GREEN INFRASTRUCTURE
Concept and application












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1. INTRODUCTION

In the face of rapid urbanization, accelerating climate change, and increasing pressure on natural resources, cities and regions are compelled to redefine the ways in which space is planned, designed, and managed. One of the key approaches addressing these challenges is the concept of green infrastructure, widely recognized in literature as an essential framework for shaping sustainable and resilient landscapes (Al Faraby et al., 2004; Ying et al., 2022).
Green infrastructure refers to a network of interconnected green spaces and natural or semi-natural ecosystems that collectively sustain the ecological, social, and economic functions of a region. As an integrated planning tool, it bridges environmental protection and spatial development, forming the foundation of adaptive and regenerative landscapes.

In contrast to gray infrastructure, which relies predominantly on technical solutions and intensive environmental modification, green infrastructure emphasizes the complementarity of natural elements (green and blue spaces) and environmentally sensitive design strategies (Al Faraby et al., 2004).
Its primary objective is to develop a sustainable spatial system capable of responding to climate change, urban development pressures, and socio-economic transformations, while maintaining environmental quality and enhancing human well-being through the provision of ecosystem services (Ying et al., 2022).

The benefits of green infrastructure extend across ecological, social, and economic dimensions. From an environmental perspective, Nature-based Solutions such as rain gardens, bioswales, and urban green networks enhance stormwater retention, reduce flood risk, improve air quality, mitigate the urban heat island effect, and support biodiversity (Wang et al., 2024; Kim & Kim, 2025). Socially and economically, green infrastructure contributes to the creation of healthy public spaces, improves living comfort, and can strengthen food security through practices such as urban agriculture and other ecosystem service-based initiatives within cities (Al Faraby et al., 2024; Fauzia et al., 2024). In this way, it serves not only as a tool for environmental protection but also as a driver of community well-being and socio-economic development (Ying et al., 2022).

Although the implementation of green infrastructure involves certain constraints such as spatial requirements, maintenance costs, and the time needed to achieve full functionality, particularly in densely built environments (Al Faraby et al., 2004) its long-term ecological and social advantages make it a strategic response to urbanization, environmental degradation, and climate change (Ying et al., 2022; Kim & Kim, 2025).

This book, “Green infrastructure. Concept and application”, addresses both the theoretical foundations and the practical dimensions of this approach. The opening chapters outline the origins of the green infrastructure concept and the key ideas that shaped its development. Subsequent sections present diverse interpretative perspectives, implementation frameworks, and discussions of its broader significance for sustainable development, environmental resilience, and societal well-being.

A central component of this volume is the examination of how green infrastructure is shaped across different spatial scales and environmental contexts, including various climatic zones and the specific challenges associated with its development in each of them. The book also includes case studies that demonstrate how theoretical principles are translated into planning and design practice.

This publication has been prepared primarily for landscape architecture students, but it may also be used by students of other disciplines whose study programs include topics related to the design and planning of green infrastructure, such as urban planning, architecture, environmental engineering, environmental protection, horticulture, forestry, and civil engineering.

By combining conceptual reflection with practical applications, it aims to foster critical understanding and solution-oriented design thinking. The book seeks to equip readers with the knowledge necessary to interpret the complexity of green infrastructure and to translate it into implementation strategies that respond creatively to contemporary challenges such as climate change, urbanization, and biodiversity loss. In doing so, it aspires not only to expand academic knowledge but also to inspire responsible, innovative, and context-sensitive approaches to shaping more sustainable and resilient landscapes.

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2. GREEN INFRASTRUCTURE: HISTORICAL FOUNDATIONS AND CONTEMPORARY APPROACHES

What is this chapter about:
This chapter examines the concept of green infrastructure (GI) and its development into a key paradigm in spatial planning, environmental governance, and sustainable urban development. It outlines how GI moves beyond traditional conservation models based on isolated protected areas and instead conceptualizes natural and semi-natural systems as interconnected, multifunctional networks that provide ecosystem services, support biodiversity, enhance human well-being, and strengthen territorial resilience.

The chapter situates GI within its theoretical foundations, drawing on landscape ecology, conservation biology, ecosystem services theory, resilience thinking, and spatial planning theory. By integrating these diverse strands of knowledge, GI emerges as a comprehensive and interdisciplinary framework that bridges environmental science and planning practice.

Overall, the chapter argues that GI should be understood not merely as an environmental planning instrument, but as a structural reconfiguration of how territories are conceptualized, managed, and developed in the context of sustainability and resilience.

What you will learn:
- How GI evolved from 19th-century social reform and public health movements into a key component of contemporary urban planning.
- How ecological planning, landscape ecology, and network thinking shaped modern approaches to spatial and environmental design.
- How the concepts of ecosystem services and resilience help us understand cities as adaptive socio-ecological systems.

2.1. SOCIAL REFORM AND THE HEALING ROLE OF NATURE IN THE INDUSTRIAL CITY

The earliest intellectual foundations of green infrastructure emerged in the 19th century as a response to the social and environmental consequences of industrial urbanization. Rapid population growth, overcrowding, inadequate sanitation, and coal-based industrial production produced cities marked by pollution, disease, and stark social inequality. Green space entered urban discourse not primarily as an aesthetic enhancement, but as a mechanism of social reform and public health protection.

Industrial cities expanded at unprecedented rates. London's population grew from approximately 1 million at the beginning of the 19th century to nearly 3 million by the mid-century, and more than 6.5 million by 1900. Similar growth patterns characterized cities such as Manchester, Paris, Berlin, and New York. In these rapidly densifying urban environments, basic infrastructure often fails to keep pace. Before the widespread introduction of modern sewer systems and safe drinking water networks, cities experienced recurring cholera outbreaks, respiratory illnesses linked to coal pollution, and high mortality rates, particularly among the working classes.

In this context, access to fresh air, sunlight, and open space became recognized as essential components of urban well-being. Reformers, planners, and early landscape architects began to argue that green spaces were not luxuries, but public necessities. Parks were increasingly framed as "lungs of the city," capable of improving air quality, providing relief from overcrowded housing conditions, and fostering moral and social order.

Under these conditions, access to fresh air, sunlight, and open space began to be seen as a key element of urban well-being. Social reformers, planners, and early landscape architects began to emphasize that green spaces should not be luxury goods but rather public goods of fundamental importance. Parks were increasingly described as the "lungs of the city," capable of improving air quality, mitigating the effects of overcrowding, and helping to maintain social and moral order.

One of the most important proponents of this vision was Frederick Law Olmsted (1822–1903), widely regarded as the founder of American landscape architecture. Olmsted viewed landscape as a form of social infrastructure. In collaboration with Calvert Vaux, he designed Central Park in New York (1858), a naturalistic landscape exceeding 340 ha embedded within a rigid urban grid. Central Park was conceived not merely as a recreational amenity but as a democratic

space accessible to all citizens, regardless of class. Olmsted believed that shared access to nature could mitigate social tensions, promote civic identity, and support both physical and psychological health.

Crucially, Olmsted's thinking extended beyond individual parks. In Boston, his Emerald Necklace project (1878–1896) introduced a connected system of parks structured along the restored Muddy River corridor (Figure 2.1). This project transformed a polluted and flood-prone landscape into a multifunctional open-space network that simultaneously provided recreation, flood mitigation, and water purification. Unlike isolated urban parks, the Emerald Necklace operated as an integrated system – anticipating contemporary principles of connectivity and multifunctionality central to green infrastructure.

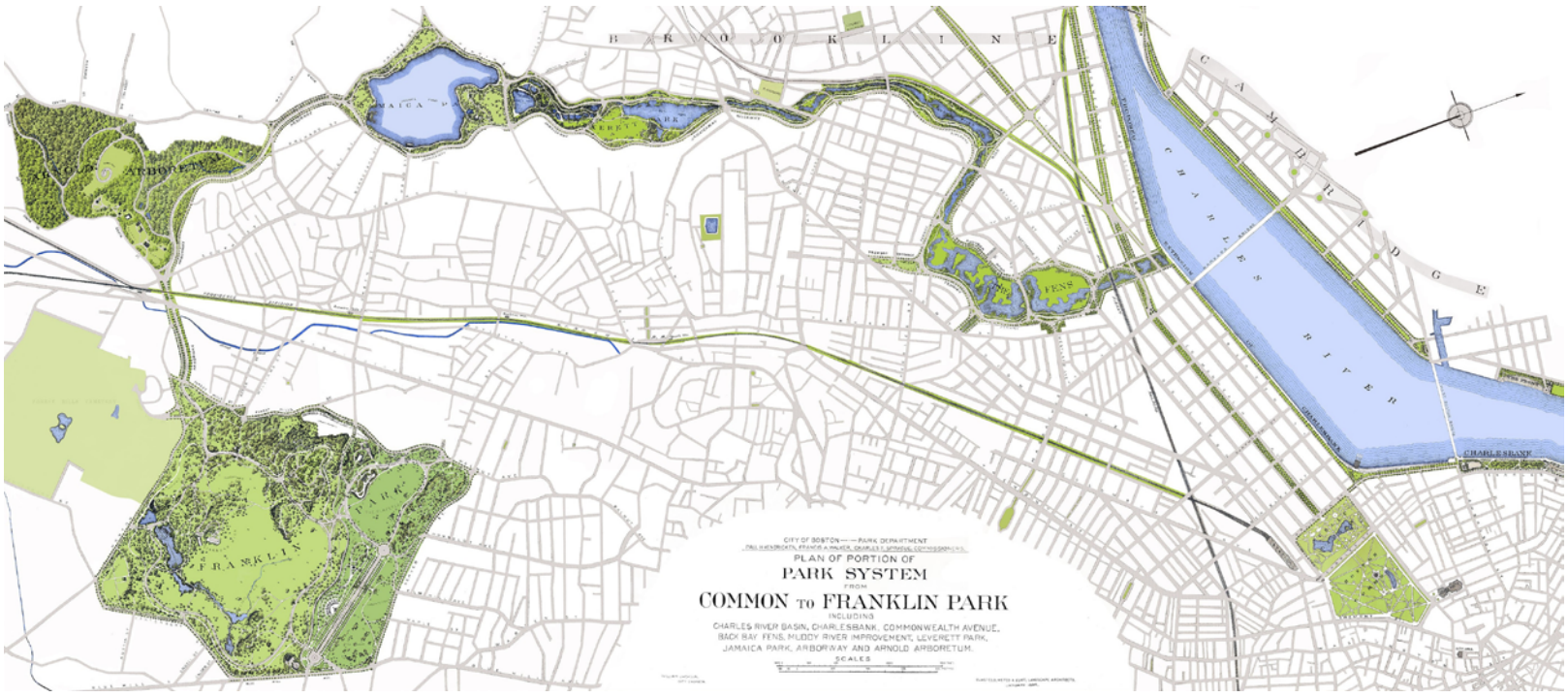

Figure 2.1. Olmsted plan for Boston's Emerald Necklace (Saporta, 2023)

Olmsted's work reflected a broader 19th-century reform movement in which landscape design was intertwined with public health, social equity, and urban governance. His belief that access to nature was a civic right rather than a privilege anticipates contemporary discussions of environmental justice. At the same time, his understanding that landscapes could perform ecological functions foreshadowed modern thinking about ecosystem services.

At the turn of the 20th century, these socially driven concerns about urban conditions evolved into more comprehensive urban reform models in Europe. Ebenezer Howard's garden city movement, introduced in "To-Morrow: A Peaceful Path to Real Reform" (1898), responded to the same industrial crises but proposed a structural reorganization of urban form rather than the insertion of parks into existing cities.

Howard envisioned self-contained towns of 30,000 to 50,000 inhabitants organized around a central park and surrounded by permanent agricultural green belts. His model sought to reconcile the economic opportunities of the city with the environmental and social advantages of the countryside. The green belt was not decorative; it ensured food production, limited urban sprawl, and maintained ecological continuity. Within the city itself, residential districts were interwoven with gardens and communal open spaces, embedding nature into everyday life.

The garden city concept represented a shift from park provision to systemic integration of landscape and settlement structure (Figure 2.2). While Olmsted worked largely within expanding metropolitan environments, Howard proposed planned decentralization through polycentric networks of cities. Yet both approaches shared a normative foundation: the conviction that access to nature was fundamental to social well-being, health, and democratic life.

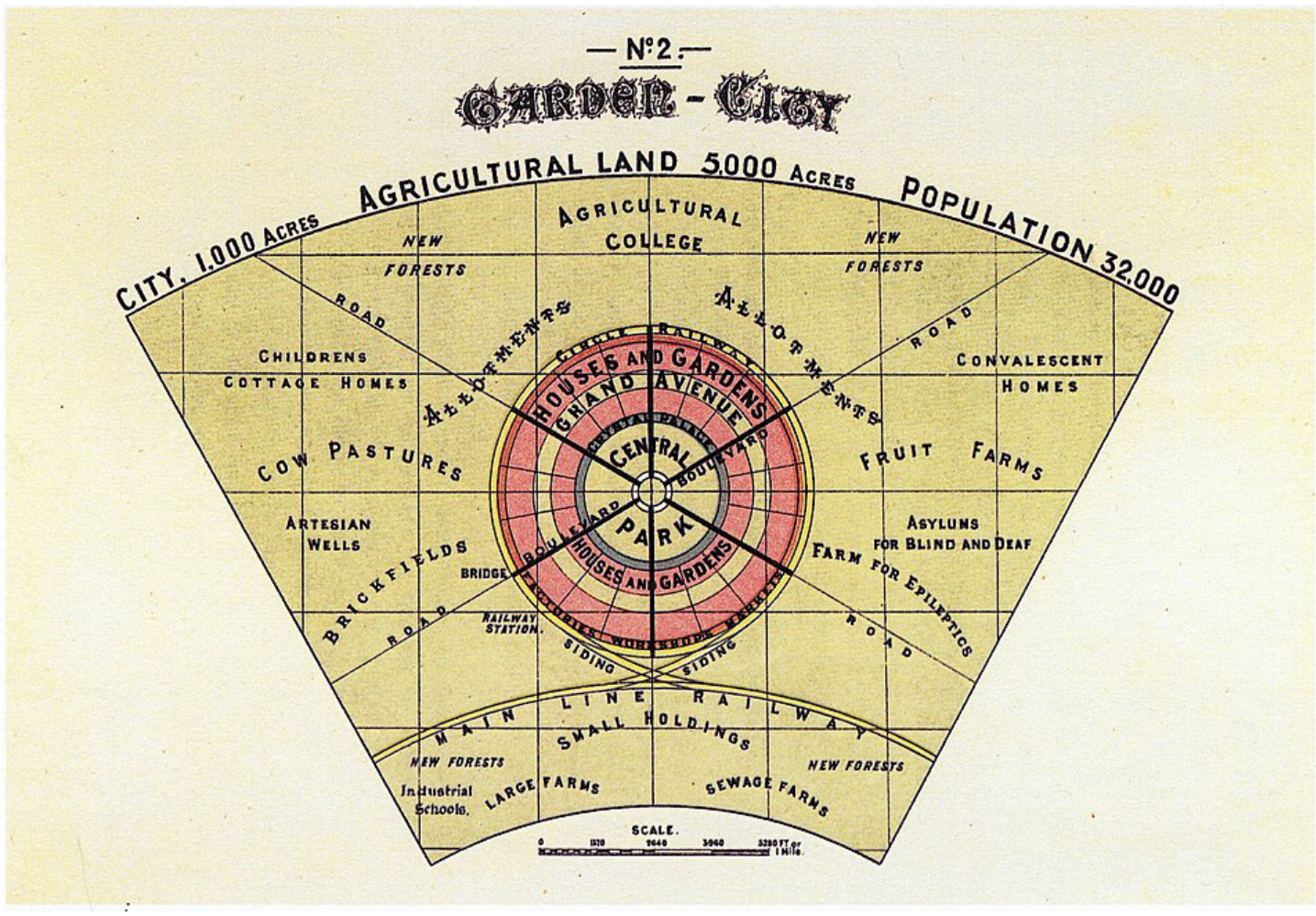

Figure 2.2. Garden City by Ebenezer Howard (Howard, 1902)

The implementation of Letchworth (1903) and Welwyn Garden City (1920) demonstrated the practical viability of Howard's ideas, even if their social reform ambitions were only partially realized. More broadly, the movement influenced 21st-century planning traditions worldwide, from British new towns to suburban planning models in Europe and North America.

Taken together, 19th-century park systems and the garden city movement established the social and ethical foundations of what would later evolve into green infrastructure. They framed green space not as an ornamental landscape but as an essential urban structure – a tool for improving public health, reducing inequality, strengthening community cohesion, and mediating the relationship between city and countryside.

This socially grounded understanding of landscape as infrastructure preceded and prepared the ground for the ecological, scientific, and network-based interpretations that would emerge later in the 20th century.

2.2. ECOLOGICAL PLANNING AND THE RISE OF NETWORK THINKING

While Olmsted and Howard established the social, spatial, and reformist foundations for integrating nature into cities, the 20th century brought a more scientific and ecological consolidation of these ideas. This phase marked a transition from aesthetic and social reform motivations toward analytically grounded environmental planning. Three interrelated intellectual currents were particularly influential: European ecological planning traditions, landscape ecology, and conservation biology.

Beginning in the 1920s, German planners and ecologists developed the concept of *Landschaftsplanung* (landscape planning), introducing a systematic ecological basis for spatial organization. Unlike earlier park-based interventions, this approach treated entire regions as ecological systems requiring comprehensive analysis. Planning decisions were grounded in assessments of topography, soils, hydrology, vegetation, and land-use patterns. The goal was not simply to insert green areas into cities but to align development with the structure and functioning of natural systems.

By the 1970s, ecological planning in Germany had evolved into a legally institutionalized framework. Regional and municipal planning documents were required to incorporate ecological assessments and designate interconnected systems of open spaces and habitats (Figure 2.3). The concept of *Biotopverbund* (ecological network) formalized the idea that habitats should function as linked systems rather than isolated patches. This regulatory embedding of ecological connectivity later influenced European spatial policy and ultimately informed the EU Green Infrastructure Strategy in the 21st century.

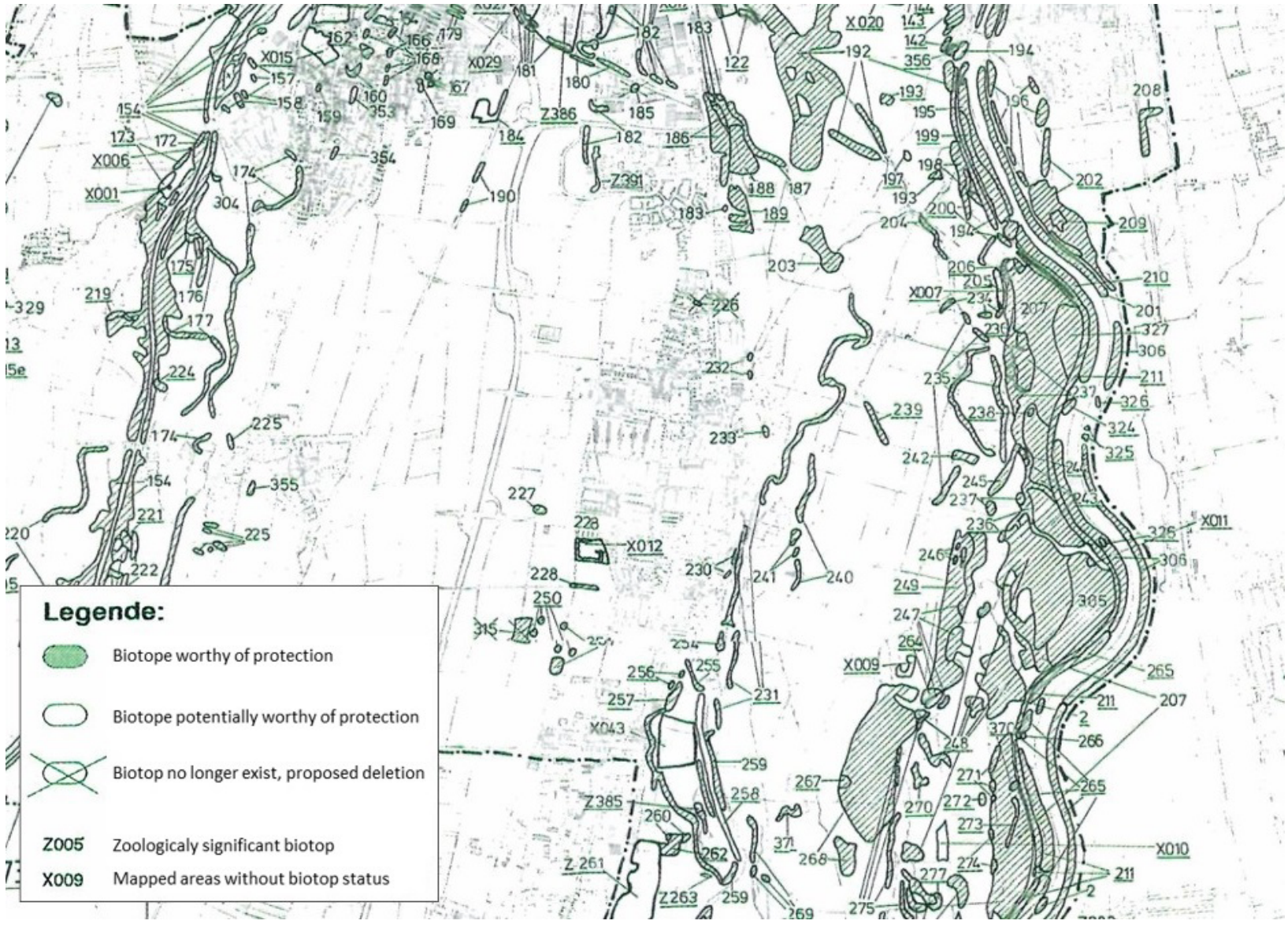

Figure 2.3. Excerpt from the 1995 landscape plan of Augsburg, incorporating the results of the biotope inventory (Müller & Waldert, 2020)

Parallel to these planning developments, landscape ecology emerged in the 1980s as a theoretical framework explaining how spatial configuration influences ecological processes. Forman and Godron (1986) conceptualized landscapes as mosaics composed of patches, corridors, and matrices (Figure 2.4). This structural perspective emphasizes that ecological performance depends not only on the amount of habitat present but also on its spatial arrangement.

Forman (1995) demonstrated that fragmentation, edge effects, and discontinuities reduce ecological integrity. These insights shifted planning attention from the creation of isolated green areas toward the design of connected spatial systems. Connectivity became understood as a fundamental ecological requirement.

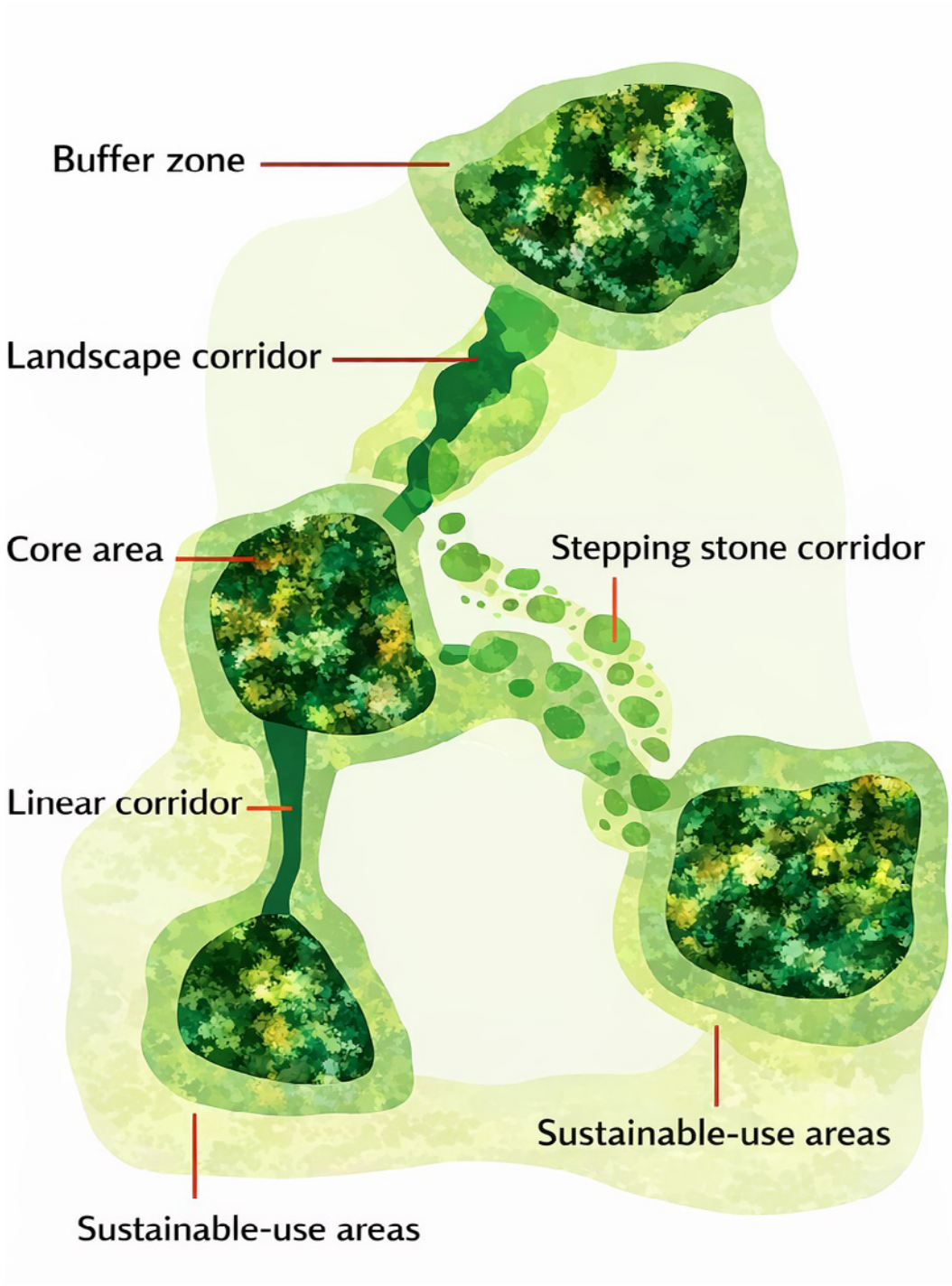

Figure 2.4. Diagrammatic representation of the spatial configuration of an ecological network (Bennett & Mulongoy, 2006)

The idea of corridors and stepping-stone habitats enabling species movement, gene flow, and recolonization (Taylor et al., 1993) provided the scientific justification for spatial connectivity. Green infrastructure later operationalized these concepts by embedding connectivity as a formal planning objective in urban and regional development frameworks.

