This correlation was highly statistically significant (p = 0.007 and p = 0.002), with the model explaining approximately 64% of the variation in noise levels (R^2 = 0.64).

This graph [Fig.7] shows a clear, direct relationship between increased ground cover and increased pollinator species. This suggests that enhancing urban vegetation can improve pollinator diversity.

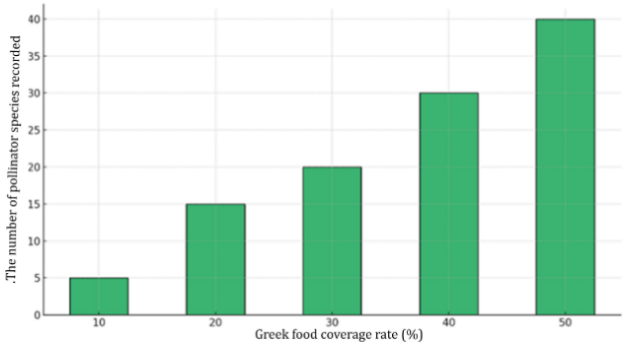

Fig.7 : The graph shows the effect of the percentage of ground cover on the number of pollinator species in green alleys. **Author.**

c. Other Ecosystem Services (Temperature Regulation and Food Provision):

- The study did not find strong, statistically significant relationships between the characteristics of plants within alleys and their ability to regulate temperature or provide food.

- This suggests that other factors, such as weather conditions or characteristics of the surrounding area, may have a greater impact on these ecosystem services.

5.5. Summary of differences and developments during the study:

• Field confirmation: Data gathered through actual measurements confirmed a strong correlation between vegetation cover (especially ground cover) and the availability of habitat for bees, as well as the role of adjacent vegetation in reducing noise.

• Unclear relationships: Contrary to expectations, no clear relationship was established between vegetation cover in alleys and temperature regulation or food provision, which may be attributed to other influencing factors or the study's limited duration.

• Evolving understanding: Throughout the study, it became clear that the extent and effect of vegetation surrounding alleys might play a more significant role in certain environmental services (such as noise reduction) than the vegetation found within the alleys themselves.

A comparison of the observations and data collected during the study with the final results revealed notable correlations between vegetation density in Ruelles Vertes and their capacity to deliver ecosystem services. Initial observations indicated that alleys with more extensive plant cover and community involvement tended to show better environmental performance, such as reduced surface temperatures and improved air quality. Spatial data provided by the City of Montreal, combined with field assessments, confirmed these trends. The final results supported these preliminary findings by demonstrating that green alleys with higher levels of vegetation significantly enhanced local biodiversity, improved stormwater absorption, and promoted social interactions among residents. Additionally, areas receiving consistent municipal support and funding displayed more sustained ecological benefits. This alignment between early observations and outcomes underscores the effectiveness of the Ruelles Vertes program as a model for urban green infrastructure, particularly when supported by policy and community engagement [Table 4].

Table 4. Analysis of Observational Data in Light of Study Outcomes, **Outher**

side	Notes and data during the study	Final results	interpretation or understanding
Vegetation cover assessment within alleys	Using data on the proportion of ground vegetation, shrubs, and canopy trees in 130 alleys, an average was determined for each alley. Twenty-four diverse alleys were chosen based on their greenness scores.	An increase in insect habitats is associated with a rise in ground plants in alleys.	In addition to increasing food availability, plant resistance enhances habitats for pollinators and insects.
Temperature recording	Throughout the study, temperature sensors were positioned to record the alleys' highest and lowest temperatures; readings were taken every ten minutes.	It was found that the vegetation characteristics in clear alleys did not affect temperature modulation.	Time or other variables might be better regulated by temperature.
Noise Score (NDSI)	Using audio recording equipment, noise levels were recorded during peak hours (morning, afternoon, and evening) over two weeks.	Within a 50-meter radius, alleys with dense vegetation and trees on either side had lower noise levels.	Vegetation attracts human mice by acting as an effective sound barrier.
Evaluation of bee habitat provision	In the alleys, flowers were identified with the iNaturalist app, counted, and photographed.	The solution was able to create suitable habitats due to the strong connections between the local plant covers.	Pollinating insects and biodiversity are supported when flowering plants proliferate.
Food Provision Assessment (Edible Plants)	The area of plants that produce food at a given time is evaluated.	has failed to create a connection between the alley vegetation and the supply	A successful service may require food modifications or other effects.

6. The results of the study can be applied practically to urban planning by:

1. Improving ground cover in alleyways

• Municipalities should be encouraged to plant more ground cover plants and wildflowers in green alleyways, as play a role in improving pollinator habitats.

• The planting of native species that provide food and habitat for beneficial insects, such as bees and butterflies, can be supported through local community initiatives.

• In both parks and urban farms, this will increase biodiversity and enhance pollination.

2. Preserving or planting trees surrounding alleyways

• Mature trees and plants surrounding alleyways play a crucial role in mitigating noise disturbances from traffic and human activities.