Conservation biology further reinforced this shift toward network thinking. In the 1980s, scholars such as Soulé (1985) emphasized that isolated nature reserves are insufficient to sustain viable populations over time. Metapopulation theory (Hanski, 1999) demonstrated that species survival depends on dynamic interactions among multiple habitat patches functioning as a network.

These insights had direct implications for spatial planning. Conservation could no longer rely solely on protected areas; it required ecological continuity across broader landscapes shaped by human activity.

Benedict and McMahon (2002) translated these scientific principles into a planning framework, arguing that conservation should function as an organizing structure for development rather than a constraint applied after development decisions are made. In their later work (2006), they defined green infrastructure as a strategically planned network of natural and semi-natural areas designed to conserve ecosystem values while delivering benefits to human populations.

This network-based understanding marked a conceptual turning point. Green infrastructure emerged not merely as a collection of green spaces but as an integrated ecological system embedded within spatial planning. It synthesized ecological science, conservation theory, and regulatory planning practice into a coherent framework that directly precedes contemporary green infrastructure policy.

2.3. ECOSYSTEM SERVICES AND SOCIO-ECOLOGICAL INTEGRATION

The concept of ecosystem services has significantly reshaped environmental planning and policy discourse by framing ecosystems in terms of the benefits they provide to human societies. While different classification systems exist, the most influential early framework was developed by the Millennium Ecosystem Assessment (MEA, 2005). The MEA fundamentally reframed the relationship between nature and society by categorizing ecosystem services into four groups: provisioning, regulating, supporting, and cultural services. This functional classification created a shared language linking ecological processes with economic and social systems.

Ecosystem services are commonly defined as the benefits that people obtain from ecosystems and the biodiversity they support (Costanza et al., 1997). These benefits include material goods, regulatory functions, and non-material values that underpin social and economic systems. Ecosystem services are generated through ecological processes, species interactions, and the functioning of ecosystems as integrated systems. They depend on ecosystem structure, biodiversity, and biophysical dynamics, meaning that their provision is closely linked to ecosystem health and resilience. As such, the ecosystem services framework provides a conceptual bridge between ecological science and socio-economic systems, highlighting the dependence of human well-being and economic development on natural capital (Loreau et al., 2001; Guerry et al., 2015).

Although the MEA (2005) classification remains highly influential, more recent research and policy frameworks increasingly rely on the Common International Classification of Ecosystem Services (CICES). Unlike the MEA, which distinguished four categories (including supporting services), CICES organizes

ecosystem services into three main groups: provisioning, regulating, and cultural services (Figure 2.5). Supporting services are treated as underlying ecological functions that enable the delivery of the other three categories, rather than as a separate group.

In the context of green infrastructure, ecosystem services constitute the primary functional, economic, and social justification for its implementation. They translate ecological processes into tangible benefits for cities and their inhabitants. Green infrastructure is often described as a system for delivering ecosystem services in a cost-effective and sustainable manner.



Figure 2.5. Ecosystem services framework (Environment Ireland, 2023)

Provisioning services refer to the material goods supplied by ecosystems that can be directly used by humans. In urban environments, their importance has often been underestimated; however, in recent years, they have gained increasing relevance in the context of local self-sufficiency and resource security. These services include, among others:

- food production (including urban agriculture, community gardens, and urban orchards),
- drinking water and water for domestic or industrial use,
- biological raw materials (biomass, timber, organic matter),
- plants with medicinal or practical applications.

Within green infrastructure systems, provisioning services support the principles of the circular economy and contribute to shortening supply chains, particularly at the local scale. Regulating services are among the most critical for urban functioning and climate change adaptation. They encompass natural processes that, when properly supported and managed, mitigate the negative impacts of human activity and extreme environmental events. Examples include:

- regulation of the local climate (air temperature reduction and mitigation of the urban heat island effect),
- regulation of the water cycle (increasing water retention and infiltration, reducing surface runoff),
- flood protection (including providing space for rivers and maintaining natural hydrological dynamics),
- improvement of air quality (filtration and phytoremediation of pollutants and particulate matter),
- carbon sequestration,
- noise reduction,
- soil stabilization and erosion control,
- maintenance of biodiversity,
- ensuring ecosystem continuity and diversity at genetic, species, and ecosystem levels.

By shaping natural processes and reducing the negative consequences of environmental transformation – such as excessive artificial runoff or insufficient air circulation and regeneration – green infrastructure offers an effective alternative or complement to conventional technical solutions.

Cultural services refer to the non-material benefits that ecosystems provide to society. In urban areas, they play a particularly important role in shaping quality of life, mental well-being, and place identity. These services include:

- provision of space for recreation and leisure,
- opportunities for outdoor tourism,
- aesthetic landscape values,
- educational and cognitive functions,
- symbolic and spiritual values influencing place identity,
- positive impacts on mental health and stress reduction,
- strengthening social relations and community integration.

A key issue in relation to cultural services is access to green spaces of adequate size and quality. Increasingly, such access is recognized as a matter of environmental (ecological) justice and an important factor in reducing social inequalities within cities.

2.4. RESILIENCE AND ADAPTIVE ENVIRONMENTAL FRAMEWORKS

In the late 20th and early 21st centuries, green infrastructure (GI) has increasingly converged with a range of complementary approaches designed to make cities more resilient, sustainable, and ecologically functional. Resilience theory, particularly as developed by Folke et al. (2010), emphasizes adaptive capacity in the face of environmental and social change. Urban areas increasingly face climate-related risks such as flooding, heatwaves, and biodiversity loss. Green infrastructure contributes to urban resilience through ecosystem-based adaptation, reducing vulnerability while providing co-benefits (Ahern, 2011). Concepts such as low impact development (LID), Nature-based Solutions (NbS), nature-based adaptation, and natural capital share a central principle with green infrastructure: the recognition that ecosystem processes can and should be harnessed to address urban challenges.

Low-impact development emerged in the United States during the 1990s as a response to the environmental consequences of conventional urban drainage systems. It emphasizes small-scale, site-specific interventions that mimic natural hydrological processes, increase infiltration and retention, and filter stormwater at the source. Green infrastructure provides an operational framework for low-impact development, translating its hydrologically sensitive techniques into spatially integrated urban design. By embedding bioretention areas, permeable pavements, vegetated swales, and constructed wetlands into the urban fabric, green infrastructure ensures that water management is addressed alongside ecological, social, and recreational goals.

Similarly, Nature-based Solutions, promoted by the European Union and the International Union for Conservation of Nature (IUCN) since 2010, highlight the potential of natural processes to mitigate environmental and societal challenges. Green infrastructure represents a tangible expression of these principles, delivering interventions such as blue-green networks, green roofs and walls, retention parks, and river restoration projects. Nature-based adaptation extends this logic to climate resilience, using ecosystem functions to reduce flood risks, counter urban heat, and support biodiversity. Across these approaches, green infrastructure serves as a unifying, practical framework that operationalizes ecological principles at multiple scales – from individual buildings to neighborhoods, districts, and entire metropolitan areas.

Underlying these strategies is the concept of natural capital: ecosystems are not only sources of biodiversity but also critical infrastructure that provides essential services, including water purification, flood control, climate regulation, and recreational opportunities. Ecosystems are natural capital assets that underpin the benefits on which society depends. How much we have (quantity), what condition it is in (quality), and where it is (location), determine the benefits

the asset provides (Lusardi et al., 2024; Figure 2.6). Green infrastructure embeds natural capital into urban planning, ensuring that ecological functions are maintained and harnessed for human and environmental benefit.

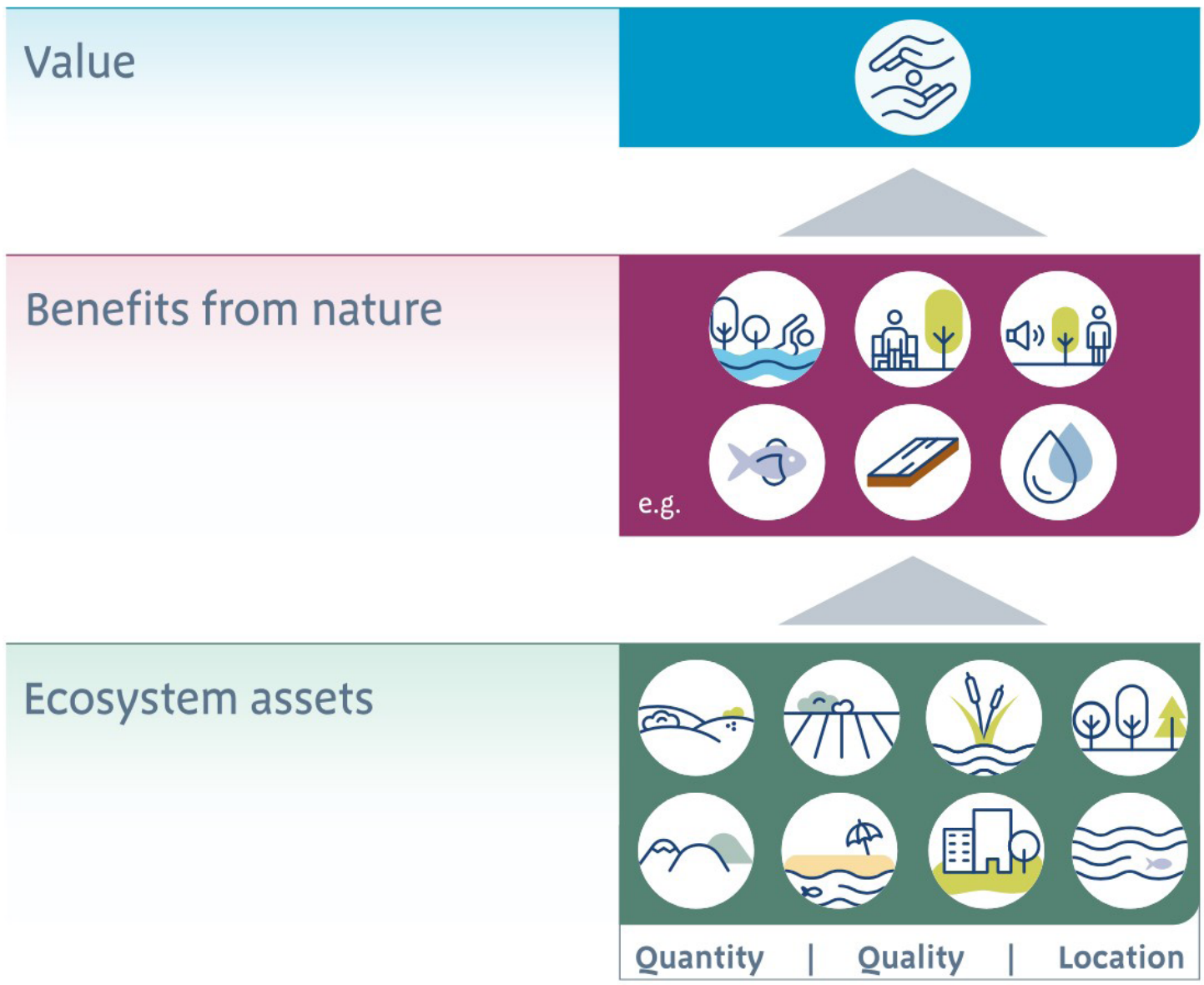

Figure 2.6. Natural capital logic chain (Lusardi et al., 2024)

Together, the frameworks mentioned above illustrate a shared vision in which urban design, ecological processes, and societal needs are integrated. Green infrastructure, in particular, unites these diverse approaches by providing a spatial, multifunctional, and adaptive system that makes cities not only more sustainable but also more resilient, healthy, and livable. Its distinctive strength lies in translating conceptual frameworks into tangible, connected networks of green and blue spaces that simultaneously support ecosystem functions, human well-being, and urban resilience.

Review questions:

1. Which ideas influenced the development of the GI concept?
2. What contemporary ideas and approaches support the GI concept?
3. What makes the GI concept distinct from other approaches?

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3. MULTIPLE PERSPECTIVES TO UNDERSTAND GREEN INFRASTRUCTURE

What is this chapter about:
This chapter examines how green infrastructure (GI) is defined and how the concept has evolved over time. It traces its development from an initial focus on ecological networks and habitat connectivity to a broader understanding that also incorporates water management and flood mitigation. Over time, these ecological and hydrological perspectives merged into a multifunctional approach, positioning GI as a structured system of connected green spaces designed to deliver environmental, social, and economic benefits while supporting biodiversity, ecosystem services, and human well-being.

Building on this evolution, the chapter identifies three dominant definitional approaches: the network-based approach, centered on ecological structure and connectivity; the water management approach, focused on hydrological functions and stormwater control; and the integrated approach, which emphasizes multifunctionality and the combined delivery of diverse benefits. The chapter argues that these differing perspectives shape how GI is interpreted and implemented in planning practice, highlighting its flexibility as a concept adaptable to various spatial, environmental, and policy contexts.

What you will learn:
- How can GI be defined?
- What are the uses of the GI concept.
- How different definitions influence the interpretation and application of GI in practice.

3.1. NETWORK-BASED APPROACH

The concept of green infrastructure was formally defined and introduced into planning practice only in the 1990s. Much like its 19th-century roots, the evolution of the terminology and the broader conceptual framework emerged as a response to escalating challenges associated with rapid urbanization, environmental

crisis – including climate change, biodiversity loss, and the growing need to integrate natural systems with the technical infrastructure of cities.

The term green infrastructure was first employed in the United States in the context of spatial planning and environmental policy. One of the first official documents to employ the concept was the report “Green infrastructure: smart conservation for the 21st century” (Benedict & McMahon, 1999), published by the Conservation Fund. The authors argued that green space should not be treated as a luxury amenity, but as a strategic component of spatial planning, equal in importance to transportation or water and sewage infrastructure. In their first handbook on green infrastructure (1999), Benedict and McMahon defined the term as a strategically planned network of natural and semi-natural areas designed to support ecosystem functioning, public health, and local economic development.

In the 1990s, American planners and ecologists began using the term green infrastructure by drawing an explicit parallel to the role of “gray” (technical) infrastructure in urban systems. This systemic perspective emphasizes that relationships between environmental components are as important as the components themselves. As a result, networks of vegetated and water-covered areas in cities came to be understood not as isolated elements, but as interconnected systems essential to urban functioning. The system of open and green spaces was increasingly recognized as performing indispensable functions for the proper operation of the city, becoming semantically and conceptually equivalent to traditional technical infrastructure such as roads, sewer systems, and energy networks.

One of the earliest operationalizations of this understanding was the Green Infrastructure Plan for the State of Maryland (Weber et al., 2006), developed by the Green Infrastructure Work Group – a joint initiative of the Conservation Fund and the U.S. Forest Service. In this case, green infrastructure was defined as a statewide ecological network composed of core areas (hubs) of high natural value connected by corridors (Figure 3.1). The identification of these areas considered not only their spatial distribution but also ecological vulnerability and development pressure. In this framework, green infrastructure was explicitly conceptualized as an ecological network designed to maintain viable and resilient populations.



Figure 3.1. Green infrastructure as habitat network (Natural England, 2023)

The network approach to green infrastructure refers to its basic meaning, i.e., a network of interconnected natural components that form a coherent ecological system on a local, regional, and national scale. At the regional level, this system will be built by protected areas connected by a network of ecological corridors; at the city level, by elements such as parks, urban forests, river valleys, allotment gardens; and at the local level, by a system of green streets with rain gardens, absorption basins, and residential greenery. The key aspect here is ecological connectivity (Figure 3.1), which enables the flow of matter, energy, and genetic information.

In the network-based approach, GI is defined mainly as:

- a spatially connected ecological system,
- a network of natural and semi-natural areas,
- a structure ensuring ecological coherence across scales.

3.2. WATER MANAGEMENT (HYDROLOGICAL) APPROACH

The hydrological approach defines green infrastructure primarily through its role in stormwater management and climate resilience, particularly in urban environments.

In regions and cities heavily affected by climate change, interconnected systems of vegetated and water-covered areas are defined as instruments addressing flooding, surface runoff, and water scarcity. In this perspective, green, or more precisely green-blue infrastructure, is conceptualized as a method of sustainable stormwater management.

Within this approach, green infrastructure is defined through specific technical and Nature-based Solutions aimed at water retention and infiltration, including:

- rain gardens,
- surface and underground retention basins,
- vegetated swales and infiltration trenches,
- permeable pavements,
- green roofs and green walls.

The primary goal is to complement or replace gray drainage infrastructure with nature-based solutions that not only manage water but also provide additional co-benefits such as air purification, urban cooling, and aesthetic enhancement (EPA, 2018). However, these additional benefits are often secondary to the core hydrological function.

The U.S. Environmental Protection Agency defines green infrastructure explicitly as an approach to wet weather management that uses soils and vegetation to mimic natural hydrological processes such as infiltration and evapotranspiration (EPA, 2008). The Water Infrastructure Improvement Act (known as the Clean Water Act) similarly defines it as a range of measures using plant or soil systems and permeable surfaces to reduce stormwater flows to sewer systems or surface waters.

Grabowski et al. (2022, p. 158), analyzing 120 plans in 20 American cities, formulate a broader but still hydrologically anchored definition: „Green infrastructure (GI) refers to a system of interconnected ecosystems, ecological–technological hybrids, and urban infrastructure that provide social, environmental, and technological functions and benefits within a specific context. As a planning concept, green infrastructure highlights how various types of urban ecosystems and technical infrastructure function in relation to one another to achieve socially agreed goals.”

Despite this broader formulation, in many cities, both in the United States and elsewhere, green infrastructure is frequently equated primarily with stormwater management (Figure 3.2). Other environmental functions, such as biodiversity enhancement, improved air circulation, or social and economic benefits, may receive comparatively less emphasis in this definitional framework.



Figure 3.2. Green infrastructure as stormwater management system (Capone, 2021)

In the hydrological approach, GI is defined mainly as:

- a stormwater control system,
- a nature-based drainage strategy,
- a hybrid ecological–technical water management network.

3.3. INTEGRATED APPROACH

The integrated approach defines green infrastructure as a strategically planned, multifunctional system delivering environmental, social, and economic benefits simultaneously. Unlike the previous two perspectives, it does not privilege

a single structuring principle (connectivity or hydrology) but instead emphasizes the combined and synergistic functions of green infrastructure.

In Europe, particularly following the adoption of the EU Green Infrastructure Strategy (Communication COM(2013)249), green infrastructure has been defined as a strategic network of natural and semi-natural areas designed to deliver ecosystem services and enhance environmental and societal resilience to climate change. This institutional recognition embeds green infrastructure within mainstream policy and spatial governance frameworks. Furthermore, this definition expands the scope of green infrastructure beyond ecological connectivity or stormwater management, embedding it within broader planning and governance frameworks.

In this approach, green infrastructure is conceptualized as a system capable of delivering a wide range of ecosystem services while also supporting social well-being and economic stability. The focus shifts toward the benefits generated for society, including climate adaptation and mitigation, public health, food and energy security, and the reduction of land-use conflicts.

The Landscape Institute position statement on green infrastructure defines it as an integrated planning and management framework capable of delivering the widest possible set of benefits (Landscape Institute, 2013). According to this interpretation, properly designed and managed green infrastructure not only supports ecological functions but also strengthens land-use coherence and helps resolve conflicts between competing development functions such as housing, industry, transport, agriculture, and energy production (Figure 3.3).

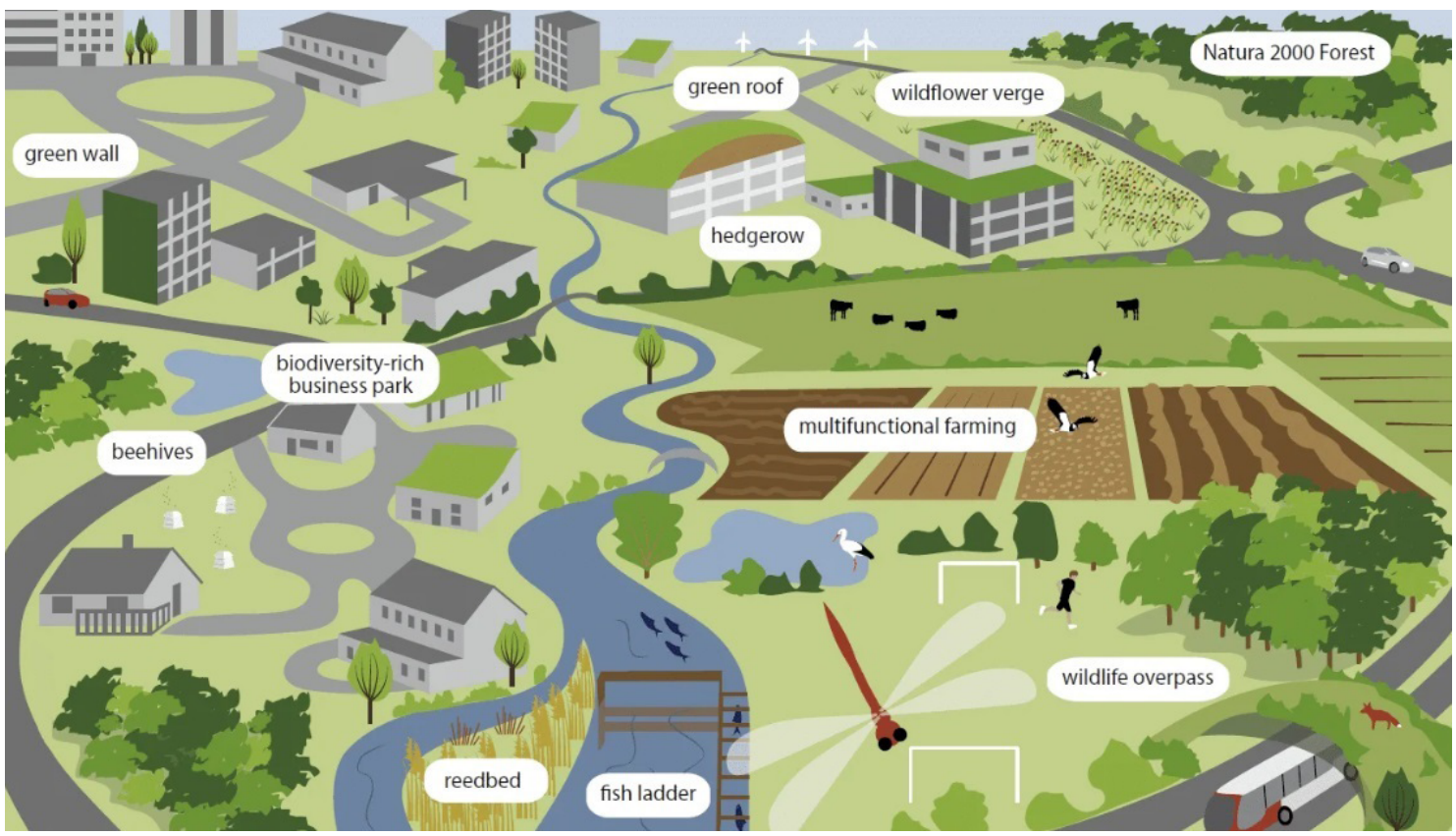

Figure 3.3. Examples of green infrastructure cross an urban-rural landscape (EEA, 2025)

In this perspective, green infrastructure is defined as a holistic socio-ecological system embedded in spatial planning, where environmental, social, and economic dimensions are treated as equally significant components of the concept.

In an integrated approach, GI encompasses:

- ecological connectivity (as in the network-based approach),
- hydrological regulation (as in the water management approach),
- ecosystem service delivery,
- social and economic functions,
- resilience in the context of environmental challenges and resource scarcity.

3.4. FROM CONCEPT TO PARADIGM AND OPERATIONAL PRACTICE

Over the past three decades, the concept of green infrastructure has undergone a profound semantic and functional evolution. Initially, it was closely associated with the preservation of ecological connectivity and ecosystem continuity, and thus primarily with nature conservation. In this early understanding, green infrastructure functioned as a strategic mechanism for safeguarding environmentally valuable areas against increasing urban development pressures. Its core components focused on large-scale protected areas – such as national and regional parks, nature reserves, and the ecological corridors connecting them – primarily at regional or national scales.

At the turn of the 20th and 21st centuries, intensifying climate change impacts, accelerating urbanization, and growing environmental degradation reshaped the conceptual framework of green infrastructure. Increasing attention was directed toward the transformation and resilience of urbanized areas. Green infrastructure began to be reinterpreted as a fundamental component of the urban ecological system, capable of delivering multifunctional ecosystem services and supporting sustainable and climate-resilient urban development (Figure 3.4). Alongside natural elements performing hydrological, climatic, and biological functions, such as urban green spaces, technical and nature-based solutions (e.g., rain gardens, infiltration wells) were introduced to enhance environmental performance. The term infrastructure (green or blue-green) thus became particularly apt, reflecting a new understanding of how natural processes can be intentionally shaped and managed within urban systems.

Contemporary interpretations define green infrastructure as a strategically planned, designed, and managed network of interconnected green and blue spaces, such as parks, squares, green roofs and walls, rain gardens, river valleys, retention basins, and semi-natural areas, integrated as an essential component of urban infrastructure. Green infrastructure is no longer perceived as a supplementary element of the built environment; rather, it is increasingly recognized as a component of equal importance to transport, water, sewage, and energy systems.



Figure 3.4. Roles of green infrastructure (John et al., 2019)

Parallel to the evolution of the green infrastructure concept, a systemic approach has gained prominence – one that emphasizes the integration of green solutions with conventional technical infrastructure. In this context, the notion of hybrid (nature and technical) infrastructure systems has emerged, combining elements of so-called gray infrastructure (e.g., sewage networks, flood embankments, drainage systems) with solutions based on natural processes such as landscape retention, infiltration, evapotranspiration, and biodiversity enhancement.

Such an approach enables the creation of cities that are more resilient, adaptive, and cost-effective, capable of responding to climate and social uncertainty. Green infrastructure thus becomes a foundation for integrated urban planning – one that aligns environmental, social, and economic objectives within a coherent vision for the sustainable city of the future.

Today, GI plays a pivotal role:

- a strategic component of urban and climate policy, supporting climate adaptation and the achievement of climate neutrality goals,
- a tool for environmental risk management, including mitigation of floods, droughts, heatwaves, and the urban heat island effect,
- a catalyst for urban regeneration processes, enabling the restoration of social, ecological, and aesthetic functions in degraded areas,
- an instrument for improving quality of life, contributing to physical and mental health, social integration, and the attractiveness of public spaces.

3.5. CONTEXT AND APPLICATIONS OF THE GREEN INFRASTRUCTURE CONCEPT IN POLAND

In Poland, the concept of green infrastructure (often referred to as blue-green infrastructure) is complex and multi-layered, and the holistic integration of green infrastructure into planning processes remains at an early stage, hindered by various institutional, legal, and practical constraints. A significant challenge is the lack of a formal legal definition of green infrastructure, its components, and the services it provides. As a result, its implementation and management often rely on strategic guidance rather than enforceable regulations.

Currently only few strategic documents in Poland explicitly defines blue-green infrastructure. One of them is the Resolution of the Council of Ministers of November 6, 2015, approving the Programme for the Conservation and Sustainable Use of Biological Diversity with the Action Plan for 2015–2020 (Uchwała nr 213 Rady Ministrów z dnia 6 listopada 2015 r. w sprawie zatwierdzenia "Programu ochrony i zrównoważonego użytkowania różnorodności biologicznej wraz z Planem działań na lata 2015-2020"). This resolution emphasizes the links between ecosystem services and ecological connectivity, aims to control uncontrolled urbanization through spatial planning measures, limits the expansion of impervious surfaces, and promotes soil retention. While the resolution encourages the incorporation of green infrastructure into spatial planning law, it does not itself have legal enforceability, functioning primarily as a strategic guideline. Consequently, it does not resolve the fundamental issue of insufficient formal recognition of green infrastructure in Poland (Antoszewski et al., 2024).

The foundations of green infrastructure in Poland draw from both internationally recognized concepts and ideas developed specifically for Polish cities. Some of these historical concepts are no longer actively implemented but have left lasting marks on urban landscapes, such as green wedges, multifunctional centers for leisure and entertainment, and standards and indicators for green space development. Others continue to shape contemporary planning, most notably the urban natural system.

The green wedges concept, developed in the early 20th century, was the first comprehensive framework for an urban green space system in Poland and is regarded as the first comprehensive framework for an urban green space system (Wilski & Ciborowski, 1990; Wilski, 1993; Kotaszewicz, 1994; Kicińska, 2000; Szulczewska & Kaliszuk, 2003, 2005; Maksymiuk, 2009). It was first applied in 1916 in Warsaw's land-use plan, proposing a radial arrangement of green wedges connecting the city center with surrounding areas. These wedges, composed of parks, children's gardens, squares, and allotments, were designed both to improve air circulation in central districts and to provide residents with recreational opportunities. Although later land-use plans reduced the scope of the wedges, the concept continued to influence urban planners and left a lasting imprint on Warsaw's green space structure.

In the 1950s, the concept of parks of culture and leisure emerged, combining recreational, cultural, and political functions, often including cinemas, amphitheatres, sports fields, and playgrounds (Czarnecki, 1961). These parks also served as venues for mass political events, reflecting the socio-political context of the time (Piątkowska, 1983; Kicińska, 2000; Szulczewska & Kaliszuk, 2003). By the 1960s and 1970s, the role of these parks evolved toward broader recreational and leisure purposes, giving rise to multifunctional centers for leisure and entertainment, designed to integrate a wide variety of recreational and sports facilities as part of a comprehensive urban open-space system (Piątkowska, 1983; Kicińska, 2000; Szulczewska & Kaliszuk, 2003; Maksymiuk, 2009).

In the 1960s, norms and standards for the development of green spaces were introduced. These specified a minimum of 8–15 m^2 of green space per resident and required that recreational facilities be located within 500 m of homes. These measures established a multi-level, hierarchical system of urban recreational green spaces ranging from neighborhood to city scale (Szulczewska & Giedych, 2011).

The growing environmental awareness of the 1970s led to a fundamental shift in how green spaces were valued, moving from primarily recreational to primarily ecological functions. This shift led to the development of the UNS

concept, which emphasizes the protection and active management of ecological systems in urban areas (Szulczewska & Kaftan, 1996). The UNS is composed of “core areas,” critical for biological, hydrological, and climatic processes, and “supporting areas,” serving specific ecological functions such as air ventilation or water management. Recreation is secondary, with green spaces primarily serving as connectors linking system components. In Warsaw, this concept has been implemented in practice as the city natural system, integrated into spatial planning since 2006 (Figure 3.5).

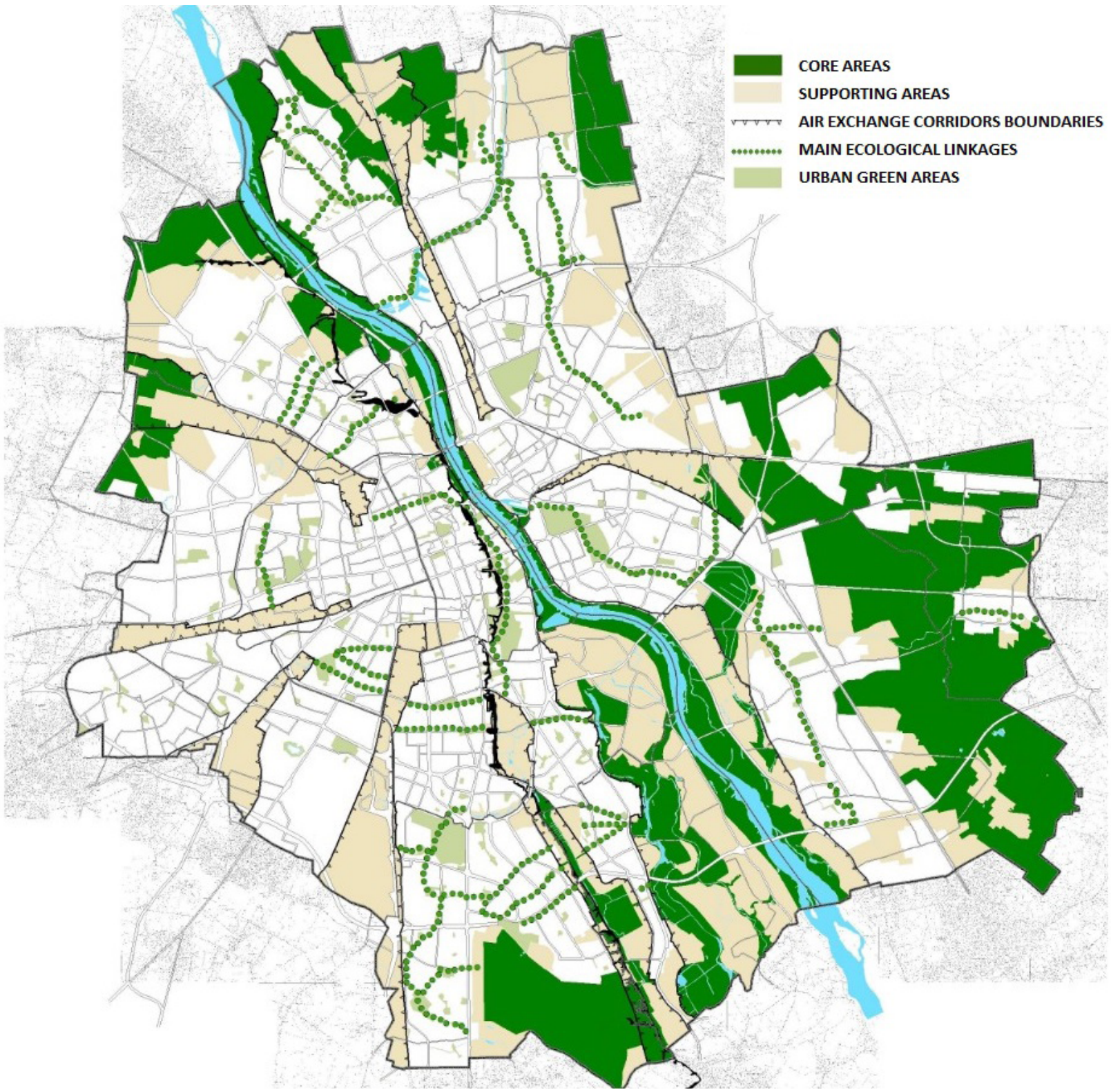

Figure 3.5. Warsaw natural system (Studium uwarunkowań i kierunków zagospodarowania przestrzennego m.st. Warszawy, 2006)

Further refinements of the urban natural system principles were proposed through the ecological framework (Przewoźniak, 2002), which does not assign specific functions to individual elements but highlights that a well-defined ecological framework can regulate ecological processes effectively. This approach emphasizes the integration of local and regional frameworks and the importance of ecological connectivity. Applications of this framework are found in cities such as Gdańsk, Gdynia, Elbląg, and Tczew. Similarly, the river parks system in Kraków (Böhm, 2001; Hrabiec, 2007) leveraged the city's hydrological network to create a multifunctional green space system, combining ecological, social, and flood-protection functions.

In recent decades, Poland's green infrastructure planning has been increasingly influenced by global sustainable development concepts, including the green city and compact city models, both grounded in ecosystem theory (Szulczewska, 2002, 2018). The green city concept emphasizes protecting and expanding natural spaces, which are crucial to ecological processes, while the compact city model prioritizes urban densification to maintain the efficiency of ecosystem functions. These competing approaches are evident in contemporary planning in Warsaw and other major cities, where urban densification pressures often challenge the expansion and protection of green areas.

Although comprehensive statutory frameworks are still lacking, a number of Polish municipalities are already advancing green-blue infrastructure through both high-level spatial strategies and concrete implementation tools. Rather than limiting such measures to policy declarations, cities are incorporating climate-adaptive and multifunctional solutions directly into planning practice. A clear illustration is the master plan for the climate district in Kraków (Figure 3.6), which operationalizes green-blue concepts within detailed design and development guidelines, demonstrating a proactive municipal approach that extends beyond formal legal requirements. This indicates the gradual institutionalization of the concept of green-blue infrastructure in the spatial planning and environmental management system.

Recent amendments to the Environmental Protection Law (Ustawa z dnia 27 kwietnia 2001 r. Prawo ochrony środowiska) have introduced an obligation to prepare urban greening plans as part of climate change adaptation plans. These regulations emphasize the growing importance of green areas and Nature-based Solutions in enhancing the resilience of urban environments to the impacts of climate change. In this context, green infrastructure in Poland is gradually evolving toward a more structured, multifunctional, and climate-oriented model, although the concept has not yet been fully incorporated into the national legal and regulatory framework.

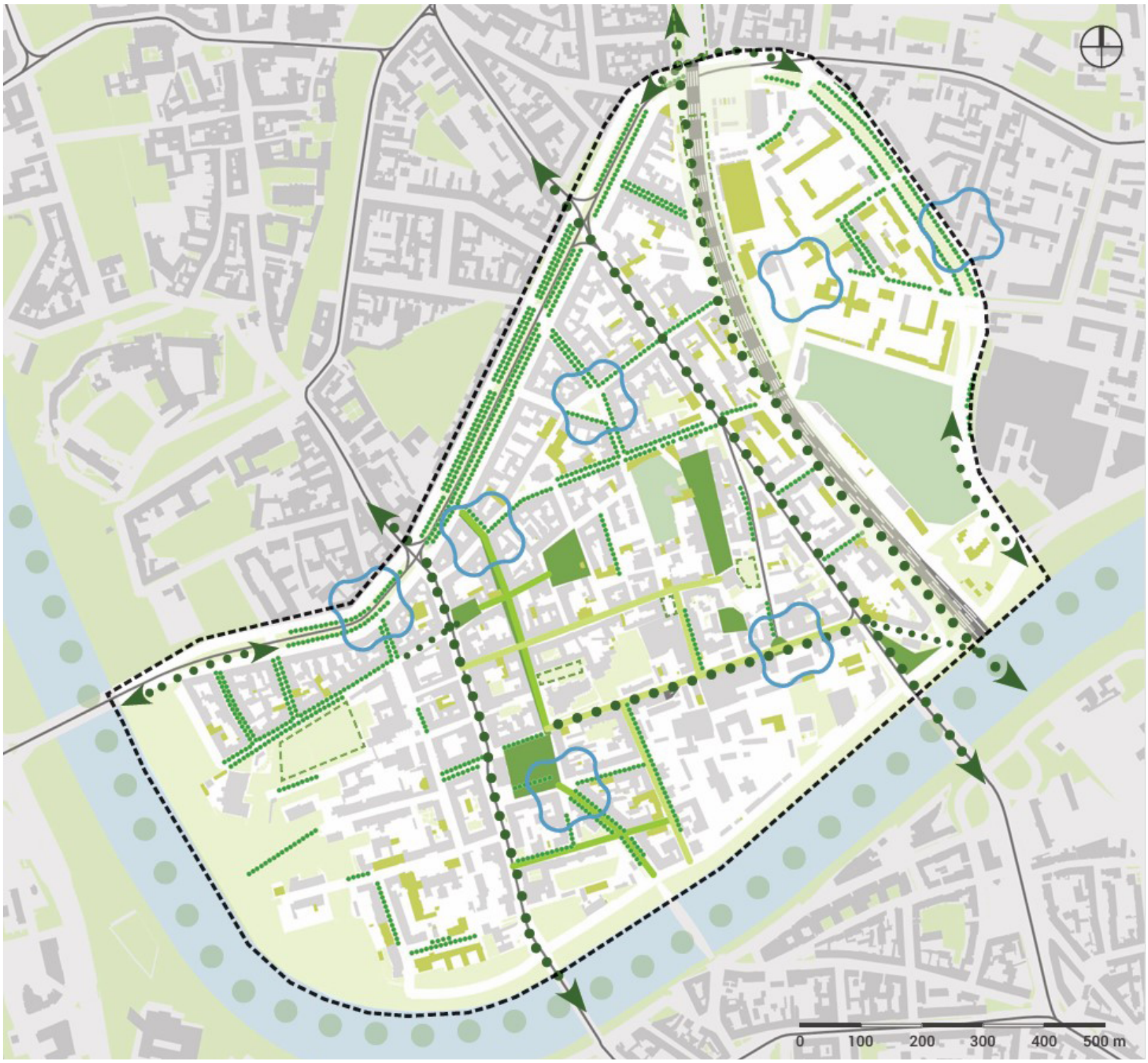

Figure 3.6. Blue-green infrastructure development proposal in Kraków (Zarząd Transportu Publicznego w Krakowie, 2021)

3.6. CONTEXT AND APPLICATIONS OF THE GREEN INFRASTRUCTURE CONCEPT IN INDONESIA

Indonesia, situated between the Asian and Australian continents and bordered by the Indian and Pacific Oceans, is characterized by a tropical climate that supports extensive rainforests and highly diverse ecosystems. Tropical forests and peatlands perform essential ecological functions, including climate regulation, hydrological stability, and biodiversity support (Harrison et al., 2020). This climatic regime, influenced by maritime and monsoonal patterns, produces consistently high rainfall and warm temperatures throughout the year, resulting in landscape features

such as tropical rainforests in Sumatra, Kalimantan, and Papua, as well as savanna ecosystems in the eastern archipelagic regions (Harrison et al., 2020). The alternation of wet and dry seasons also influences agricultural practices, particularly rice cultivation, while abundant water resources support river and lake systems, simultaneously increasing vulnerability to flooding and drought under changing climate conditions.

Within this environmental context, green infrastructure plays a crucial role in sustaining environmental quality and enhancing resilience and well-being by harnessing ecosystem functions and services that mitigate hydro-meteorological hazards and support sustainable land use. For example, the effectiveness of green infrastructure interventions, such as retention ponds, bioswales, and urban vegetation, has been shown to reduce peak flood levels and improve runoff retention capacity in Indonesian cities, offering a more resilient alternative to traditional gray infrastructure for flood risk mitigation (Kumar et al., 2025).

At regional and coastal scales, ecosystem restoration and rehabilitation programs, such as mangrove reforestation (Figure 3.7) and forest landscape restoration (Figure 3.8), contribute to biodiversity conservation, carbon sequestration, hydrological stability, and coastal protection. Mangrove ecosystems not only reduce coastal erosion and buffer storm surges but also regulate microclimates, filter pollutants, and provide critical habitats for fisheries and wildlife, supporting both ecological resilience and human livelihoods (Sumarga et al., 2023). Peatland restoration further contributes to climate change mitigation by reducing carbon emissions and sustaining hydrological functions.

At the urban scale, green infrastructure includes features such as urban forests, parks, green roofs, bioswales, and retention ponds. These interventions have been shown to reduce peak flood levels, increase stormwater retention capacity, mitigate the urban heat island effect, improve air quality, and enhance biodiversity within densely built environments (Kumar et al., 2025). Rapid urban expansion and the conversion of green spaces into built-up areas, however, threaten the provision of ecosystem services, highlighting the critical need for systematic integration of green infrastructure into urban planning and development strategies (Purwantiningrum et al., 2025).

Despite the growing recognition of its benefits, green infrastructure development in Indonesia faces significant challenges, including limited space in major cities, maintenance requirements, and the need for long-term planning and community engagement to realize its full potential. Nevertheless, the ecological, social, and economic advantages of green infrastructure make it a strategic solution for addressing urbanization, flooding, pollution, and climate change, ultimately contributing to sustainable urban development.



Figure 3.7. Mangrove reforestation in Jakarta (TWA Angke Kapuk, 2025)



Figure 3.8. Forest of Halimun Salak National Park (CIFOR-ICRAF, 2017)

One of the most important foundations for green infrastructure planning in Indonesia is Law No. 26 of 2007 concerning spatial planning (Spatial Planning Law of 2007), which established the legal basis for the provision of green open space in urban planning. According to this law, every city is required to allocate at least 30% of urban area for green open spaces, consisting of 20% public green space managed by local governments and 10% ptivate green space provided by private landowners or developers (Setiowati, 2019). The regulation defines

green open space as areas dominated by vegetation that serve ecological, social, and aesthetic functions within urban spatial structure. The primary goal of this requirement is to maintain ecological balance in cities, improve environmental quality, regulate microclimate conditions, and support hydrological functions such as water infiltration and flood mitigation. In this sense, the law established a long-standing planning tradition focused on green open space provision (Figure 3.9), which later became the basis for more comprehensive green infrastructure strategies (Jundiani et al., 2025).

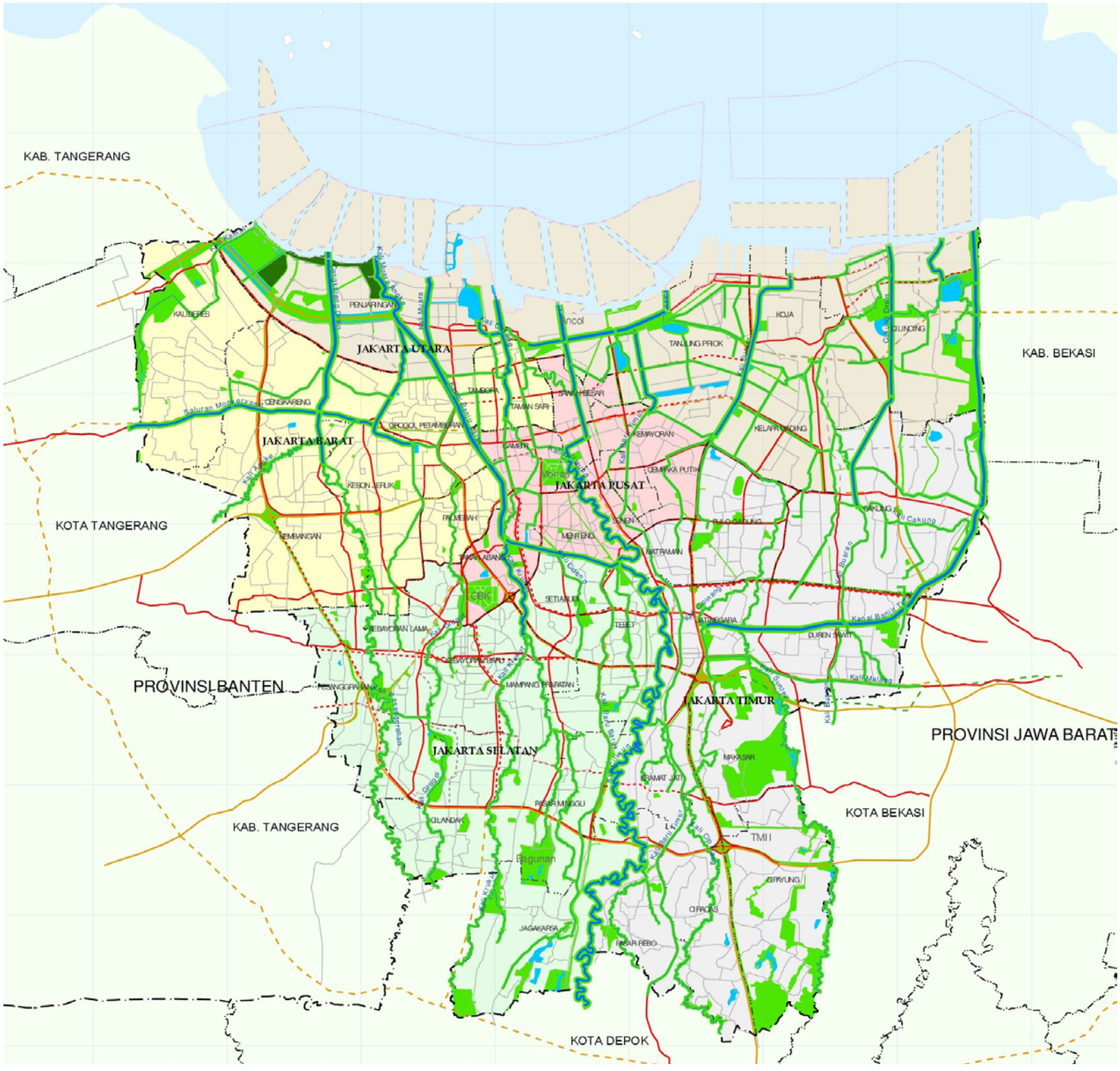

Figure 3.9. Green open space plan of Jakarta (2030 Regional Plan of the Capital City of Jakarta, 2012)

Building on the legal framework introduced by the Spatial Planning Law of 2007, the Indonesian government launched the Green City Development Program (Program Pengembangan Kota Hijau – P2KH) in 2011 through the Ministry of Public Works and Housing. The program was designed as a national initiative to support local governments in implementing sustainable urban development and improving the quantity and quality of green open spaces. P2KH promotes a broader urban sustainability framework based on several attributes of a "green city," including green planning and design, green open space, green transportation, green water management, green waste management, green energy, green buildings, and community participation. Through this program, municipalities receive technical guidance and planning support for integrating green spaces into spatial plans and urban development projects, thereby translating the requirements of Spatial Planning Law of 2007 into practical urban policies and development strategies (Hayati et al., 2013).