• Therefore, urban planning should focus on increasing green spaces and tree cover in areas surrounding alleyways and residential neighborhoods.

• Vegetated buffer zones can be created between busy roads and residential areas to reduce noise and improve the quality of life for residents.

3. Integrating Green Alley Planning into Urban Policies

• Repurposing abandoned alleys as green spaces through initiatives such as Royal Verts can benefit the environment and society in many ways.

• These programs help achieve sustainability goals, reduce the impact of the "urban heat island" phenomenon, and strengthen relationships between residents.

4. The Need for Further Studies and Uses

• A more comprehensive assessment or study of other factors (such as soil quality, urban design, and climatic conditions) may be necessary, although the study did not conclusively prove that plants affect regulating temperature within alleys.

• To determine how green alleys can improve the efficiency of climate control and food provision, further research is needed.

7. Discussion

Even though several studies have looked at the ecosystem service capacity of more conventional types of urban green infrastructure, like parks and urban forests, it is still necessary to develop appropriate techniques for evaluating and implementing the ecosystem services offered by various forms of green infrastructure in light of the growing demand for ecosystem services in urban areas .he availability of pollinator habitats was not substantially correlated with alley vegetation. However, there was a strong correlation between temperature, anthropogenic noise, and the surrounding vegetation. These findings imply that the study's rapid assessment approach might not be entirely effective in identifying correlations between corridor attributes and ecosystem service capacity. Nonetheless, findings may help shape future methods for evaluating ecosystem services in green alleys. Ground-cover plants were essential for pollinator habitat in green alleys because their species have higher floral coverage. Mattison et al found that flowering species increased when decisions were made to plant in adjacent blocks. Also found that herbaceous plants and floral resources for pollinators were positively correlated. The results of this study supported our hypothesis that ground cover can serve as a clear and useful indicator of whether green alleys are likely to support pollinator habitat. Green alleys vary in width and proximity to multi-story residential buildings and private backyards. These factors can affect alley air temperature and anthropogenic noise because of their effects on exposure, sound insulation, appearance, and shading. Liu et al also found that rustling trees in the surrounding landscape may affect soundscapes, supporting the relationship between the noise control index and canopy cover within a 50-m buffer zone. Green alleys were contrasted with nearby "non-green" alleys to account for shifts in ecosystem services from baseline conditions and to examine the effects of elements inside the alley versus surrounding land cover. Further data collection on the four ecosystem services is also required.

8. Conclusion

The study's findings validate how important green infrastructure is for improving ecosystem services in cities. In its many forms, green infrastructure has proven to be effective in reducing the heat island effect, controlling stormwater, improving air quality, and creating recreational areas that all help to improve urban life. These results highlight the necessity of methodically incorporating green infrastructure into sustainable development plans and urban policies, with an emphasis on improving stakeholder collaboration and community involvement. Thus, green infrastructure can help create cities that are more resilient and sustainable in the face of rapid urbanisation and climate change.

However, the study faced limitations such as variations in local implementation, lack of long-term data, and limited access to private green spaces, which may affect the generalizability of the findings. Future research should prioritize longitudinal studies that assess the long-term effects of green infrastructure interventions and explore innovative methods for integrating green solutions into privately owned urban areas. Additionally, practical applications should focus on participatory design approaches, ensuring that communities are actively involved in planning and maintaining green spaces to maximize both environmental and social benefits.

9. Recommendations

1. Integrate green infrastructure into urban planning frameworks. Urban development policies should explicitly integrate green infrastructure as a core component, ensuring it is not merely an afterthought but rather a fundamental element of sustainable urban growth.
2. Promote cross-sectoral collaboration. Effective implementation requires coordinated efforts among local authorities, urban planners, environmental organizations, private sector stakeholders, and local communities. Encouraging cross-departmental collaboration will enhance the multifunctionality of green infrastructure.
3. Prioritize the equitable distribution of green spaces. Future strategies should focus on addressing disparities in access to green spaces, particularly in low-income and marginalized neighborhoods, to ensure social and environmental justice.
4. Encourage community participation. Involving residents in the planning, design, and maintenance of green spaces (as in Montreal's Rueil Vert) promotes social cohesion, a sense of ownership, and long-term sustainability.
5. Promote private sector participation and provide incentives. Governments should explore incentive programs, such as tax breaks or subsidies, to encourage the private sector and homeowners to contribute to the development of green infrastructure (such as green roofs, parks, and permeable pavements).
6. Invest in monitoring and longitudinal research. Establish monitoring systems to assess the long-term environmental, social, and economic impacts of green infrastructure. Longitudinal studies will provide deeper insights into effectiveness and inform evidence-based decision-making.
7. Adopt climate-resilient and climate-responsive designs. Green infrastructure should be designed to respond dynamically to the impacts of climate change, including increased precipitation, higher temperatures, and biodiversity loss.
8. Promote public awareness and environmental education. Educating the public about the benefits of green infrastructure will foster supportive attitudes and behaviors that encourage the use, care, and protection of these spaces.

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