A further conceptual step toward integrated ecological planning was introduced with the Green City Roadmap developed by the Ministry of Public Works in 2015. Unlike these earlier frameworks, which mainly focused on meeting quantitative targets for green open spaces, the Green City Roadmap provides a broader conceptual and operational framework for transforming cities into environmentally sustainable systems. It emphasizes the integration of ecological principles into spatial planning and infrastructure development, promoting the creation of connected green networks that combine natural landscapes, urban parks, water systems, and green corridors with built infrastructure. The Green City Roadmap also identifies key strategic priorities, including strengthening urban ecological functions, improving climate resilience, enhancing water management and biodiversity, and encouraging community participation in green city initiatives. By outlining planning principles, development directions, and strategic actions for municipalities, the roadmap serves as an important bridge between national spatial planning regulations and the practical implementation of green infrastructure systems in Indonesian cities (Faisal et al., 2022).

Review questions:

1. What are the three main approaches to defining GI?
2. What are the basic differencies and similarities between main approaches to defining GI?
3. What does the multitude of approaches to defining GI tell us?
4. What is the understanding of GI concept in Poland?
5. What is the understanding of GI concept in Indonesia?

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4. OPERATIONALIZING GREEN INFRASTRUCTURE

What is this chapter about:
This chapter explores the development and implementation of green infrastructure (GI) within an international policy context. It begins by highlighting the global frameworks that support GI, such as the United Nations' Sustainable Development Goals and the New Urban Agenda, as well as guidance from the World Health Organization. It also emphasizes the importance of GI for sustainable urban and environmental planning by referencing European-level strategies such as the Green Infrastructure Strategy and the EU Biodiversity Strategy.

The chapter then examines practical tools for implementing GI, covering planning and policy instruments, regulatory and legal mechanisms, design and technical solutions, financial and economic approaches, and strategies for community engagement and capacity building.

Finally, it outlines the core principles guiding GI, emphasizing connectivity, multifunctionality, multiscale approaches, integration with other systems, ecological and functional diversity, strategic planning, active participation, and sustainable management. Together, these frameworks, tools, and principles provide a comprehensive foundation for creating resilient, multifunctional, and socially inclusive green spaces.

What you will learn:
- Gain insight into the global and European policy frameworks that shape the development of GI.
- Understand the institutional and strategic systems that guide the planning and long-term implementation of GI in sustainable urban and environmental planning.
- Understand how combining international guidance, practical tools, and core principles can create resilient, multifunctional, and socially inclusive urban green spaces.

4.1. INTERNATIONAL POLICY FRAMEWORKS SUPPORTING GREEN INFRASTRUCTURE

International initiatives and United Nations documents play a key role in promoting green infrastructure as a universal measure for solving environmental, social and climate problems. Agenda 21, adopted in Rio de Janeiro in 1992 at the United Nations Conference on Environment and Development (Rio Earth Summit 1992), already emphasizes the need to protect ecosystems as the basis for sustainable social and economic development. The document stresses that environmental degradation poses a threat to economic stability and quality of life, which is why countries should implement the principles of sustainable spatial planning, taking into account natural conditions and the long-term consequences of their decisions. For the first time on such a large scale, it was recognized that economic development and environmental protection do not have to be mutually exclusive, if planning activities are long-term and based on reliable knowledge about the functioning of ecosystems. Agenda 21 has inspired many subsequent strategies, including the UN Sustainable Development Goals (Elder & Grünewald, 2025).

The United Nations Sustainable Development Goals explicitly recognize the value of nature-based approaches in achieving sustainable development (Resolution A/RES/70/1). Several goals are particularly relevant to green infrastructure, primarily SDG 11 (Sustainable cities and communities), SDG 13 (Climate action), and SDG 15 (Life on land). SDG 11 emphasizes the importance of creating inclusive, safe, resilient, and sustainable urban environments, paying particular attention to the role of green spaces in improving quality of life. SDG 13 calls for urgent action to combat climate change and its impacts, with green infrastructure providing adaptation solutions such as urban cooling, stormwater management, and carbon sequestration. SDG 15 focuses on protecting, restoring, and promoting the sustainable use of terrestrial ecosystems, which aligns with the objectives of green infrastructure, such as habitat restoration and ecological connectivity. Through these goals, green infrastructure is framed not only as an environmental measure but also as a means of achieving social and economic sustainability at local and global scales.

Lombardía and Gomez-Villarino (2023) indicate that green infrastructure can be an effective tool for implementing sustainable development goals. Their analysis shows that green infrastructure can contribute to 60–90% of the targets in SDG 1 (No poverty), SDG 2 (Zero hunger), SDG 11 (Sustainable cities and communities), SDG 13 (Climate action), and SDG 15 (Life on land) (Figure 4.1).



Figure 4.1. Contribution of green infrastructure in realization Sustainable Development Goals (Lombardía & Gomez-Villarino, 2023)

Another important international document promoting the development of green infrastructure is the New Urban Agenda (United Nations, 2017). This document points to the need to promote the planning, creation and maintenance of coherent and well-distributed networks of open, multifunctional, safe, accessible and high-quality green public spaces that promote social inclusion, strengthen the resilience of cities to natural disasters and the effects of climate change – including floods, droughts and heat waves – and support food security and the physical and mental health of residents. By promoting inclusive, green, and resilient cities, the New Urban Agenda establishes a global framework for implementing sustainable development principles (Nesmachnow & Callejo, 2025).

The World Health Organization also highlights the important role of green infrastructure development. In publications such as “Urban green spaces and health: a review of evidence” (WHO, 2016) and “Urban green spaces: a brief for action” (WHO, 2017), the organization emphasizes the importance of urban greenery for physical and mental health, reducing air pollution, and improving the quality of life in cities. The WHO recommends incorporating green infrastructure as an integral part of spatial planning and health policies, treating it not as a supplement but as a standard tool to support communities in adapting to environmental and climate challenges. The World Health Organization has proposed “square metres of green space per capita” as a health indicator of sustainable cities and recommends providing at least 9 m² of green space per person within a 15-minute walking distance (WHO, 2012). The WHO Regional Office for Europe has proposed an “urban green space indicator” that measures the proportion of the population able to access a green space of at least 0.5 ha within a 300 m radius (UN-Habitat, 2018).

As research by Jafrin and Beza (2018) indicates, many cities worldwide do not meet the World Health Organization’s recommended standard of at least 9 m² of green space per capita. These analyses show that the lack of adequate access to urban green spaces is particularly evident in densely populated urban areas and in developing cities, where development pressure and limited land resources make it difficult to create and maintain open, multifunctional green spaces (Table 4.1).

Table 4.1. Open space in cities below the World Health Organization recommended standard (Jafrin & Beza, 2018)

Region	City and country	Total population (in million)	Urban population (in million)	City area [km²]	Density [km²]	Open space per capita [m²]
Europe	Istanbul, Turkey	15.02	14.79	1 539	2 813	6.4
	Barcelona, Spain	5.47	1.60	102	16 000	5.6
America	Colima, Mexico	7.11	1.70	5 627	130	6.2
	Mexico City, Mexico	20.90	8.91	1 485	6 000	3.5
	Buenos Aires, Argentina	13.59	2.89	203	14 237	1.9

Table 4.1. Open space in cities below the World Health Organization recommended standard (Jafrin & Beza, 2018) (cont.)

Region	City and country	Total population (in million)	Urban population (in million)	City area [km^2]	Density [km^2]	Open space per capita [m^2]
Asia	Tokyo, Japan	38.30	13.61	2 188	6 224	3.0
	Kuala Lumpur, Malaysia	7.20	1.79	243	6 890	6.5
	Mumbai, India	20.74	12.30	603	21 000	1.1
	Shanghai, China	24.10	22.20	4 000	3 800	6.1
	Hong Kong, China	–	7.40	2 754	6 777	2.7
	Dhaka, Bangladesh	18.89	14.39	306	28 410	0.2
	Chittagong, Bangladesh	5.20	4.10	168	14 200	0.2

The European Union considers green infrastructure to be a key element of sustainable development and a tool for addressing environmental, social, and climate challenges. In 2013, the European Commission formally adopted a Green Infrastructure Strategy (Communication COM(2013)249), which recognizes it as a component of natural capital with high ecological, social, and economic value. The document emphasizes that green infrastructure should be taken into account in all relevant EU policy areas and not treated merely as an optional environmental solution.

In practice, this means that natural systems – such as park networks, ecological corridors, wetlands, green roofs and urban green spaces – should be an integral part of spatial planning, climate change adaptation measures and sectoral policies across the European Union. Although the 2013 strategy itself is not legally binding, unlike a directive or regulation, green infrastructure is supported and implemented through existing EU legislation, including the Water Framework Directive, the Floods Directive, and sectoral strategies such as the EU Strategy on Adaptation to Climate Change and the EU Biodiversity Strategy to 2030.

The EU Biodiversity Strategy (Communication COM/2020/380) promotes green infrastructure as a tool to counteract biodiversity loss, environmental degradation, and urbanization pressure, while highlighting social benefits such

as improved public health and the integration of public spaces. To reintegrate nature into urban environments, the strategy urges all cities with more than 20,000 inhabitants to develop urban nature plans, emphasising that such plans are essential for integrating nature into urban environments. The European Commission has developed a dedicated guideline to assist cities in the European Union with designing urban nature plans (DG ENV EU, 2024). The guideline outlines the optimal approach for creating and implementing an urban nature plan and provides recommendations structured around a ten-step process to effectively guide cities through each stage (Figure 4.2).

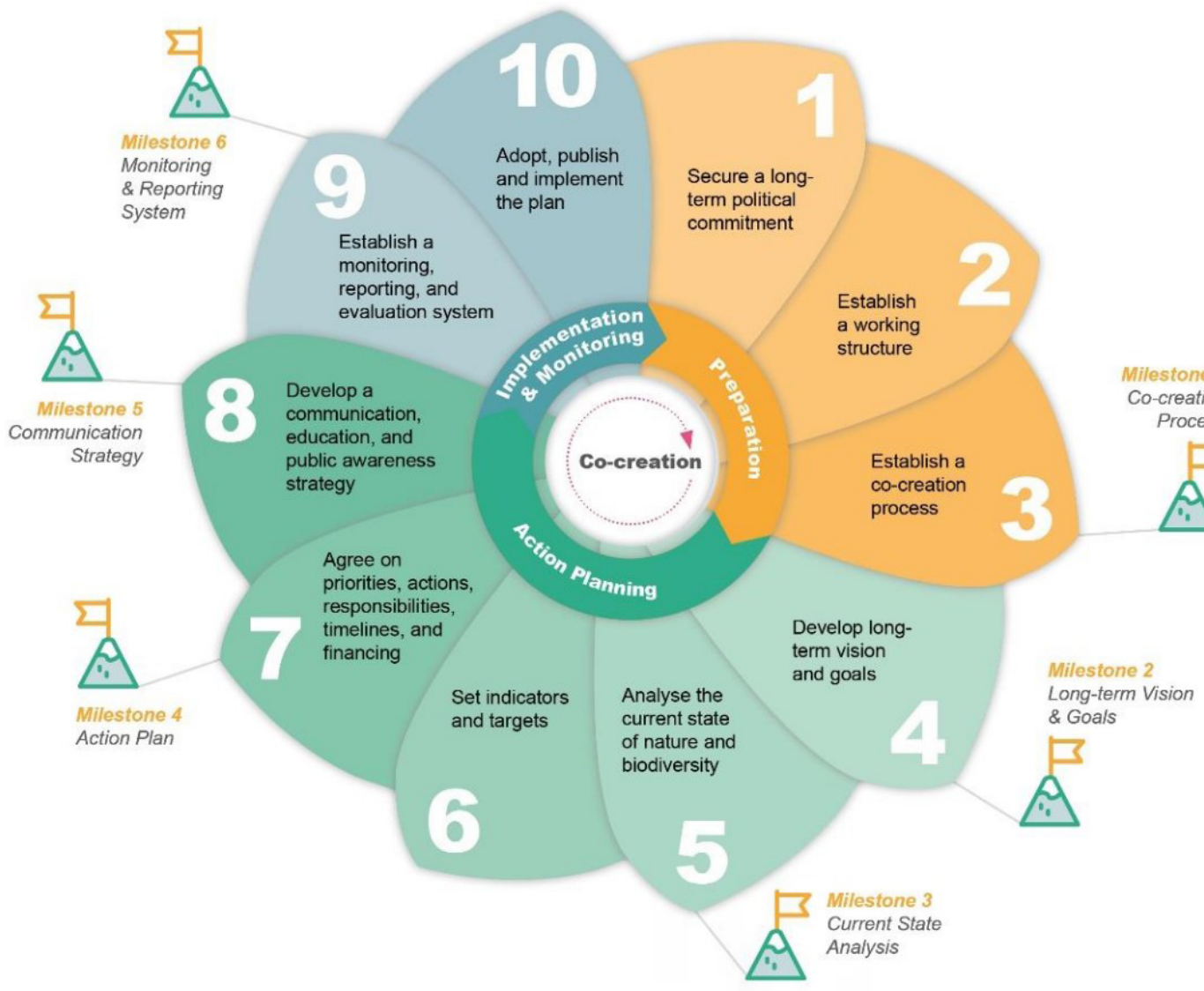

Figure 4.2. Steps for establishing an urban nature plan (DG ENV EU, 2024)

4.2. GREEN INFRASTRUCTURE IMPLEMENTATION TOOLS

Green infrastructure implementation tools are strategies, policies, technologies, and planning mechanisms used by communities, governments, and organizations to plan, finance, construct, and maintain green infrastructure systems. These tools help integrate natural processes into urban environments to manage stormwater, improve water quality, reduce heat, enhance biodiversity, and provide recreational and aesthetic value.

Depending on the institutional and territorial context, green infrastructure can be implemented in various ways using a variety of tools, including planning, regulatory, technical, financial, and social tools. It can be implemented at many

levels of governance, from national to local, where strategies and legal frameworks are translated into specific spatial and investment actions. This process involves a wide range of stakeholders, including public administrations, private companies, financial institutions, non-governmental organizations, scientists, and local communities. This emphasizes the multi-level and multi-actor nature of implementing green infrastructure as part of sustainable development.

Planning and policy tools are national, regional, and local strategic frameworks that incorporate green infrastructure into land use planning and spatial development processes. These tools are used around the world to embed green infrastructure into long-term territorial planning, and include comprehensive plans, climate adaptation strategies, biodiversity action plans, and regional development frameworks. These tools help to designate ecological corridors, protect natural assets, guide sustainable urban expansion, and align infrastructure investments with environmental resilience goals. Incorporating green infrastructure at the policy and planning stage ensures that green solutions are systematically embedded in urban and regional development, rather than being implemented as isolated projects. The following are examples of instruments belonging to the planning and policy tools that are related to the implementation of green infrastructure:

- The New York City Green Infrastructure Plan: A Sustainable Strategy for Clean Waterways (2010) aims to reduce water pollution and lower flood risks by implementing green roofs, rain gardens, and permeable pavements. It also promotes improved air quality and increased green spaces, benefiting both the environment and residents' health (Culligan, 2019).
- Barcelona Green Infrastructure and Biodiversity Plan 2020 (2013), outlines long-term actions necessary to develop green infrastructure capable of performing a wide range of environmental and social functions, thereby integrating nature and biodiversity into the urban fabric. The plan also aims to strengthen the city's links with the surrounding region, thereby increasing Barcelona's efficiency and resilience in the face of environmental pressures and challenges (Titz & Chiotha, 2019).
- The Greening Sydney Strategy (2021) is the City of Sydney's long-term plan to transform the urban environment of the by increasing green cover and resilience. The aim is to create a cooler, healthier, and more liveable city. The strategy sets out targets to expand tree canopy and increase overall greenery, integrate nature into streets, parks, and buildings, and ensure that everyone benefits from urban nature. The strategy also outlines actions and partnerships to reduce the impact of heat, improve well-being, and support biodiversity in Sydney (Franzén, 2024).

Regulatory and legal tools include laws, regulations, codes, and standards that mandate or incentivise the integration of green infrastructure into new developments and redevelopment projects. Examples of these tools include

stormwater management requirements, green building standards, biodiversity offset policies, minimum open space ratios, and zoning regulations that promote permeable surfaces or green roofs. These instruments create enforceable frameworks that influence private and public investment decisions while ensuring environmental performance. By embedding green infrastructure requirements into legal systems, governments can promote sustainable practices and provide developers, planners, and engineers with clear expectations across different jurisdictions. Legislation and regulations may also encompass legal provisions to protect green infrastructure from changes in land use, as well as provisions for establishing nature conservation areas. Examples of tools belonging to the group of regulatory and legal measures related to the implementation of green infrastructure as follows:

- Ordinance of 22 December 2000 on the Protection and Restoration of Nature in Tokyo (Japan) introduces specific quantitative and qualitative standards that apply to green space provision in new developments in Tokyo. Any newly constructed, repaired, or extended buildings with a flat roof area of more than 1,000 m² for private facilities or 250 m² for public facilities must have 20% of their surface area covered by greenery. The ordinance was further amended in 2009 to stipulate that 25% green coverage is required for a roof with an area of over 5,000 m² (Jim et al., 2022).
- Law of 28 June of 2007 on Green Spaces of the Republic of Lithuania treats green areas as essential public infrastructure, contributing to environmental sustainability, climate resilience, and quality of life. This law plays a key role in shaping green infrastructure by establishing the legal framework for the protection, planning, and management of green areas (Baniulienė, 2025).
- Law of 26 June 1998 on Nature Conservation and Protected Areas in Extremadura (Spain) incorporated ecological corridors into the region's nature protection system. This defined their role in maintaining spatial connectivity between ecologically important areas (Giedych, 2018).

Design and technical tools provide practical guidance, standards, and best practices for planning, designing, constructing, and maintaining green infrastructure. They include, e.g., hydrological modeling tools, technical guidelines for rain gardens and bioswales, urban forestry standards, and performance monitoring frameworks. These tools support designers and contractors in delivering context-sensitive, climate-responsive, and technically reliable solutions. They can also serve as practical guidelines for residents and municipalities, helping to implement and maintain green infrastructure effectively across diverse environmental and socio-economic settings.

Examples of instruments belonging to the design and technical tools that are related to the implementation of green infrastructure, as follows:

- Urban Green Best Practice Guidelines provide practical recommendations for planning, designing, and managing urban green spaces in Cape Town (South Africa). The document promotes sustainable landscaping, water-wise practices,

and biodiversity conservation within the city's urban environment. It aims to support resilient communities by integrating green infrastructure into long-term urban development strategies (City of Cape Town, 2024).

- The Street Garden Guidelines Melbourne (Australia) is the manual offering residents clear, easy-to-read information and advice on designing, installing, and maintaining green spaces within public streetscapes. The aim is to enhance urban biodiversity, improve stormwater management, and make streets more attractive and liveable for communities (City of Melbourne, 2015).
- Accessible Natural Greenspace Standard (ANGSt) was developed in the mid-1990s in the United Kingdom to ensure that people have adequate access to natural green spaces near where they live. It sets specific distance and size criteria for green areas and is intended as guidance for local authorities, urban planners, and developers to support community health and well-being through better access to nature (Maksymiuk et al., 2019).

Financial and economic tools support the funding, implementation, and long-term sustainability of green infrastructure projects worldwide. Examples include public investment programs, green bonds, climate funds, development bank financing, public–private partnerships, user-based stormwater fees, and fiscal incentives for property owners. International financial institutions and multilateral development agencies often play a pivotal role in securing capital for green infrastructure in both developed and developing contexts. By aligning economic incentives with environmental outcomes, these tools can help to increase the scale of green infrastructure, reduce financial barriers, and ensure ongoing maintenance and performance over time.

Examples of tools belonging to the group of financial and economic measures related to the implementation of green infrastructure, as follows:

- The Greater Manchester Green Spaces Fund is a communityfocused grant program in the Greater Manchester region (the United Kingdom). Its main goal is to support local groups in creating new green spaces or improving existing naturerich areast where people and wildlife need them most (GMEF, 2022).
- Green Roof Subsidies, the city of Vienna (Austria) has introduced a financial support program for green roofs, offering subsidies of around 8–25 EUR per 1 m^2 of green roof area, up to a maximum of around 2,200 EUR per project (Burszta-Adamiak & Fiałkiewicz, 2019).
- Adopt a Park, it is an official program of the Brazilian government, created to raise funds for the protection and conservation of national parks and other nature conservation areas. The program enables companies (both Brazilian and foreign) and individuals to provide financial or material support to national parks struggling with limited state budgets (da Silva Freitas et al., 2021).

Community engagement and capacity-building tools focus on ensuring the equitable, inclusive, and participatory implementation of green infrastructure across different cultural and governance contexts. Examples of these tools include stakeholder consultations, participatory design processes, co-creation workshops, public awareness campaigns, and professional training programs for planners and local authorities. These tools empower communities to contribute local knowledge, identify priorities, and foster shared ownership of projects. Strengthening institutional capacity and social engagement improves transparency and builds trust, enhancing the long-term effectiveness and resilience of green infrastructure initiatives worldwide. Examples include:

- Neighbohood with Climate, a serious simulation game developed at the Department of Landscape Architecture of Warsaw University of Life Sciences (SGGW) as part of the project entitled CoAdapt – Communities for Climate Change Action. Its purpose is to support residents of housing estates in understanding and selecting climate-adaptive measures, as well as to stimulate collective decision-making regarding green infrastructure solutions in their neighborhoods (Kuchcik et al., 2024).
- Million Trees for Warsaw, the mobile application developed and issued by the Warsaw City Hall (Poland), available on Google Play (Android) and the App Store (iOS). The app actively engages residents, who can suggest tree-planting locations. The primary objective of the program is to increase tree cover along the city's main streets and in parks, squares, and other accessible public spaces where residents expect greenery (Wyrzykowski & Mościcka, 2024).
- Participatory Budget of Lisbon is a citizen-driven democratic process in which residents and other stakeholders propose, discuss, and vote on how a portion of the municipal budget is spent. It was first introduced in 2008, making it one of the first European capitals to introduce this democratic tool. Since 2019, it has operated as a "green participatory budget," meaning that allocated funds are specifically directed toward environmental sustainability and climate-related initiatives. The program supports projects focused on green infrastructure, such as urban gardens, tree planting, and the renaturalization of public spaces. It also includes sustainable mobility projects, such as cycling paths and pedestrian improvements, as well as climate adaptation measures, such as water retention systems (Falanga et al., 2021).

The implementation of IG can be based on:

- planning and policy tools,
- regulatory and legal tools,
- design and technical tools,
- financial and economic tools,
- community engagement and capacity building tools.

4.3. GREEN INFRASTRUCTURE PRINCIPLES

Green infrastructure principles refer to the foundational concepts and guidelines used to plan, design, and manage networks of natural and semi-natural systems that provide environmental, economic, and social benefits. These principles aim to integrate nature into urban and regional development frameworks to enhance sustainability and resilience.

One of the most frequently repeated and fundamental assumptions is to treat green infrastructure as a coherent, functional network. The principle of connectivity (Hansen & Pauleit, 2014; Szulczewska, 2018; Monteiro et al., 2020; Natural England, 2023) refers to ecological connections (migration corridors, riverside corridors, habitat connections), functional connections (water flow, climate regulation, continuity of natural processes), social connections (recreational routes, walking and cycling paths), as well as institutional cooperation between spatial management entities. A coherent network of green and water corridors is crucial for maintaining biodiversity, strengthening the resilience of natural systems, and ensuring the continuity of ecosystem services.

The second key principle, common to most approaches, is multifunctionality. Green infrastructure should combine ecological (habitat protection, water retention, climate regulation), social (recreation, public health, social integration), cultural, and, in certain cases, economic functions (Hansen & Pauleit, 2014; Szulczewska, 2018). Monteiro et al. (2020) point out that multifunctionality increases the efficiency of space use, especially in cities where available land is limited. Multifunctionality also increases the resilience of the system – spaces that serve a variety of roles are less susceptible to degradation and better adapt to climate change. Natural England (2023) emphasizes that green infrastructure should simultaneously support nature, the health of residents, the local economy, and climate resilience.
The socio-ecological dimension of multifunctionality is also emphasized by Tzoulas et al. (2007), who link green infrastructure to public health, social cohesion, and environmental justice.

Diversity is also an indispensable element of the green infrastructure implementation process. The principle of diversity refers to the inclusion of various types of green spaces and water bodies: from city parks and private gardens, through urban forests and agricultural areas, to water reservoirs and watercourses (Szulczewska, 2018; Monteiro et al., 2020; Natural England, 2023). The diversity of the green infrastructure network increases the resilience of the system, allows for a better response to the diverse needs of residents, and strengthens ecological and landscape functions.

A very important aspect of implementing green infrastructure is a large-scale approach. Green infrastructure operates on many spatial levels from a single plot of land (e.g., green roofs), through the scale of a housing estate and city,

to the regional and national level (Hansen & Pauleit, 2014; Szulczewska, 2018; Monteiro et al., 2020). Natural England (2023) emphasizes that green infrastructure should function as a “living network” at all levels from a single site to the national scale. Therefore, effective green infrastructure planning requires taking into account the relationships between scales, integrating local actions with regional systems, and designing a hierarchical green structure.

Another important principle is the integration of green infrastructure with gray infrastructure (transport, buildings, water management). Hansen and Pauleit (2014) point to the need to coordinate the development of green infrastructure with other urban systems in physical and functional terms. Monteiro et al. (2020) extend this approach by emphasizing the synergy between nature-based solutions and traditional technical infrastructure. This integration includes, among other things, sustainable stormwater drainage systems, green transport corridors, and the adaptation of buildings to nature-based solutions. In this context, green infrastructure should not be treated as an addition to development planning, but as an integral part of it.

As emphasized by many authors (Benedict & McMahon, 2002; Firehock & Walker, 2015; Szulczewska, 2018; Grace, 2025), green infrastructure planning should be strategic and long-term. This means that actions must be taken ahead of urbanization processes so that the natural structure is an equal element in shaping the space, rather than merely a supplement to the buildings. A strategic approach also requires taking into account projected climate and demographic changes, including an increase in the frequency of extreme events. Green infrastructure should therefore be designed as a flexible and adaptive system capable of providing ecosystem services in the long term. In this context, proactive planning should be treated not only as a pro-environmental measure but also as a rational strategy for managing space and public resources.

The overview of principles presented above does not exhaust the entire issue. Among the defined principles of green infrastructure, there are also those that make the effectiveness of green infrastructure development dependent on cross-sectoral cooperation and the involvement of local communities (Benedict & McMahon, 2006; Szulczewska, 2018; Monteiro et al., 2020) and a transdisciplinary approach and the use of current data and scientific evidence (Hansen & Pauleit, 2014; Szulczewska, 2018; Natural England, 2023).

To help understand the importance of green infrastructure principles as a coherent and transparent approach to planning and implementing Nature-based Solutions, interpretative frameworks are also presented that enable the organization and categorization of individual principles, emphasising their diverse nature and functions in the planning and implementation process. Hansen and Pauleit (2014) divide the principles of green infrastructure planning into two groups: principles addressing the green structure (integration, multifunctionality,

connectivity, multiscale approach, multi-object approach) and principles addressing the governance process (strategic approach, social inclusion, transdisciplinarity). Szulczewska (2018) takes a slightly different approach, dividing the principles of green infrastructure into foundational and creating principles (Figure 4.3).

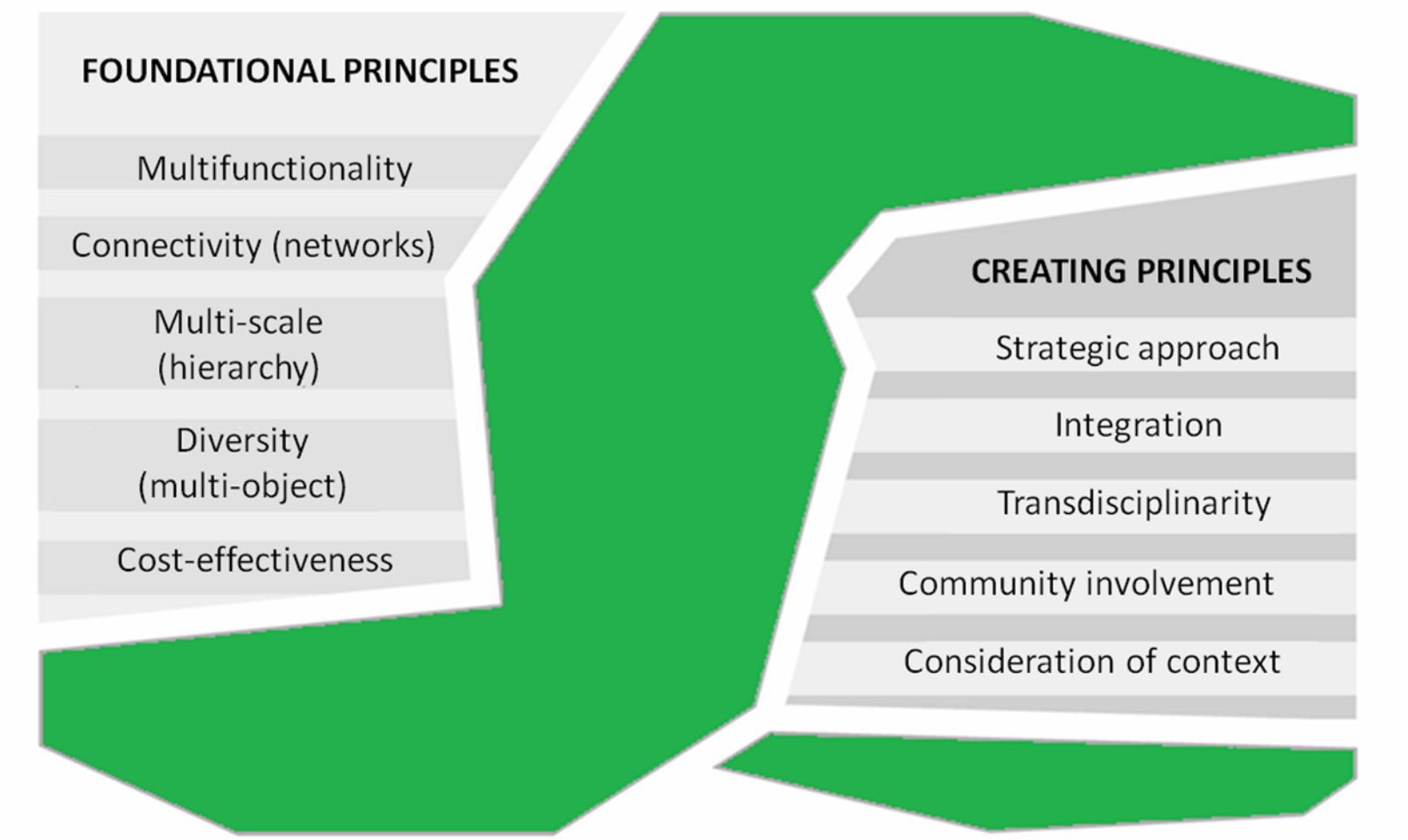

Figure 4.3. Green infrastructure principles (Szulczewska, 2018)

An interesting approach to grouping green infrastructure principles is presented in a guide developed by Natural England (2023). The fifteen principles presented there are divided into three groups: benefit principles, descriptive principles, and process principles (Table 4.2).

Table 4.2. Green infrastructure principles (Natural England, 2023)

Principle	Interpretation
Benefit principles	
Nature-rich, beautiful places	Green infrastructure supports nature to recover and thrive everywhere, in towns, cities, and countryside, conserving and enhancing natural beauty, wildlife, and habitats, geology and soils, and our cultural and personal connections with nature
Active and healthy places	Green neighborhoods, green/blue spaces, and green routes support active lifestyles, community cohesion, and connections to nature, which benefit physical and mental health, well-being, and quality of life. Green infrastructure also helps to mitigate health risks such as urban heat stress, noise pollution, flooding, and poor air quality

Table 4.2. Green infrastructure principles (Natural England, 2023) (cont.)

Principle	Interpretation
Thriving and prospering places	Green infrastructure helps create and support thriving communities that benefit everyone by fostering high-quality environments that attract businesses and investors, generating green jobs, supporting retail and high streets, and strengthening the local economy and regeneration
Improved water management	Green infrastructure reduces flood risk, improves water quality and natural filtration, helps maintain the natural water cycle and sustainable drainage at local and catchment scales, reducing pressures on the water environment and infrastructure, bringing amenity, biodiversity, economic, and other benefit
Resilient and climate-positive places	Green infrastructure makes places more resilient and adaptive to climate change and helps to meet zero-carbon and air quality targets. Green infrastructure itself should be designed to adapt to climate change to ensure long-term resilience
Descriptive principles	
Multifunctionality	Green infrastructure should deliver a range of functions and benefits for people, nature, and places, address specific issues, and meet their needs. Multifunctionality (delivering multiple functions from the same area of green infrastructure) is especially important in areas where provision is poor quality or scarce
Variety	Green infrastructure should comprise a variety of types and sizes of green and blue spaces, green routes, and environmental features (as part of a network) that can provide a range of different functions, benefits, and solutions to address specific issues and needs
Connectivity	Green infrastructure should function and connect as a living network for people and nature at all scales (e.g., within sites, and across regions/at the national scale). It should enhance ecological networks and support ecosystem services, connecting the provision of green infrastructure with those who need its benefits
Accessibility	Green infrastructure should create and maintain green liveable places that enable people to experience and connect with nature, and that offer everyone, wherever they live, access to good quality parks, green spaces, recreational, walking, and cycling routes that are inclusive, safe, welcoming, well-managed, and accessible for all
Responding to an area's character	Green infrastructure should respond to an area's character so that it contributes to the conservation, enhancement and/or restoration of landscapes; or, in degraded areas, creates new high-quality landscapes to which local people feel connected

Table 4.2. Green infrastructure principles (Natural England, 2023) (cont.)

Principle	Interpretation
Process principles	
Partnership	Work in partnership and collaborate with stakeholders from the outset to co-plan, develop, and deliver a vision for green infrastructure in the area. Engage a diverse and inclusive range of people and organizations, including citizens, local authorities, developers, landowners, communities, green space managers, environmental, health, climate, transport, and business representatives
Evidence	Use scientific evidence and good land use practices when planning and enhancing green and blue infrastructure. Understand the evidence for the benefits of current green infrastructure assets, and data on environmental, social, and economic challenges and needs in the area
Strategically planned	Plan strategically and secure green infrastructure as a key asset in local strategy and policy, at all scales. Fully integrate and mainstream green infrastructure into environmental, social, health, and economic policy. Create and maintain sustainable places for current and future populations and address inequalities in green infrastructure provision
Beautiful, well-designed places	Understand an area's landscape/townscape, natural, historic, and cultural character, to create well-designed, beautiful, and distinctive places
Managed, valued, monitored, and evaluated	Plan good governance, funding, management, monitoring, and evaluation of green infrastructure as a key asset from the outset and secure it for the long-term. Make the business care for green infrastructure. Engage communities in stewardship where appropriate. Celebrate success and raise awareness of green infrastructure benefits

It should be noted that the general principles of green infrastructure should always be tailored to the specific location, taking into account natural, social, and economic conditions. An example of green infrastructure principles is those set out in the Harlow and Gliston Garden Town Green Infrastructure Framework (LUC, 2022). These principles provide guidance for planners and designers on how to create context-led, ecologically sensitive, and multi-functional assets. The document defining the green infrastructure framework sets out a total of eight principles for the development of green infrastructure, which are specified in detail for individual landscape zones (Figure 4.4).

Principle 1: Adaptable green infrastructure that supports a variety of uses, can adapt to climate change, is a healthy space and is biodiverse

Produce a Green Wedge and Green Finger Management Plan, guided by an assessment of quality, character and need to determine the most appropriate forms of management interventions and biodiversity enhancements.

Principle 2: Enhancing the Green Belt and expanding the Green Wedge network

Where Green Wedges interface with growth areas or new development, they should form a continuous nature recovery, active travel and amenity network.

Principle 3: Landscape-led masterplanning which responds to natural character and function

Where Green Wedges adjoin with growth areas, they should be appropriate in scale to the surrounding network and follow the alignment of existing watercourses.

Principle 4: Designing in biodiversity, climate change mitigation and food security

Ensure biodiversity is designed into all new greenspaces / Green Wedges and contains a mosaic of habitats, including linear connecting features, stepping stones and core habitat areas.

Principle 5: Anticipating change and future proofing infrastructure

Where roads are present within Green Wedges, consider the reclamation of amenity green space or adjacent grass verges for SuDS, such as linear rain gardens, meadows or urban boulevards.

Principle 6: Changing the character of roads to streets

Where roads are present within Green Wedges, explore opportunities to create green buffers between people and vehicles through tree planting and segregated cycle and footpaths

Principle 7: Revitalising the cycle, horse riding and walking network

Ensure all existing and new Green Wedges accommodate direct, spacious and safe multi-user routes, taking the focus away from vehicle movement and more towards active travel.

Principle 8: Responsive and distinctive design

Protect and reinforce the character of existing Green Wedges respecting Gibberd's vision and green framework.

Figure 4.4. Green infrastructure principles for green wedges landscape zone (LUC, 2022)

The principles of GI focus on several key pillars:

- connectivity
- multifunctionality,
- a multiscale approach,
- integration with other systems,
- diversity,
- strategic planning,
- participation,
- sustainable management.

Review questions:

1. Which international frameworks support the development of GI?
2. What are some key European strategies for promoting GI?
3. Name at least three types of tools used to implement GI.
4. What are the core principles that guide the design and management of GI?

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5. SIGNIFICANCE OF GREEN INFRASTRUCTURE FOR SOCIAL WELL-BEING, ENVIRONMENTAL RESILIENCE, AND SUSTAINABLE DEVELOPMENT

What is this chapter about:
This chapter focuses on the importance of green infrastructure (GI), highlighting how parks, trees, rivers, and other elements of nature contribute to social well-being, environmental resilience, and sustainable development. It discusses the numerous benefits of GI, including its role in promoting physical and mental health, supporting recreational activities, and improving quality of life. It also addresses the planning and management of GI, helping readers understand what needs to be considered to create a healthy, resilient, and sustainable urban environment.

What you will learn:
- What benefits are provided by GI.
- What links exist between ecosystem services and human well-being.
- What are the reasons for introducing GI.

5.1. BENEFITS OF GREEN INFRASTRUCTURE

Ecosystems and their functions are crucial to shaping the human environment, influencing natural processes such as air and water purification, climate stabilization, soil fertility maintenance, nutrient cycling, plant pollination, flood regulation, carbon storage, and habitat creation and maintenance. In addition, ecosystems provide resources such as food, timber, and medicinal plants, directly supporting human livelihoods. Ecosystems also offer opportunities for recreation and cultural and aesthetic experiences.

Ecosystem functions represent the fundamental engine that drives the entire ecological system. These are the complex suite of biological, geochemical, and physical processes, such as nutrient cycling, energy flow, and soil formation, that occur through interactions between species and their environment to sustain the ecosystem’s structure and operation. In essence, ecosystem

functions describe how natural systems work. The benefits that human populations derive from these processes are termed ecosystem services, which constitute the tangible and intangible goods like food, clean water, and climate regulation that humanity obtains from nature. This relationship is one of direct dependence; ecosystem services are wholly contingent upon the continued, unimpeded functioning of underlying ecological processes. Consequently, any disruption to a core ecosystem function will inevitably lead to the degradation of the services it supports.

Ecosystem services are broadly defined as the benefits human populations derive, directly and indirectly, from natural ecosystems and the biodiversity within them (Costanza et al., 1997; MEA, 2005), often conceptualized as “nature’s contributions to people”. These services are not produced in isolation but are the direct result of complex, underlying ecological processes and functions arising from interactions between species and their physical environment. Consequently, the concept of ecosystem services provides a critical framework for understanding the interdependence of human well-being and economic development on the health of natural systems (Xue et al., 2019), thereby forming a vital bridge between ecology, society, and the economy.

Figure 5.1 visualizes the robust but variable connections between ecosystem services and human well-being, showing how socioeconomic factors can sometimes weaken these links (e.g., by buying substitutes for a lost service). These relationships are context-specific, differing by region and ecosystem. The diagram presents a critical part of a larger, dynamic system where well-being is also influenced by other economic, social, and technological factors, and where ecosystems are subsequently affected by human outcomes.

Ecosystem services are fundamental to human life, supporting four essential dimensions of existence:

1. Human well-being: Regulating services provide clean air, water, and climate stability, which are prerequisites for physical health. Provisioning services deliver food and water security, while cultural services from natural spaces are vital for mental and psychological well-being.

2. Economic prosperity: Provisioning services are direct capital inputs for industries like agriculture, forestry, food, and pharmaceuticals. Regulating services provide immense cost savings by mitigating disasters and reducing infrastructure needs, delivering both market and non-market economic value.

3. Social cohesion: Ecosystems foster community bonds through shared resource management and provide spaces for social interaction. Their degradation often exacerbates social inequality, making their protection a matter of environmental justice.

4. Cultural identity: Ecosystems form the bedrock of cultural heritage, providing spiritual, aesthetic, and educational value. They shape worldviews, inspire creative expression, and are fundamental to a society's sense of place and identity.

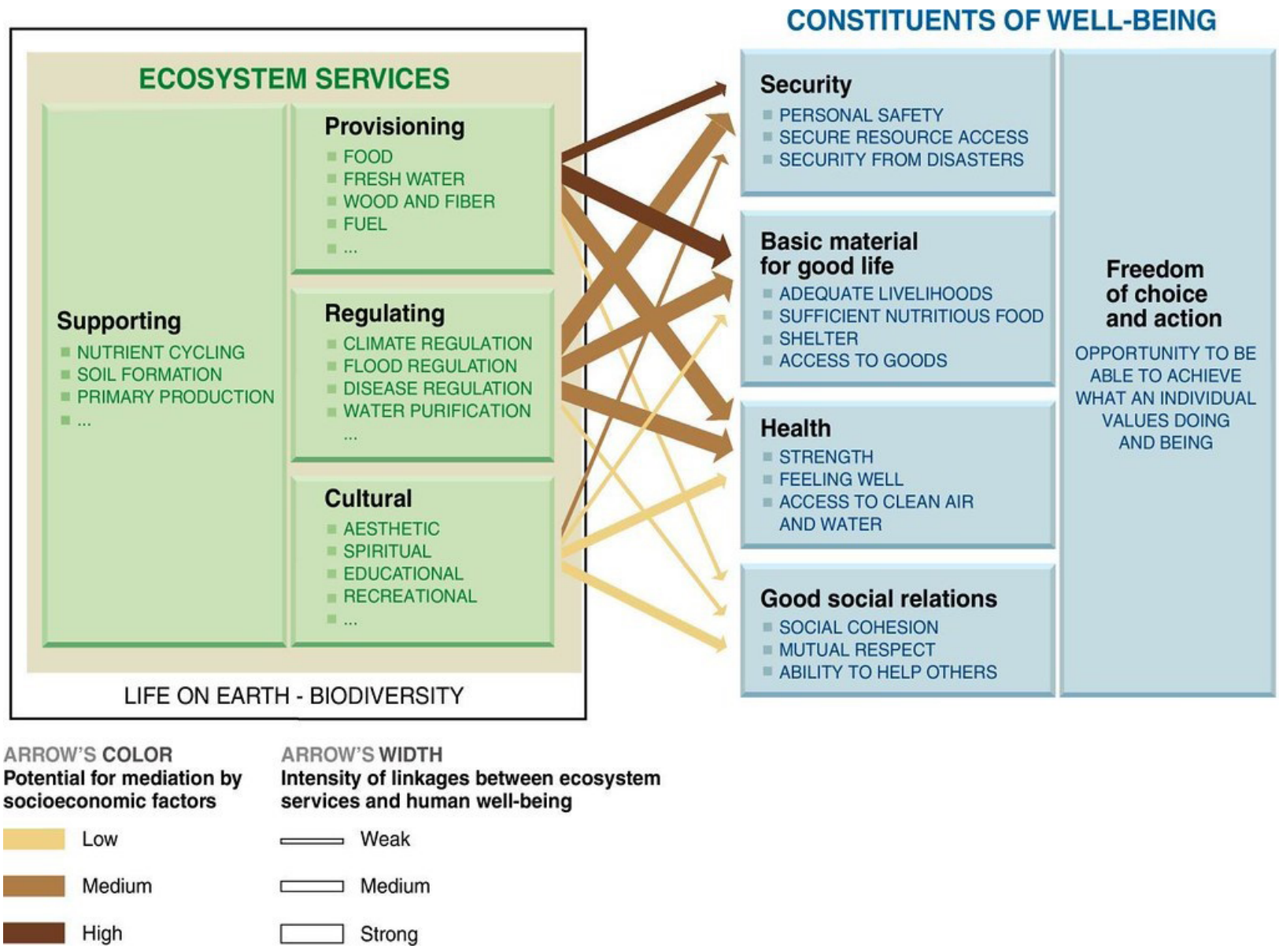

Figure 5.1. Linkages between ecosystem services and human well-being (MEA, 2005)This interconnected framework of ecosystem services becomes tangible when applied to a specific ecosystem. A forest serves as a powerful, real-world case study, demonstrating how a single natural system simultaneously contributes to human wellness, economic prosperity, social cohesion, and cultural identity (Table 5.1).

Table 5.1. The impact of forest ecosystems on ecosystem services and quality of life (own work)

Service category	What it provides	Impact on quality of life
Provisioning and supporting	timber, wild foods The trees and soil are part of the global nutrient and water cycles	Physical health: cleaner air reduces asthma rates Mental well-being: opportunities for recreation reduce stress and improve mood Economic prosperity: the timber industry provides jobs; clean water reduces municipal treatment costs; tourism generates revenue Social cohesion and cultural identity: the forest may be a cherished community landmark, a place for family gatherings, and part of the local heritage
Regulating	Captures carbon (climate regulation), cleans the air, and stabilizes slopes to prevent erosion	
Cultural supporting	A place for hiking (recreation), spiritual solace, and scientific study	

Ecosystem services are the indispensable link between healthy natural systems and human societies. They are not merely “environmental amenities” but are fundamental to our survival, health, economic stability, and cultural fulfillment. Recognizing their value is the first step toward making decisions that protect and enhance these vital services, thereby securing long-term human well-being and quality of life. However, the concept of ecosystem services is not widely known outside the scientific community and is often perceived as complex or overly academic (Giedych et al., 2026). As a result, many stakeholders involved in green infrastructure development, such as planners, investors, local communities, and decision-makers, may find it difficult to engage with this approach. Presenting these services in terms of clear and practical benefits can therefore improve understanding, support communication, and help identify needs and priorities for green infrastructure investment (John et al., 2019). This approach will facilitate understanding of the multifunctional role of green infrastructure in supporting environmental quality, social needs, and economic opportunities (Figure 5.2), making it a key element of sustainable landscape planning and management.



Figure 5.2. Groups of benefits of green infrastructure (John et al., 2019)

5.2. PROMOTING HEALTH AND WELL-BEING THROUGH GREEN INFRASTRUCTURE

Conventional urban planning, often dominated by automotive infrastructure, can create environments that discourage physical activity. The resulting sedentary lifestyles are a significant risk factor for chronic diseases. In response, green infrastructure, including parks, urban forests, and greenways, is increasingly recognized as a critical public health strategy. This chapter examines the mechanisms by which green infrastructure promotes well-being, detailing how accessible and attractive green spaces incentivize routine physical activity and how exposure to natural settings reduces stress, anxiety, and depression, thereby enhancing both physical and mental resilience.

The strategic placement of green infrastructure is a critical public health and environmental justice measure. Prioritizing parks, street trees, and green spaces in historically underserved neighborhoods can reduce air pollution and asthma rates, promote physical and mental well-being, and provide shade that mitigates heat stress, particularly in vulnerable communities (Di Marino & Lapintie, 2018; Grabowski et al., 2023).

Green infrastructure promotes physical activity by creating environments that are accessible, safe, and attractive. Accessibility, achieved by locating parks and greenways within a short walking distance, removes the barrier of convenience. Safety is ensured through design features that provide passive surveillance, separation from traffic, and good maintenance. Crucially, the inherent attractiveness of natural settings, with aesthetic pleasure, varied terrain, and comfort from tree shade, serves as a key incentive. In essence, green infrastructure transforms the built environment to actively encourage walking, cycling, and play.

Green infrastructure promotes mental health and well-being by reduction of stress, anexity and depression through exposure to natural settings. This pathway is more psychological and physiological, explaining how even passive exposure to nature can heal and restore the mind. Modern life, especially in cities, is filled with stimuli that cause “directed attention” (e.g., screens, traffic noise, work deadlines). This constant mental effort leads to attention fatigue, increasing stress, irritability, and mental exhaustion. This is a key contributor to the high prevalence of stress-related disorders, anxiety, and depression.

Exposure to natural environments within green infrastructure facilitates psychological restoration through two key theoretical frameworks: stress reduction theory (Ulrich, 1983) and attention restoration theory (Kaplan & Kaplan, 1989). Stress reduction theory suggests that natural settings prompt an innate, positive physiological shift. This response reduces stress hormones, lowers blood pressure, and relaxes muscle tension, effectively moving the body from a state of “fight-or-flight” to “rest-and-digest” (Ulrich, 1983). Attention restoration theory posits that nature engages the mind through “soft fascination,” such as watching clouds or flowing water. This effortless engagement allows the brain’s directed attention mechanisms to recover, thereby reducing mental fatigue and restoring focus and cognitive capacity. In essence, green infrastructure provides a dual restorative benefit: it mitigates physiological stress and facilitates mental recovery, serving as a vital countermeasure to anxiety, burnout, and cognitive exhaustion (Kaplan & Kaplan, 1989).

Both theories explain how green infrastructure supports health, highlighting the importance of contact with green spaces for human well-being. This aspect is often addressed in urban policy documents, which, although rarely using the term ecosystem services, clearly appreciate the benefits of urban greenery in practice (Hansen et al., 2015). In this context, the importance of specific elements of green infrastructure, such as parks, which materialize these benefits in the everyday lives of residents, is particularly evident.

Parks are spaces where environmental, social, and health elements come together to form a coherent whole. The natural environment promotes regeneration and tranquillity, the presence of other people supports the building of social relationships, and the opportunity for outdoor activities strengthens physical and mental health. As Maller et al. (2009) emphasize, parks are places where different dimensions of well-being complement and reinforce each other (Table 5.2).

Table 5.2. A summary of the contribution of parks to human health and well-being (Maller et al., 2009)

Component of health	Contribution of parks
Physical	Provide a variety of settings and infrastructure for various levels of formal and informal sport and recreation, for all skill levels and abilities, e.g., picnicking, walking, dog training, running, cycling, ball games, sailing, surfing, photography, birdwatching, bushwalking, rock climbing, camping
Mental	Make nature available for restoration from mental fatigue; solitude and quiet; artistic inspiration and expression; educational development (e.g. natural and cultural history)
Spiritual	Preserve the natural environment for contemplation, reflection, and inspiration; invoke a sense of place; facilitate a feeling of connection to something beyond human concerns
Social	Provide settings for people to enhance their social networks and personal relationships, from couples and families to social clubs and organizations of all sizes, from casual picnicking to event days and festivals
Environmental	Preserve ecosystems and biodiversity, provide clean air and water, maintain ecosystem function, foster human involvement in the natural environment (Friends of Parks groups, etc.)

The WHO report on urban green spaces and health emphasizes that the availability, accessibility, and quality of green spaces shape both environmental benefits, such as cleaner air, temperature regulation, and biodiversity support, and opportunities for physical activity, social interaction, and relaxation (WHO, 2016). These factors, in turn, affect physical health, mental well-being, and social cohesion. The report presents this as a comprehensive framework showing how thoughtful planning and design of urban green spaces can promote healthier and more resilient cities (Figure 5.3).

Similarly, the German Federal Agency for Nature Conservation (BfN) emphasizes in its report on green spaces and health that urban green areas must be designed to meet several key criteria to provide real benefits to residents. First of all, accessibility and inclusiveness are essential so that all groups – including people with limited mobility or low incomes – can use these spaces without barriers. The diversity of functions and zones is also important, including areas for activity, quiet relaxation, contact with nature, and recreation, allowing green spaces to respond to the varied needs of users. Proximity and easy pedestrian access enable residents to use parks on a daily basis rather than only occasionally. Finally, for green spaces to deliver real health and environmental benefits, their design should incorporate natural health-supporting effects such as microclimate cooling and air purification. Only when these criteria are met can urban green spaces fully realize their potential and contribute to improving residents' health and quality of life (Rittel et al., 2014).

The Landscape Institute position statement on public health and landscape (Landscape Institute, 2013) emphasizes that public health can be supported through integrated planning and design processes, such as:

- integrating the protection of natural resources (air, water, soil) into spatial development,
- integrating health considerations into master plans and new development projects,
- designing green infrastructure that promotes physical activity and active travel (walking and cycling),
- creating accessible and inclusive public spaces that strengthen social cohesion,
- shaping green spaces that support physical and mental well-being.

This document emphasizes that the creation of healthy places should be guided by several key principles. According to the statement, healthy places improve environmental conditions including air, water, and soil, as well as incorporate features that help communities adapt to and mitigate the impacts of climate change. They address health inequalities and encourage healthy lifestyles, while also promoting social cohesion, reducing stress, isolation, and antisocial behavior. Furthermore, these spaces provide opportunities for work, learning, and personal development. Ultimately, healthy places are restorative and uplifting environments that support both physical and mental health. Together, these principles highlight the importance of thoughtfully planned landscapes in fostering well-being and creating environments that enable healthier, more resilient communities.



Figure 5.3. A causal model of the impacts of urban green spaces on health and well-being (WHO, 2016)

Contact with nature can support residents' health in multiple ways. Conversely, limited access to natural environments is increasingly associated with rising mental health problems, weakened immune function, and a higher risk of chronic diseases. Green infrastructure can mitigate these effects by facilitating regular interaction with natural environments in everyday urban life. Studies have shown a positive relationship between exposure to urban green spaces and residents' self-rated health (Takano, 2002). Living in areas with accessible green spaces has also been linked to increased longevity among older adults, regardless of age, gender, marital status, baseline functional status, or socioeconomic status (Song et al., 2022). Moreover, physical activity in urban green spaces contributes to the prevention of cardiovascular diseases in adults (Matsunaga et al., 2011; Igarashi et al., 2015; Hoffman et al., 2018; Ng et al., 2018; Uijtdewilligen et al., 2019; Pratiwi et al., 2019, 2020). Exposure to natural environments has also been shown to positively influence immune system functioning (Lee et al., 2009, 2012; Park et al., 2009, 2010; Miyazaki et al., 2015; Ochiai et al., 2015; Song et al., 2016).

Green infrastructure not only provides spaces for daily contact with nature, bringing numerous health benefits to the entire community, but it can also serve as therapeutic environments for individuals with already diagnosed health needs. In response to the growing interest in the impact of nature on health, a variety of nature-based interventions have been developed in recent years, using natural environments as tools to support medication, rehabilitation, and overall psychophysical well-being (Shanahan et al., 2019).

The most commonly applied methods include forest therapy (silvotherapy), horticultural therapy (therapeutic gardens and gardening activities), adventure therapy (outdoor programs and educational expeditions), and ecotherapy (meditation and mindful engagement with nature). All of these interventions involve deliberate and organized use of nature, where participants engage with planned, safe green spaces designed to promote active interaction with the environment.

The primary goals of these therapies are stress reduction, mood improvement, enhancement of cognitive functions, and increased quality of life and psychological well-being (Lee, 2015; Pratiwi et al., 2025), as well as physical health (Takano, 2002). Additionally, regular contact with nature through such interventions supports the development of social bonds (He et al., 2025), encourages physical activity, and enhances the body's adaptive processes, making them a valuable complement to traditional treatment and recovery methods.

5.3. GREEN INFRASTRUCTURE AS A FOUNDATION FOR THE DEVELOPMENT OF HEALTHY AND RESILIENT CITIES

The integration of green infrastructure and ecosystem service considerations into spatial planning and policy is not just an “environmental nice-to-have”. It is a fundamental prerequisite for building resilient, sustainable, and equitable cities for the 21st century and beyond. The importance of this integration can be understood by contrasting the old paradigm with the new, and by examining the profound benefits it delivers. The paradigm shift shows that urban development is transitioning from a gray-first, reactive approach that relies on engineered solutions to fix environmental problems, toward a green-integrated paradigm that embeds nature into urban systems from the outset, promoting multifunctional, cost-effective, and sustainable infrastructure that enhances resilience and overall urban quality of life (Ahern, 2007; Austin, 2014; Grabowski, 2023).

Taking green infrastructure and ecosystem services into account in urban strategies and planning decisions is essential to shift from fragmented initiatives to a cohesive, city-wide system, maximizing long-term environmental, social, and economic benefits while enhancing urban resilience and overall quality of life. Cities face escalating climate threats, including extreme heat, flooding, and drought. Green infrastructure offers a powerful adaptation strategy. Policy measures such as mandating green roofs, preserving urban forests, and creating green corridors can reduce urban heat, lower energy costs, prevent heat-related mortality, and mitigate flood risks through effective stormwater management (Di Marino & Lapintie, 2018; Monteiro et al., 2020).

Cities function as ecosystems and integrating green infrastructure fosters connected habitat networks rather than isolated green spaces. Developing a city-wide plan that links parks, river corridors, and greenways that support pollinators, birds, and other wildlife, enhancing biodiversity and maintaining essential ecological functions within urban environments (Ahern, 2007; Austin, 2014; Di Marino & Lapintie, 2018; Monteiro et al., 2020).

An example of this approach is Singapore’s Park Connector Network, designed using biophilic principles. The concept promotes linking green spaces, major parks, and nature reserves through a continuous system of green corridors (Figure 5.4). The park connector provides several ecosystem services. It supports provisioning services, particularly freshwater supply – an important function given Singapore’s water scarcity – as well as the provision of food and raw materials. It also contributes to regulating services, including watershed protection, climate regulation, and carbon sequestration. In addition, the network delivers cultural

ecosystem services, offering opportunities for education, recreation, and tourism, while also supporting intangible benefits such as aesthetic appreciation, spiritual values, and a stronger sense of place among residents (Friess, 2017; Sini, 2020).

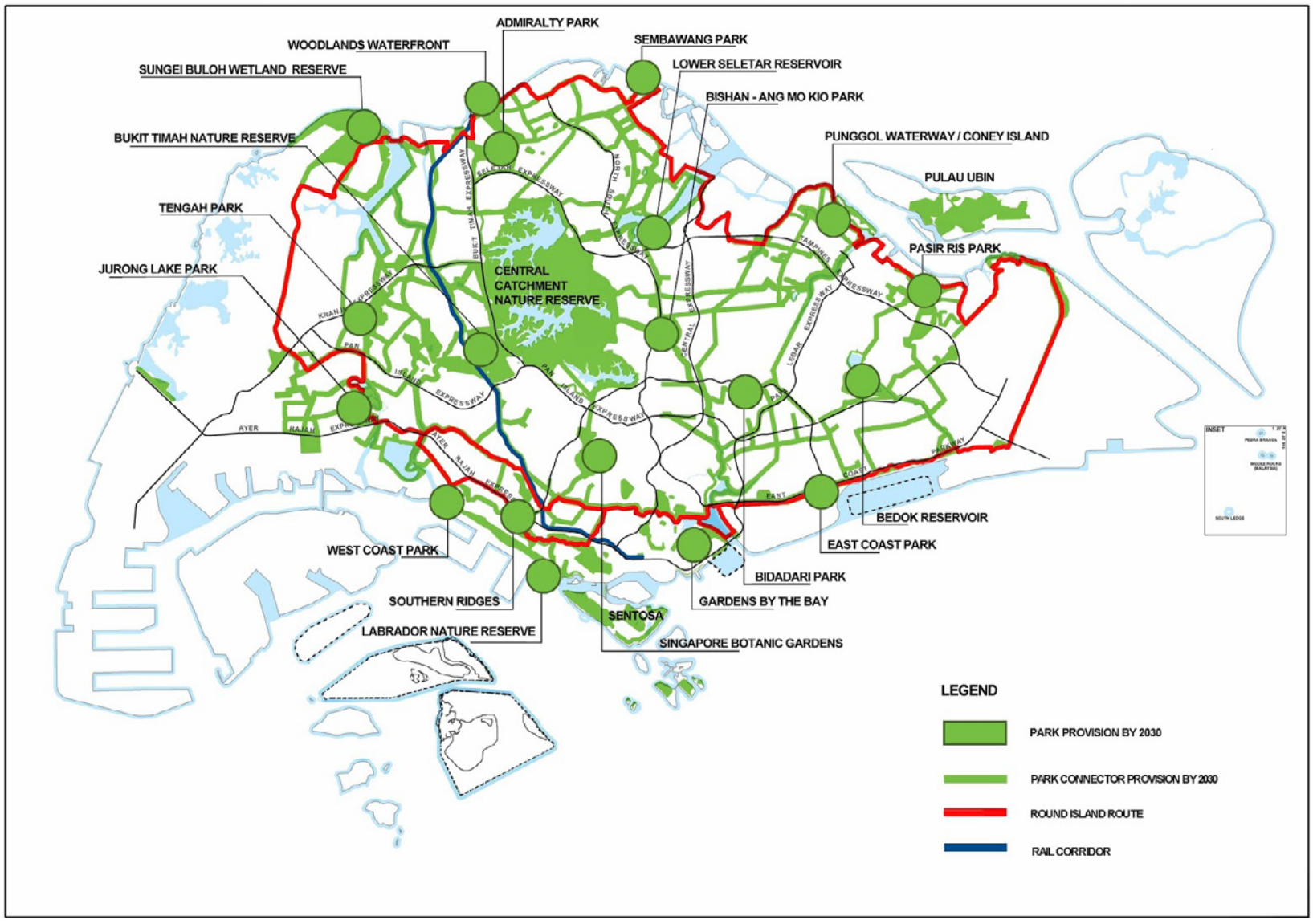

Figure 5.4. Singapore's Park Connector Network (Books & People, 2017)

Green infrastructure represents a smart investment that delivers substantial economic value and cost savings. By using green rather than gray solutions, cities can avoid costly infrastructure expansion, increase property values and tax revenues, stimulate tourism, and benefit from lower long-term maintenance expenses (Monteiro et al., 2020).

The successful implementation of green infrastructure depends on demonstrating its economic value. Cost–benefit framing can strengthen political and financial support. Incentives and regulatory tools such as density bonuses, development rights transfers, impact fees, and tax credits can encourage broader adoption. Phased implementation through pilot projects helps test feasibility and build momentum. Because green infrastructure spans administrative boundaries, coordinated funding and governance across jurisdictions (e.g., public works, parks, health, and transportation departments) are essential for long-term success (Hickie, 2004; Austin, 2014; Monteiro et al., 2020).

In the United Kingdom, there is a growing emphasis on natural capital valuation, which involves estimating the value that nature brings to society and the economy. The aim is to incorporate environmental issues into public policy and investment planning so that decisions on urban development, nature conservation, and infrastructure reflect the real social, health, and economic benefits of nature. In this context, the Greater London Authority, National Trust and Heritage Lottery Fund (2017) prepared the “Natural capital account for London”, which estimated the economic value of green spaces in London, including parks, trees, rivers, and other elements of urban nature. The report demonstrates that the natural environment delivers tangible benefits, such as improved public health, opportunities for recreation, climate regulation, carbon storage, and increased property values. It serves as a practical tool for planners and decision-makers, allowing the value of green infrastructure to be incorporated into city development strategies and public investments, treating nature as a significant urban asset rather than merely a maintenance cost.

The report presents an estimated annual economic value of various ecosystem services provided by public green spaces in London. The summary presented in Table 5.3 shows the specific benefits that parks and other green areas provide and their annual financial value. It includes, among other things, the value of recreation and daily use of green spaces by residents, health benefits from physical activity and improved well-being, increased property values near parks, and key environmental functions such as urban temperature regulation, carbon sequestration, and air quality improvement. These data indicate that green spaces generate substantial economic benefits, often exceeding their maintenance costs. Overall, the findings clearly demonstrate that urban greenery should be regarded not only as a landscape feature or recreational space but as an essential component of a city’s natural capital, delivering measurable social, health, and economic benefits.

Table 5.3. Main sources of value derived from parks (Greater London Authority, National Trust, & Heritage Lottery Fund, 2017)

Park benefit type	Value (in billion) [GBP]	Share [%]
Physical health	11	12
Mental health	7	7
Residential property amenity	56	61
Recreation	17	19
Others	1	1
Gross asset value	92	100

The early integration of green infrastructure in urban planning is essential. It should be conceived at the outset or alongside urban development rather than as a later addition after construction. Meaningful public participation and stakeholder engagement foster local support, align projects with community values, and help identify multifunctional opportunities. Successful implementation also depends on strong interdisciplinary coordination, bridging fields such as landscape architecture, ecology, environmental engineering, urban planning, and public works to ensure a coherent and effective design process (Austin, 2014; Monteiro et al., 2020; Grabowski et al., 2023).

Green infrastructure performs a variety of functions, from water retention to climate and air quality improvement to biodiversity enhancement, all of which contribute to health and comfort and the resilience of a city. The synergy effect plays a key role here (Figure 5.5): individual processes support each other, so that the total ecological, social, and health value of the system exceeds the sum of the benefits of individual actions.

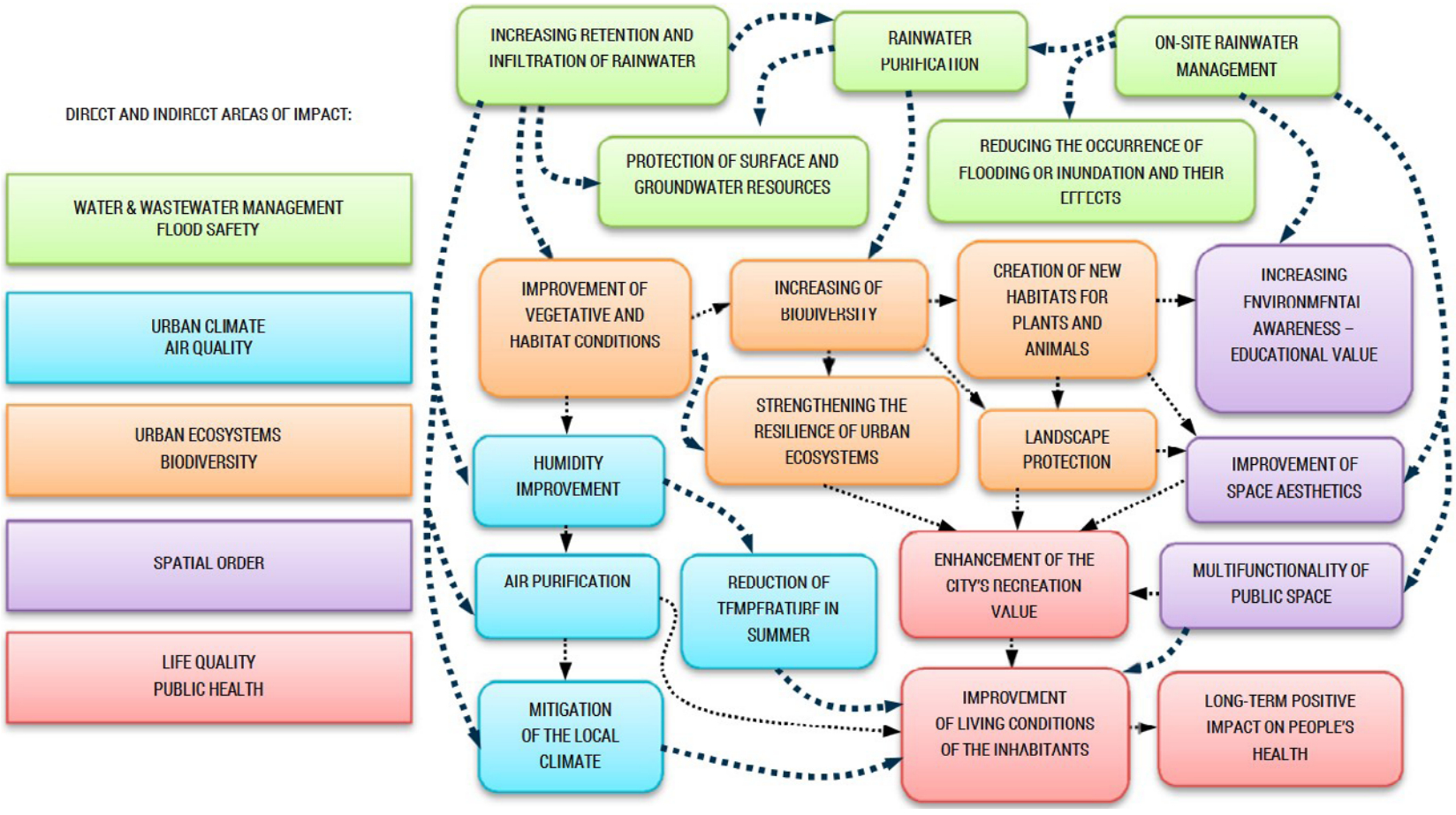

Figure 5.5. Synergy effects in the implementation of blue-green infrastructure (Bernaciak et al., 2025)

The decisions made today will shape urban resilience and livability for decades to come. Investing in green infrastructure is an investment in intergenerational equity. Updating zoning codes, development standards, and long-term comprehensive plans to embed green infrastructure requirements equips cities to address future challenges, with cleaner air, more reliable water, and healthier environments for future generations (Di Marino & Lapintie, 2018; Monteiro et al., 2020).

Failing to integrate green infrastructure and ecosystem services into urban development is a missed opportunity of monumental scale, leading to higher costs, greater vulnerability, and poorer public health. Strengthening implementation through public–private partnerships can encourage developers to incorporate parks, green streets, and natural areas as value-added, multifunctional amenities. Education and capacity building equip professionals to design and apply green infrastructure effectively. By consciously planning cities with nature, we activate a powerful, multi-beneficial toolset to build urban environments that are resilient, equitable, and economically vibrant for generations to come.

Review questions:

1. How do ecosystem services contribute to human well-being?
2. How do ecosystem services contribute to economic prosperity?
3. What is the importance of GI for nature and environmental protection?
4. How do ecosystem services contribute to social cohesion?
5. How do ecosystem services contribute to cultural identity?
6. How does GI support physical health?
7. How does GI support mental health?

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6. SPECIFICS OF GREEN INFRASTRUCTURE DEVELOPMENT IN DIFFERENT SPATIAL SCALES AND CONTEXTS

What is this chapter about:
The first part of the chapter explores the spatial scales of green infrastructure (GI) and explains how GI functions as a hierarchical and interconnected system operating from the site level to the continental scale. It discusses the multi-scale approach and the importance
of cross-scale connectivity for ensuring ecological continuity and system effectiveness. The chapter also presents different models of scale classification and highlights how definitions and typologies of GI elements vary depending on planning traditions, institutional frameworks, and analytical perspectives. Particular attention is given to the functional role, implementation mechanisms, and governance challenges associated with each spatial level.

In the second part, challenges related to GI development in different spatial contexts are discussed, with a distinction made between urban, suburban, and rural settings. The analysis links specific constraints characteristic of each context with appropriate GI solutions.

What you will learn:
- What does a multiscale approach to GI planning involve.
- How does spatial scale influence the selection of GI elements.
- How do spatial constraints, competition for land use, and the dominance of gray infrastructure affect GI planning in cities.
- What is specific about designing GI in suburban areas.
- What are the main elements and functions of GI in agricultural landscapes.

6.1. MULTI-SCALE APPROACH OF GREEN INFRASTRUCTURE

One of the fundamental characteristics of green infrastructure is its hierarchical and network-based structure, which enables it to operate across different spatial scales (Szulczewska, 2018). The definition of green infrastructure is complex, as the concept is applied for different purposes and at different spatial levels.

At the largest scale, the European Union defines green infrastructure as a component of a continental (pan-European) ecological network connecting Natura 2000 sites, ensuring habitat continuity and enabling the migration of species of community importance. At smaller scales, the concept refers to specific technical solutions, such as green roofs, green walls, and stormwater management systems (Tahvonen, 2018).

Green infrastructure is not a collection of isolated green spaces but a system of spatially and functionally interconnected elements. Its effectiveness depends not only on the quality of solutions implemented at a given scale, but primarily on maintaining connectivity. This connectivity has a dual character: it concerns relationships between elements within the same scale, as well as linkages between different spatial levels. Such an understanding is referred to as the multi-scale approach and assumes that green infrastructure functions in an integrated manner across multiple scales simultaneously (Hansen & Pauleit, 2014).

Green infrastructure planning may encompass initiatives ranging from the level of an individual parcel to the regional and even national scale (Benedict & McMahon, 2002), or the continental scale (Zulian et al., 2021). The multi-scale approach implies that locally implemented solutions should remain connected to broader spatial structures, while strategic decisions at the regional level provide the framework for design and investment activities at the site scale. At each scale, green infrastructure contributes to shaping ecological processes and strengthening environmental and social resilience.

In ecological network analysis, the multi-scale perspective demonstrates that the same spatial element may perform different functions depending on the level of reference. An area that constitutes a habitat patch at the local scale may form part of an ecological corridor at the regional scale, connecting larger core areas. This relativity of landscape elements is widely discussed in landscape ecology literature (Forman, 1995). Consequently, the interpretation of a given green infrastructure element depends on the spatial context in which it is analyzed.

The multifunctionality of green infrastructure enables a cross-scale approach that combines assessments across different governance levels with active stakeholder engagement. Research conducted from this perspective enhances the understanding of green infrastructure multifunctionality and its role in diverse spatial contexts (Zulian et al., 2021). An example of such an approach is the implementation of green infrastructure in the Lombardy, where even highly urbanized areas can contribute to the development of a continental ecological network.

The division of green infrastructure into specific spatial levels is not universal. The number and scope of scales depend on the adopted definition of green infrastructure, the institutional context, and the objective of the analysis. At the same time, the definition of green infrastructure itself may result from the applied scale (Tahvonen, 2018). In some approaches, scale differentiation is based on administrative divisions, in others, on ecosystem types, and in others, on functional landscape linkages.

The model proposed by the U.S. Environmental Protection Agency (Figure 6.1) presents a hierarchical framework for planning and implementing green infrastructure, in which actions undertaken at lower scales derive from objectives defined at the regional level. In this approach, communities can plan for and promote a network of green infrastructure implementation across a region to protect natural resources, meet regulatory requirements, and achieve long-term environmental and development goals. These regional objectives are then translated into more targeted interventions at the neighborhood and site scale, where actions focus on implementing specific green infrastructure solutions within clearly defined, smaller areas.

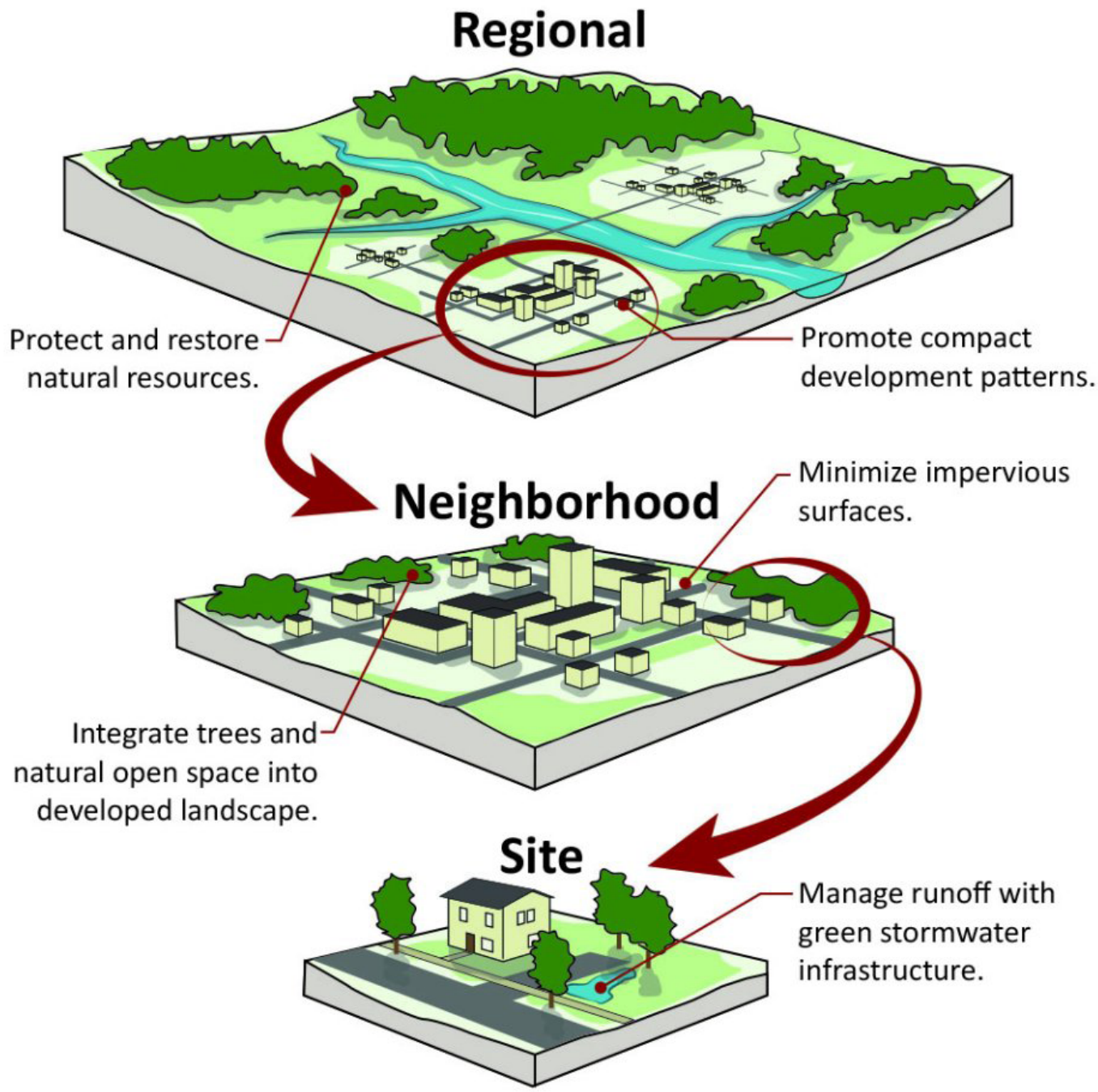

Figure 6.1. Green infrastructure at different scales (EPA, 2025)

Green infrastructure analyses within a given area are closely linked to the spatial planning system. This relationship results from the availability of legal, financial, and organizational instruments that enable the implementation of green infrastructure objectives. The most operational and direct tools are typically identified at more detailed scales. However, it is the hierarchical spatial planning system that ensures coherence of objectives and spatial continuity of the entire green infrastructure network. For this reason, it is justified to refer not only to local and regional levels but also to the national and even continental scale.

The continental scale is primarily addressed in strategic documents and reports prepared for the European Commission (Szulczewska, 2018). In the EU Biodiversity Strategy for 2030 (Communication COM/2020/380), the continental level is a means of instrumentally implementing green infrastructure to support a coherent transnational ecological network of protected areas and to maintain and restore terrestrial ecosystems (Communication COM(2019) 236).

The continental approach was tested in the Lombardy (Zulian et al., 2021). Figure 6.2 presents the configuration of three levels of green infrastructure and their relationships, illustrating the interdependencies within the Italian spatial planning system and explaining the connections between the different decision-making levels.

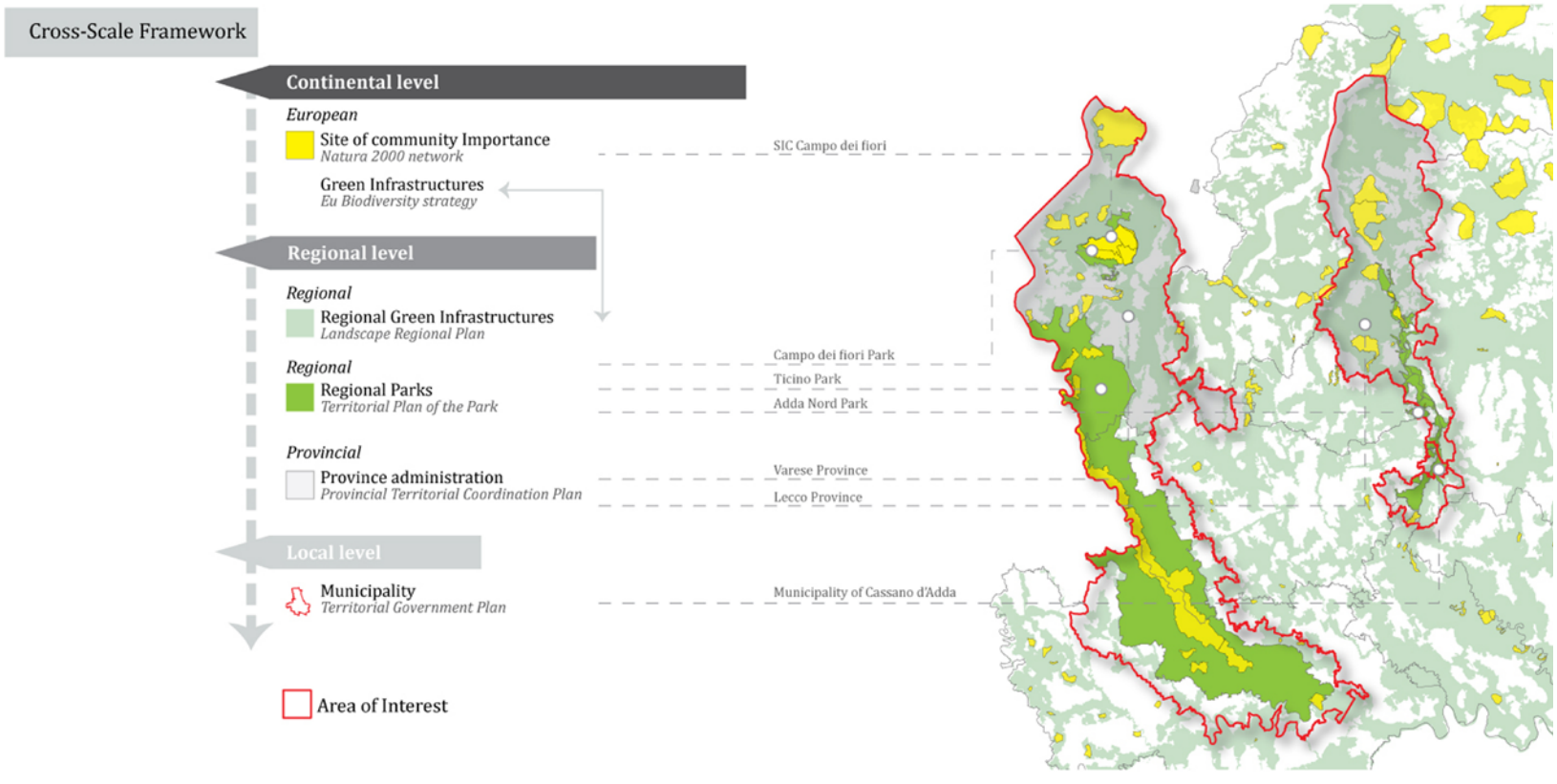

Figure 6.2. The cross-scale framework based on the three governance levels of the Italian planning system (Zulian et al., 2021)

Other examples of green infrastructure at the continental scale are presented in the Mesoamerican Biological Corridor (see Chapter 8.1.2) and the Great Green Wall (see Chapter 8.1.4).

Another four-level model enables a more precise differentiation of spatial levels within the settlement structure. In this framework, green infrastructure is analyzed at the regional, city, neighborhood, and site scale (Tauhid, 2019). The city scale is explicitly distinguished as an intermediate level between the regional and neighborhood scales.

This model emphasizes the functional differentiation of green infrastructure elements across scales, from ecological corridor systems at the landscape level to retention and infiltration solutions implemented at the level of an individual parcel. Regardless of the spatial level, however, all these elements share a common objective: maintaining natural hydrological functions through absorption, infiltration, and stormwater retention (Tauhid, 2019).

The scope and level of detail of the identified scales, as well as the number of hierarchical levels and the elements constituting each scale, depend on the purpose of the analysis and the specific characteristics of the study area. Depending on the adopted analytical perspective, the hierarchy may be extended beyond the classical site scale to include more detailed levels.

In some approaches, additional levels refer to the neighborhood, block, plot, and even detail scale (Figure 6.3). Such differentiation makes it possible to examine how the selection and design of garden-scale interventions and residential greenery influence the performance of green infrastructure at the block and neighborhood level. At the same time, it may provide the basis for developing practical tools, such as checklists for designers and urban planners, supporting proper stormwater management, effective use of vegetation to enhance habitat diversity at the block scale, and the use of private plots to contribute to a local ecological network (Tahvonen, 2018).

In the context of the previously presented scale models, it should be emphasized that the delineation of specific spatial levels is neither unequivocal nor fully standardized in terminological terms. The definition of scales depends both on planning traditions and on the institutional context.

Particular difficulties arise with regard to the regional scale. The term region and term regional may be interpreted in different ways, referring either to an entire country (especially in the case of small countries) or to a designated administrative or functional subnational area. A similar ambiguity concerns the local scale. It may denote an administrative level below the regional one, such as a commune, but it may also be defined by referring to specific types of areas, such as a city, village, district, or neighborhood (Szulczewska, 2018).

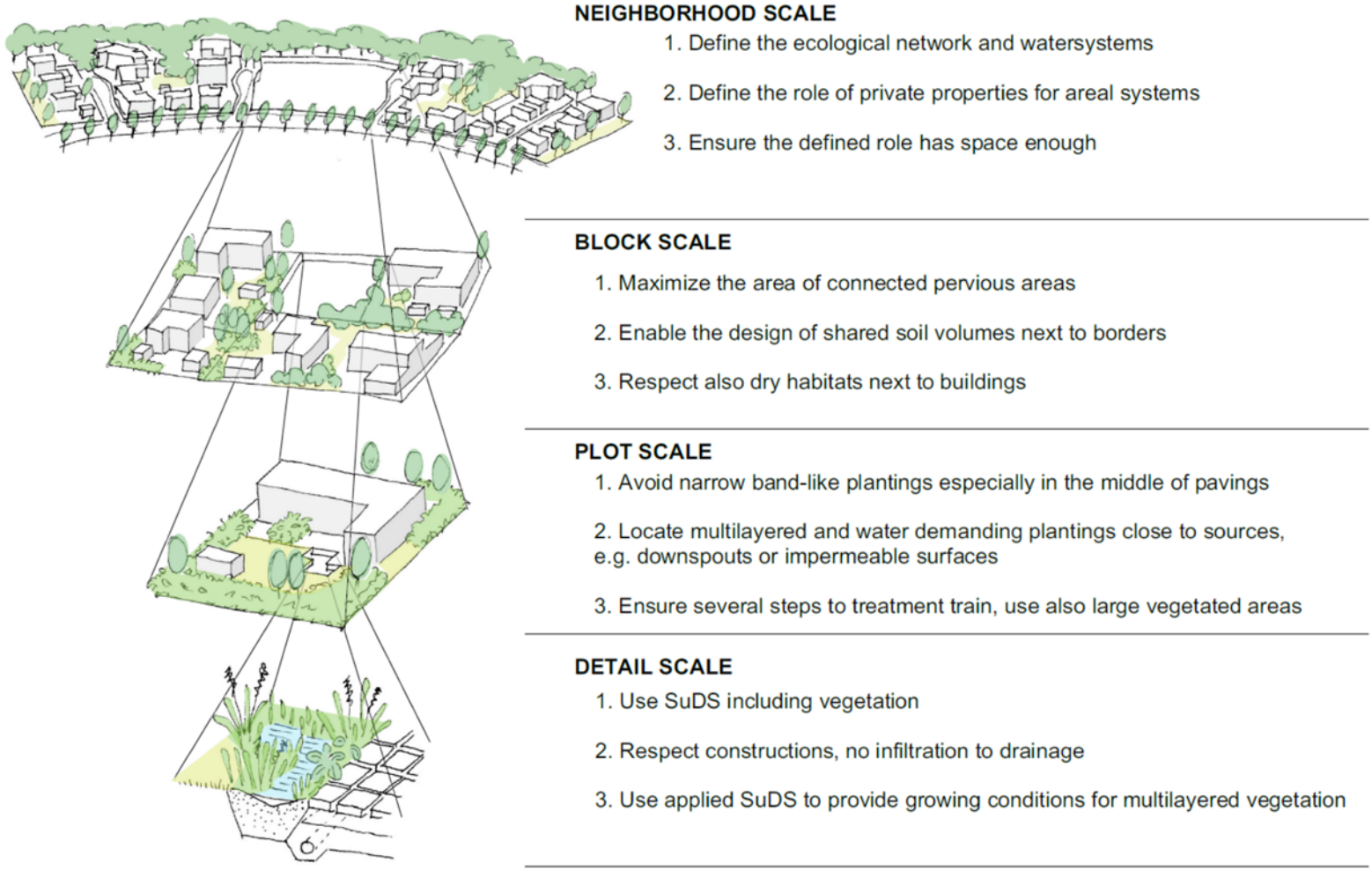

Figure 6.3. Proposed checklist for designers to work with scalable green infrastructure in low-density housing (Tahvonen, 2018)

This diversity demonstrates that the classification of scales in green infrastructure requires explicit clarification of the adopted spatial scope in each case. A lack of coherence between different planning levels weakens the functioning of the entire green infrastructure system. Therefore, ensuring continuity between the strategic and implementation scales is essential.

6.2. CORE SPATIAL SCALES OF GREEN INFRASTRUCTURE

6.2.1. Regional (landscape) scale

At the regional scale, green infrastructure performs a strategic and systemic function. Its primary objective is to maintain the continuity of ecological processes, ensure ecological connectivity, and protect natural resources of supra-local importance. Green infrastructure at this level counteracts landscape fragmentation, enables species migration, and stabilizes water cycles and climatic conditions at the macro scale.

Regional planning encompasses multiple administrative units and has a long-term character. It aims to establish policies and regulatory frameworks that promote green infrastructure implementation across municipalities and/or watersheds (U.S. Environmental Protection Agency website). Implementation takes place through regional development strategies, spatial development plans, river basin management plans, and climate adaptation strategies. An example of a green infrastructure solution at this scale is the green belt concept (see Chapter 8.1.1).

6.2.2. Municipal or city scale

At this scale, green infrastructure takes the form of interconnected networks of parks, river valleys, urban forests, open spaces, and blue-green corridors. It serves as a tool for managing spatial development, supports climate adaptation, and integrates technical infrastructure with natural processes.

Key challenges at this level include spatial fragmentation, development pressure, and the protection of so-called “pinch points” that determine the continuity of ecological networks. At the municipal or city scale, green infrastructure operates systemically by reducing urban heat island effects, supporting stormwater management, improving environmental quality, and enhancing resilience to extreme events. At the same time, this scale plays a crucial role in linking regional strategies with local implementation.

Implementation occurs through spatial planning documents, development strategies, and public space design standards. The active involvement of residents and civil society organizations in planning processes is also essential. An example at this scale is the Chinese sponge city concept (see Chapter 8.2.1).

6.2.3. Neighborhood (district) scale

The neighborhood scale includes districts, housing estates, and small towns. It integrates environmental and social functions while strengthening environmental justice by ensuring access to ecosystem services. Challenges at this level include limited land availability and functional conflicts arising from the diverse needs of user groups. The management of small green spaces can also be difficult, particularly when their perceived benefits are less visible compared to large urban parks. Nevertheless, pocket parks may play a crucial role where larger green areas cannot be introduced.

Planning at this scale focuses on implementing green infrastructure within clearly defined areas that respond to neighborhood priorities, such as increasing tree canopy and green space, reducing impervious surfaces, mitigating local

flooding, and enhancing native vegetation and habitats. Neighborhood planning should remain consistent with regional planning objectives (U.S. Environmental Protection Agency website).

Implementation is carried out through local planning instruments (e.g., zoning regulations concerning greenery and retention), regeneration programs, participatory budgets, green street standards, and co-management models, particularly in the case of community gardens. This scale provides a natural arena for public participation, which enhances the durability of interventions. Social awareness plays a significant role not only in the use of space but also in co-decision processes. Residents who understand the functions of green infrastructure can actively engage in public consultations, submit comments on planning documents, and monitor administrative decisions to prevent the degradation of existing green infrastructure assets.

6.2.4. Site scale

The site scale refers to the microscale of a single building, parcel, or small public space. It represents the design and implementation level at which specific technical solutions are applied, such as rain gardens, green roofs, and retention systems.

At this level, green infrastructure contributes to improving microclimate conditions, increasing water retention, reducing local flooding, and enhancing the quality of spaces directly used by residents. Site-scale planning is typically more detailed and less programmatic in nature. It may involve identifying specific locations and assessing their physical characteristics to determine which green infrastructure elements are feasible. Strategic decisions taken at the regional or city scale provide guidance and a framework for selecting and implementing projects at this level (U.S. Environmental Protection Agency website).

Implementation involves interdisciplinary design processes, integration of green infrastructure with technical infrastructure, and the activation of incentive mechanisms for private stakeholders (e.g., standards, guidelines, tax incentives, funding programs). Importantly, the site scale enables implementation by property owners themselves, both private and public. Housing associations, estate managers, business owners, and entrepreneurs can independently introduce green infrastructure elements on their properties. Green infrastructure systems do not rely solely on public land. Privately owned land, particularly working farms and forests, can play a crucial role in a green space network (Benedict & McMahon, 2002).

The significance of this scale lies in the cumulative effect of multiple small interventions. Numerous dispersed actions can generate systemic impacts, as described in the concept of urban environmental acupuncture (created by architect and urban planner Manuel de Solà-Morales) (Hemingway, 2024). An example of such cumulative implementation is the Portland's Green Streets Program (see Chapter 8.2.4). However, the effectiveness of this site-scale approach depends on social awareness and the recognition that green infrastructure is not solely the responsibility of public authorities. Public education is therefore essential to unlock the full potential of this scale.

6.3. TYPOLOGIES OF GREEN INFRASTRUCTURE ELEMENTS ACCORDING TO SCALE

In studies addressing the spatial scales of green infrastructure, individual levels are often defined through the sets of elements that constitute them. In this approach, each scale is described by characteristic types of objects and areas. However, the classification of specific sites as elements of green infrastructure is not unequivocal and is subject to varying interpretations. As noted by Szulczewska (2018), approaches to green infrastructure typology are strongly embedded in the environmental, institutional, and cultural contexts of a given country or landscape.

Many classical typologies were developed in the United Kingdom and the United States, which means that the categories they propose, particularly at the regional and local scales, reflect the spatial and planning traditions of those contexts.

One of the more widely recognized approaches is the framework presented by the Landscape Institute in "Green infrastructure: connected and multifunctional landscapes" (2009), later referenced and further elaborated in the European Environment Agency report "Green infrastructure and territorial cohesion: the concept of green infrastructure and its integration into policies using monitoring systems" (EEA, 2011). Table 6.1, presenting potential green infrastructure assets grouped into three scale categories, illustrates how green infrastructure resources can be organized according to spatial level (EEA, 2011).

Table 6.1. Potential assets that make up green infrastructure grouped into three scale groups (EEA, 2011)

Local, neighborhood, and village scale	Town, city, and district scale	City-region, regional, and national scale
• street trees, verges, and hedges • green roofs and walls • pocket parks • private gardens • urban plazas • town and village greens and • commons • local rights of way • pedestrian and cycle routes • cemeteries, burial grounds, and churchyards • institutional open spaces • ponds and streams • small woodlands • play areas • local nature reserves • school grounds • sports pitches • swales (preferably grassed) • ditches • allotments • vacant and derelict land	• business settings • city/district parks • urban canals • urban commons • forest parks • country parks • continuous waterfronts • municipal plazas • lakes • major recreational spaces • rivers and floodplains • brownfield land • community woodlands • (former) mineral extraction sites • agricultural land • landfill	• regional parks • rivers and floodplains • shorelines • strategic and long-distance trails • forests, woodlands, and community forests • reservoirs • road and railway networks • designated green belt and strategic gaps • agricultural land • national parks • national, regional, or local • landscape designations • canals • common lands • open countryside

6.4. CHALLENGES OF GREEN INFRASTRUCTURE DEVELOPMENT ACROSS URBAN, SUBURBAN, AND RURAL CONTEXTS

6.4.1. Challenges of green infrastructure in urban areas

The development of green infrastructure in urban environments is particularly important due to their specific characteristics. Cities are marked by a high degree of transformation of the natural environment, resulting primarily from the extensive share of built-up areas and a characteristic urban geometry that

includes, among other features, numerous street canyons that modify ventilation conditions. At the same time, the proportion of areas covered by vegetation and surface waters is relatively low, while the dominance of impervious surfaces leads to reduced infiltration and excessive surface runoff of stormwater. Under conditions of extreme weather events, cities face problems such as flash floods and local inundations, as well as heatwaves, droughts, and the intensification of the urban heat island effect.

As is frequently emphasized, one of the key ways to address these challenges is the implementation of green and blue-green infrastructure solutions. This subsection discusses selected green infrastructure solutions tailored to local urban environmental conditions.

One of the fundamental challenges in the development of green infrastructure in cities is the limited availability of space and strong competition for land. Urban areas are characterized by high land values and intense development pressure, while different functions – residential, transport-related, service-oriented, or associated with technical infrastructure compete for every fragment of space. Under such conditions, allocating land for large-scale green infrastructure solutions, such as parks, ecological corridors, or retention basins, often gives way to short-term economic priorities or development plans. As a result, green infrastructure projects in cities are frequently limited to small, fragmented interventions rather than large, connected systems.

However, in line with the concept of green infrastructure as a system of strategically planned and implemented elements operating across multiple spatial scales, small-scale solutions also gain importance. Under spatial constraints, green infrastructure in cities often takes the form of small elements that must be integrated into the existing urban fabric. Despite their limited size, such interventions can significantly contribute to improving the ecological functioning of the city, for example, by increasing stormwater retention, supporting biodiversity, and ensuring habitat continuity.

In areas of particularly dense development, small, site-specific green infrastructure interventions – sometimes referred to as “green acupuncture” – become especially important. Their effectiveness does not stem from the scale of individual solutions, but from the cumulative effect generated by the multiplication of numerous small, local interventions throughout the city. This capacity to generate aggregated impacts is one of the key characteristics of green infrastructure and Nature-based Solutions. In the context of spatial constraints and the dominance of gray infrastructure, such dispersed yet systemically connected interventions may represent a realistic and effective strategy for implementing green infrastructure in cities. At the same time, spatial pressure encourages the development of innovative and multifunctional solutions

that can operate both as components of the urban system and as elements integrated into larger facilities, such as parks.

Another significant challenge related to the implementation of green infrastructure in cities is the dominance of existing gray infrastructure. Many cities are characterized by extensive networks of roads, buildings, and underground infrastructure that were designed without consideration of ecological processes. Integrating green infrastructure into such systems (so-called retrofitting) can be technically complex, costly, and disruptive. For example, the installation of bioretention basins, bioswales, infiltration trenches, or permeable pavements may require substantial modifications to existing drainage systems and transport networks, as well as compliance with formal and legal requirements, such as obtaining water permits.

Streets and road corridors represent a particularly important area for integrating green infrastructure in cities. It is estimated that globally 30–35% of urban land area consists of streets and other paved surfaces (UN-Habitat, 2013). Streets constitute the largest share of public space in cities, exceeding parks and squares, and a significant proportion of outdoor activities takes place along transportation corridors. Due to the hierarchical and networked structure of transportation systems, these spaces offer exceptional opportunities for the strategic integration of Nature-based Solutions into the urban fabric (Maksymiuk et al., 2025).

Street greening through the introduction of street trees, rain gardens, bioretention trenches, permeable pavements, or vegetated tram tracks, can complement and enhance the ecosystem services provided by other green infrastructure elements, such as parks. In contrast to large green areas, which are often unevenly distributed, interventions within street space allow for a more equitable distribution of environmental and social benefits, particularly in areas with high traffic intensity and deficits of greenery (Cox et al., 2017).

Street vegetation plays an important role in reducing stormwater runoff and mitigating air pollution. Moreover, an organized and interconnected network of “green streets” can function as ecological corridors, facilitating species movement within the city and linking urban areas with peri-urban and rural landscapes. In this way, even small, point-scale interventions – when planned as part of a network – can contribute to improving green space connectivity, protecting urban ecosystems, and enhancing urban ecological resilience (Maksymiuk et al., 2025).

When designing green infrastructure solutions in cities, it is necessary to consider not only spatial constraints but also the specific local problems that need to be addressed in a given area. Selected green infrastructure solutions adapted to different types of urban land use are discussed and summarized in Table 6.2.

Table 6.2. Green infrastructure solutions adapted to different spatial contexts in cities (own work based on City of Philadelphia, 2014; Adamowski et al., 2017; NY DEP, 2022; Osipiuk et al., 2023)

Solution	Application context						
	streets	urban squares and parking areas	multi-family housing estates	single-family housing	dense urban fabric	public buildings	parks
Permeable surfaces	☐	☐	☐	☐	☐	☐	☐
Runoff channels	☐	☐	☐	☐	☐	☐	☐
Swales and infiltration ditches		☐	☐			☐	☐
Rain gardens		☐	☐	☐	☐	☐	☐
Stormwater bump-out, stormwater curb extension, curb cut, stormwater planter	☐	☐			☐		
Bioretention basins			☐	☐		☐	☐
Surface retention reservoirs			☐	☐		☐	☐
Underground retention tanks	☐	☐	☐	☐	☐	☐	☐
Infiltration crates	☐	☐	☐	☐	☐	☐	☐
Structural soil cells (root boxes)	☐	☐			☐	☐	
Green and blue roofs			☐	☐	☐	☐	
Retentive fountains		☐	☐		☐	☐	☐
Water plazas		☐	☐			☐	☐
Soak ways	☐	☐	☐		☐	☐	
Green gutter/Green strip			☐	☐	☐	☐	
Ground-based green facades/ Climbing plants			☐	☐	☐	☐	
Facade-bounded greening/ Green wall			☐			☐	
Street trees	☐	☐					
Stormwater tree/Stormwater tree with trench	☐	☐			☐	☐	

When selecting green infrastructure solutions for streets and transportation corridors, it is important to consider which functions these solutions should fulfill and which problems they should address as a priority. Commonly identified issues associated with street environments include excessive solar exposure, noise, poor microclimatic conditions (including reduced air quality), and flooding during heavy rainfall events.

Linear tree and shrub plantings, for example, in the form of hedges, can provide shading, increase interception and air humidity, and ultimately reduce ambient temperatures, thereby improving user comfort. Vegetated strips can also separate pedestrian, bicycle, and vehicular traffic and incorporate recreational infrastructure such as seating.

A key group of solutions suitable for street environments is those collectively referred to as sustainable stormwater management systems, which help reduce flood risk. These include rain gardens, retention basins, swales, and infiltration trenches. Street-side rain gardens are particularly popular in American cities (e.g., Portland, Philadelphia, New York, Washington, D.C.), where, besides their retention function, they are also used as traffic-calming elements near intersections (then referred to as stormwater bump-outs). Depending on their design and cross-section, such features may also be called stormwater planters when located along pedestrian routes, or curb cuts when implemented near parking entrances (Figure 6.4).



Figure 6.4. Street bump-outs in Portland, OR (photo by Gabriela Maksymiuk, 2025)

Introducing vegetation in narrow spaces with high pedestrian or vehicular traffic often poses challenges for plant growth. These difficult site conditions can be improved through the use of structural soil cells and engineered soil mixtures. In street canyon conditions with continuous building frontages, infiltration crates collecting roof runoff may also be applied. Additionally, carefully selected plant species can enhance the aesthetic quality of the surroundings.

The defining feature of parking areas and urban squares is their paved surface. Depending on pedestrian traffic intensity and the specific role of a space within the city (e.g., hosting mass events), appropriate vegetation should be introduced (Figure 6.5). As with streets, recommended tree planting solutions include engineered soil mixtures and structural soil cells. Urban squares may also incorporate water features such as fountains, including those with retention functions. Where possible, permeable pavements and underground retention tanks should be considered.



Figure 6.5. Curb-cut located by the parking lot in Portland, OR
(photo by Gabriela Maksymiuk, 2025)

Dense block development poses challenges similar to those of street environments, primarily due to limited space and existing underground infrastructure. Recommended solutions include planting individual trees or tree

rows using structural soil cells and engineered soil mixtures, installing permeable pavements in pedestrian areas (e.g., inner courtyards), and implementing green and blue roofs – particularly in new developments.

Multi-family housing estates typically offer more space for green infrastructure than dense block development. Accordingly, a wide range of surface-based stormwater retention solutions can be applied, including retention ponds, bioretention basins, swales, infiltration ditches, and rain gardens in the form of sunken ornamental planting beds. New buildings can also be equipped with green or blue roofs, increasing the proportion of biologically active surfaces.

An important design consideration is the creation of shaded areas through the planting of tall trees, shrubs, and hedges, shaping recreational spaces for different user groups. Children's playgrounds should include both sunny and shaded zones. The introduction of community gardens supports social integration and provides opportunities for leisure and hobby activities.

Single-family housing areas are the least affected by challenges related to gray infrastructure or spatial constraints. Nevertheless, effective green infrastructure solutions in these areas include rainwater harvesting for garden irrigation and the implementation of small-scale retention features such as ornamental rain gardens (Figure 6.6).



Figure 6.6. Location of a bump-out in a single-family housing in Portland, OR (photo by Gabriela Maksymiuk, 2025)

Public buildings – such as schools, universities, hospitals, administrative offices, libraries, and sports facilities – offer particularly favorable conditions for the implementation of green infrastructure. They are often publicly owned, serve large numbers of users, and occupy strategically located plots within the urban structure. For these reasons, they can function both as practical components of the city's green infrastructure system and as demonstrative examples of sustainable design.

One of the most widely applied green infrastructure solutions in public buildings is the installation of green roofs. These systems enable the introduction of vegetation without requiring additional land area. Green roofs improve thermal insulation, reduce energy consumption for heating and cooling, retain part of the stormwater runoff, and mitigate the urban heat island effect. In dense urban areas, blue roofs, designed to temporarily store rainwater before controlled discharge, can further support stormwater management. Roof-based solutions may also be combined with photovoltaic panels, increasing the multifunctionality of the building.

At ground level, the surroundings of public buildings provide opportunities for implementing rain gardens, bioretention basins, permeable pavements, and infiltration systems. These elements allow for on-site stormwater management by enhancing infiltration, retention, and natural purification processes. For example, parking areas and entrance plazas can be designed with permeable surfaces and vegetated strips that reduce runoff while maintaining their primary function (Figure 6.7).

Public buildings often generate significant volumes of roof runoff, which can be collected in underground retention tanks and reused for non-potable purposes such as irrigation or toilet flushing. This contributes to more efficient water resource management (Figure 6.7).

An additional advantage of implementing green infrastructure in public buildings is their educational value. In schools and universities, green roofs, rain gardens, or small retention ponds can serve as practical teaching tools, helping students understand ecological processes and climate adaptation measures. In this way, public buildings not only improve environmental performance but also raise awareness and promote sustainable behavior.

Urban parks are fundamental components of green infrastructure systems. Unlike small-scale, dispersed interventions, parks often provide sufficient space to implement larger and more complex green infrastructure solutions. They therefore function as key nodes within the urban ecological network.



Figure 6.7. Green walls as artistic interventions in Portland, OR (photo by Gabriela Maksymiuk, 2025)

One of the main roles of green infrastructure in parks is stormwater management. Parks can accommodate retention ponds, wetlands, swales, and other surface-based water management systems. These elements temporarily store excess rainwater during heavy precipitation, reducing flood risk in other parts of the city. In some cases, parks are intentionally designed as floodable areas that can safely retain water during extreme events.

Parks also play a crucial role in microclimate regulation. Extensive tree cover provides shade, reduces surface and air temperatures, and improves thermal comfort during heatwaves. Diverse vegetation structures – including trees, shrubs, meadows, and aquatic plants – enhance biodiversity and create habitats for various species. This supports ecological stability and resilience within the urban environment.

Another important function of parks is ensuring ecological connectivity within the city. When linked with green corridors, river valleys, or vegetated streets, parks serve as hubs that facilitate the movement of species across the city. Such connectivity is essential for maintaining healthy urban ecosystems.

At the same time, parks fulfill important social and health-related functions. Well-designed green spaces encourage physical activity, social interaction, and psychological well-being. Integrating water features, shaded pathways,

and natural play areas increases the attractiveness and usability of parks while maintaining their ecological functions.

In summary, parks represent multifunctional spaces where environmental, hydrological, and social benefits converge. Their role within the broader green infrastructure network makes them indispensable elements of sustainable urban development and climate adaptation strategies.

In an urban environment, under conditions of spatial scarcity, particular importance is attached to green infrastructure solutions designed for small-scale spaces, such as:

- green roofs and green walls, which allow vegetation to be introduced without occupying additional land, improve building insulation, and mitigate the urban heat island effect,
- rain gardens and bioretention basins, located along streets, in courtyards, or within parking areas, supporting the infiltration and treatment of stormwater,
- green public transport stops, as well as vegetated shelters and pergolas,
- “pocket parks”, created on small, previously undeveloped plots or in areas released through the removal of road infrastructure,
- permeable pavements applied on sidewalks, squares, and parking areas, enabling increased water retention while maintaining their functional use,
- vegetated tram tracks and green strips along transportation corridors.

These solutions are multifunctional, combining stormwater retention, microclimate improvement, enhanced biodiversity, and improved quality of public space. Under conditions of strong spatial pressure, it therefore becomes crucial to integrate green infrastructure with existing urban functions and to design it as a complementary element to technical infrastructure rather than as a competing one.

6.4.2. Challenges of green infrastructure in suburban areas

Suburban areas occupy a transitional zone between dense urban centers and rural landscapes, and their spatial form creates a distinct set of challenges for green infrastructure development. These areas are often shaped by low-density development and urban sprawl, which can undermine the efficiency and connectivity of green infrastructure systems.

A key issue is landscape fragmentation. Suburban development patterns typically consist of dispersed residential zones, commercial centers, and transportation corridors, resulting in disconnected green spaces. This fragmentation reduces ecological functionality, limits biodiversity benefits, and weakens the ability of green infrastructure to manage stormwater or provide climate regulation at a larger scale.

Urban sprawl also increases dependence on private land for green infrastructure implementation. Unlike urban cores, where public land may dominate, suburban landscapes often consist of privately owned parcels. This complicates coordinated planning efforts and requires negotiation with multiple landowners, each with different priorities and capacities. As a result, green infrastructure initiatives may be implemented unevenly or remain voluntary rather than systematic.

Peri-urban areas concentrate development problems as if through a lens. An example is the development plan of one small municipality near Warsaw with a population of 6,000, where it was proposed that all non-urbanized land be designated for construction. This would mean that, in the case of compact development, up to 200,000 people could potentially live there. As an autonomous decision of the municipality, such a development plan does not have to be coordinated with neighboring municipalities, even though it affects economic, social, and environmental conditions beyond its boundaries. Most often, this situation leads to inefficient land use. New development typically emerges in a chaotic and dispersed pattern, which makes it:

- extremely costly to maintain (due to the construction of excessively long access roads, infrastructure networks, transportation of children to schools, and rising energy prices),
- environmentally unfriendly (it hinders water resource management and flood protection, limits air exchange and regeneration, and causes fragmentation and isolation of environmentally valuable areas),
- detrimental to agriculture (fragmentation of agricultural production areas complicates farming operations and increases distances to cultivated land),
- associated with additional costs, such as increased healthcare expenditures related to air pollution.

In many countries, the costs of spatial chaos are estimated not only at the regional scale but also for individual local governments. In Poland, the annual costs of spatial disorder are estimated at 84.3 billion PLN (Śleszyński & Kukołowicz, 2021). These costs are borne both by residents and by local authorities. The lack of coordination in spatial development at the level of the entire agglomeration results in an increasing amount of chaotic developed land, which in turn generates conflicts and problems, worsens residents' quality of life, and makes it more difficult to preserve environmental assets.

One response to the challenges associated with uncontrolled urban sprawl is the concept of urban green belts, meaning the preservation of green open areas around cities with a minimal share of built development (less than 10%). Urban green belt areas usually include: forests, surface waters, wetlands (peatlands and marshes), as well as agricultural land, including meadows, pastures, arable fields, and orchards.

Urban green belts operate in many countries and can be found on almost all continents, although they do not always take the form of a continuous ring surrounding a city (Amati, 2008). In Europe, apart from the United Kingdom, they can be found in Denmark (Copenhagen), Sweden (Stockholm), France (Paris), and Germany (Berlin). They also exist in Asia (Hong Kong, Seoul, Beijing), Australia (Sydney, Melbourne), and North America (Ottawa, Toronto, Portland, San Francisco). One of these examples, discussing the green belt around Toronto, namely the Ontario's Greenbelt, is presented in Chapter 8.1.1.

The first urban green belts were established in the 20th century, although attempts to control urban sprawl had been made earlier. Formally, the first green belts were introduced in the United Kingdom under the Green Belt Act of 1938, aimed at protecting the outskirts of London from rapidly expanding development. In 1945, the Greater London Plan was presented, incorporating a green belt surrounding the city (Abercrombie, 1945).

Green belts are clearly defined areas that can have different structures and forms (Cieszewska, 2019; Figure 6.8):

- a continuous ring surrounding a city (London, Paris, Beijing, Hong Kong, Toronto),
- wedges of open land penetrating the city from surrounding areas (Copenhagen, Stockholm, Melbourne),
- islands of undeveloped land, often forming a system of protected areas (mainly regional parks) encircling the city (Berlin, Vienna),
- a network of environmentally valuable areas connected by ecological corridors around a city (Frankfurt, Rome),
- a green, undeveloped area within a highly urbanized territory composed of multiple cities (the Green Heart of the Netherlands between Amsterdam, Rotterdam, and Arnhem).

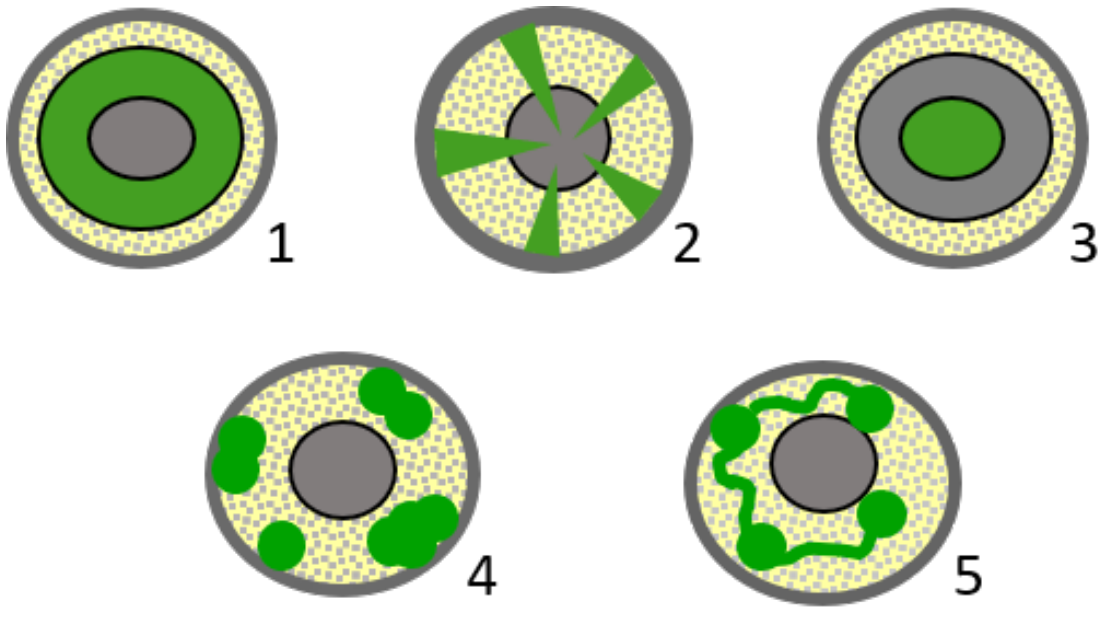

Figure 6.8. Urban green belt structure types: (1) continuous green belt, (2) green wedges, (3) green heart, (4) system of protected areas, (5) green network (Cieszewska, 2019)

Green belts usually includes a strip approximately 20 km wide surrounding a city (Amati, 2008). However, they may range from relatively small areas of several hundred hectares near small towns (e.g., 720 ha around Burton upon Trent in England) to hundreds of thousands of hectares around large metropolises such as London or Paris (over 450,000 ha).

Green belts fulfill numerous environmental, economic, and social functions. They support air circulation and regeneration by cooling urban areas, mitigating the urban heat island effect, and improving air quality. They enhance water management by facilitating rainwater infiltration, slowing surface runoff, and contributing to the replenishment of water resources. In addition, green belts help reduce the risk of flooding. Undeveloped agricultural areas, such as meadows and fields, particularly those located in river valleys and floodplain, can function as flood polders (dry retention basins), temporarily storing excess water during high-water events and thereby limiting damage in built-up areas.

Green belts also strengthen ecological connectivity by forming networks of ecological corridors, which promote biodiversity and decrease risks related to wildlife movement. They play an important role in protecting environmentally valuable areas exposed to intense pressure of urbanization. From an economic perspective, green belts provide cities with a range of resources and services, including food production (crucial for food security), timber and other forestry products, areas for mineral extraction, waste management and storage sites, and space for renewable energy generation. Socially, they offer recreational and leisure opportunities, create spaces for sports and outdoor activities, foster social integration by serving as community meeting places, and function as sites for environmental education (Cieszewska, 2019).

Green belt governance may take different institutional forms depending on the country and administrative context. It can be managed by a separate local government unit or administrative region, as in the United Kingdom and Canada (see Chapter 8.1.1). In other cases, it is overseen by a voluntary association of local government units or within a broader metropolitan structure, as in Germany and the Netherlands.

In large, administratively unified cities, responsibility for the green belt may rest with the central municipal authorities, as exemplified by Frankfurt and Copenhagen. Alternatively, green belt-related responsibilities may be carried out within existing administrative frameworks at the metropolitan level, as in the United States. A comparable approach is applied in Poland, where plans for functional urban areas are adopted by regional self-governments.

A common feature of all governance models is the control and limitation of chaotic development. Municipalities within the green belt strictly ensure that new construction occurs only in designated development zones. In all

cases, green belts are designated areas surrounding cities where development restrictions have been introduced. Local spatial development plans define permitted land uses and functions for such areas. In some cases, local regulations also specify compensation rules for landowners due to restrictions on changing land use designation.

6.4.3. Challenges of green infrastructure in rural settings

Rural settings are frequently perceived as inherently “green,” which can obscure the unique challenges associated with green infrastructure development in these areas. While rural landscapes may offer abundant natural space, they also face structural and socio-economic barriers to coordinate green infrastructure implementation.

One significant challenge is dispersed populations. Low population density can reduce political attention and financial investment in green infrastructure projects, particularly when benefits are perceived as indirect or long-term. Limited municipal budgets and technical capacity further constrain the ability of rural authorities to plan and maintain green infrastructure systems.

Another major issue is fragmented land ownership. Rural areas often consist of large numbers of privately owned agricultural or forested parcels. Coordinating green infrastructure across these lands requires collaboration among multiple stakeholders, including farmers, landowners, and regional authorities. Differences in land-use objectives – such as agricultural productivity versus ecological restoration – can create conflicts and slow implsementation.

In addition, rural green infrastructure initiatives may struggle with limited institutional support and policy integration. Planning frameworks often prioritize agricultural or extractive land uses, leaving green infrastructure underrepresented in development strategies. As a result, green infrastructure in rural contexts may remain piecemeal and heavily dependent on voluntary participation or external funding programs.

In rural areas, green infrastructure plays a distinct role compared to urban settings. Its primary purpose is to support and protect natural processes in open landscapes, which are often shaped by agricultural and other human activities. In this context, green infrastructure not only helps maintain ecological balance but also provides climatic, hydrological, geodynamic, and biological functions, mitigating the negative impacts of human activity such as soil erosion, habitat degradation, and biodiversity loss. Therefore, planning and designing green infrastructure in rural areas require careful consideration of both the landscape’s characteristics and the natural processes occurring within it.

With regard to climatic processes, it is essential to ensure air circulation and regeneration by creating areas of air renewal in the form of tree clusters or groups of trees, belts of tall vegetation, or larger forest complexes.
In agricultural areas, it is also important to reduce excessive ventilation caused by the lack of natural wind barriers (Figure 6.9). Strong winds contribute to soil desiccation and intensify wind erosion of the topsoil. Shelterbelts and mid-field tree plantings serve a protective function by slowing wind speeds (Mize et al., 2008).

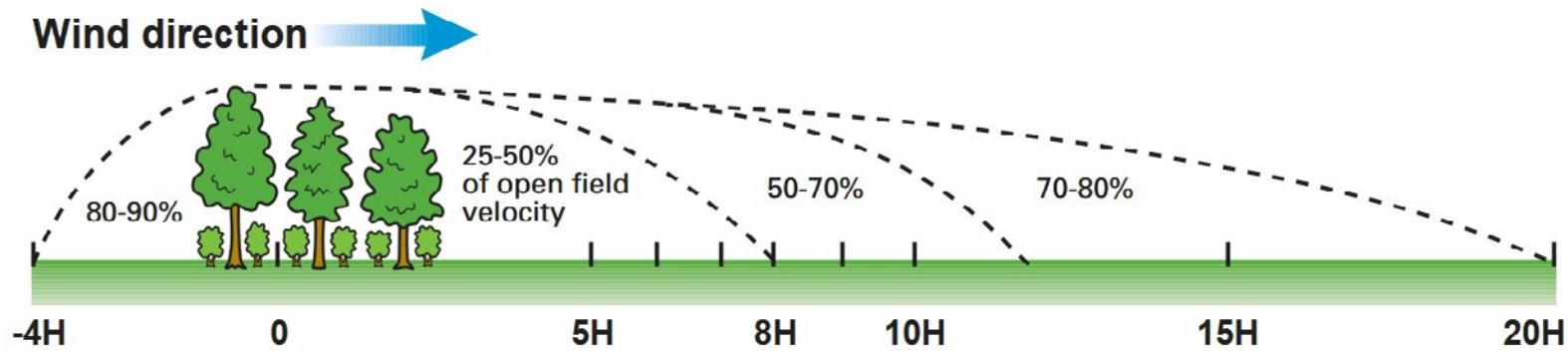

Figure 6.9. Zones of reduced wind velocity downwind of barrier as percentage of open field velocity (vertical scale exaggerated) (Wray et al., 1997)

Hydrological processes in agricultural areas have been altered by accelerated drainage of rainwater, leading to water shortages for plants and insufficient replenishment of water resources. The removal of riparian vegetation along watercourses and reservoirs further reduces the natural filtration of pollutants flowing from fields. It is also crucial to leave space for rivers by preserving floodplains, which can absorb excess water during high flows and thereby reduce flood risk.

Geodynamic processes in agricultural landscapes are primarily associated with increased water and wind erosion, particularly on slopes. The intensity of these processes rises with greater slope gradients and higher soil susceptibility to erosion, especially in silty soils.

In terms of biological processes, the main problems are the decline in biodiversity, the disruption of ecological connectivity, and the isolation of valuable natural areas. Understanding these biological challenges provides a foundation for discussing the role of green infrastructure in rural landscapes, including the importance of hedgerows as elements that support ecological and landscape processes. The multifunctional significance of hedgerows is reflected in the English language through the use of various terms applied interchangeably to describe belts of trees or shrubs, such as shelterbelts, windbreaks, and riparian buffer strips, which highlight their diverse functions. This multifunctionality is illustrated in Figure 6.10.

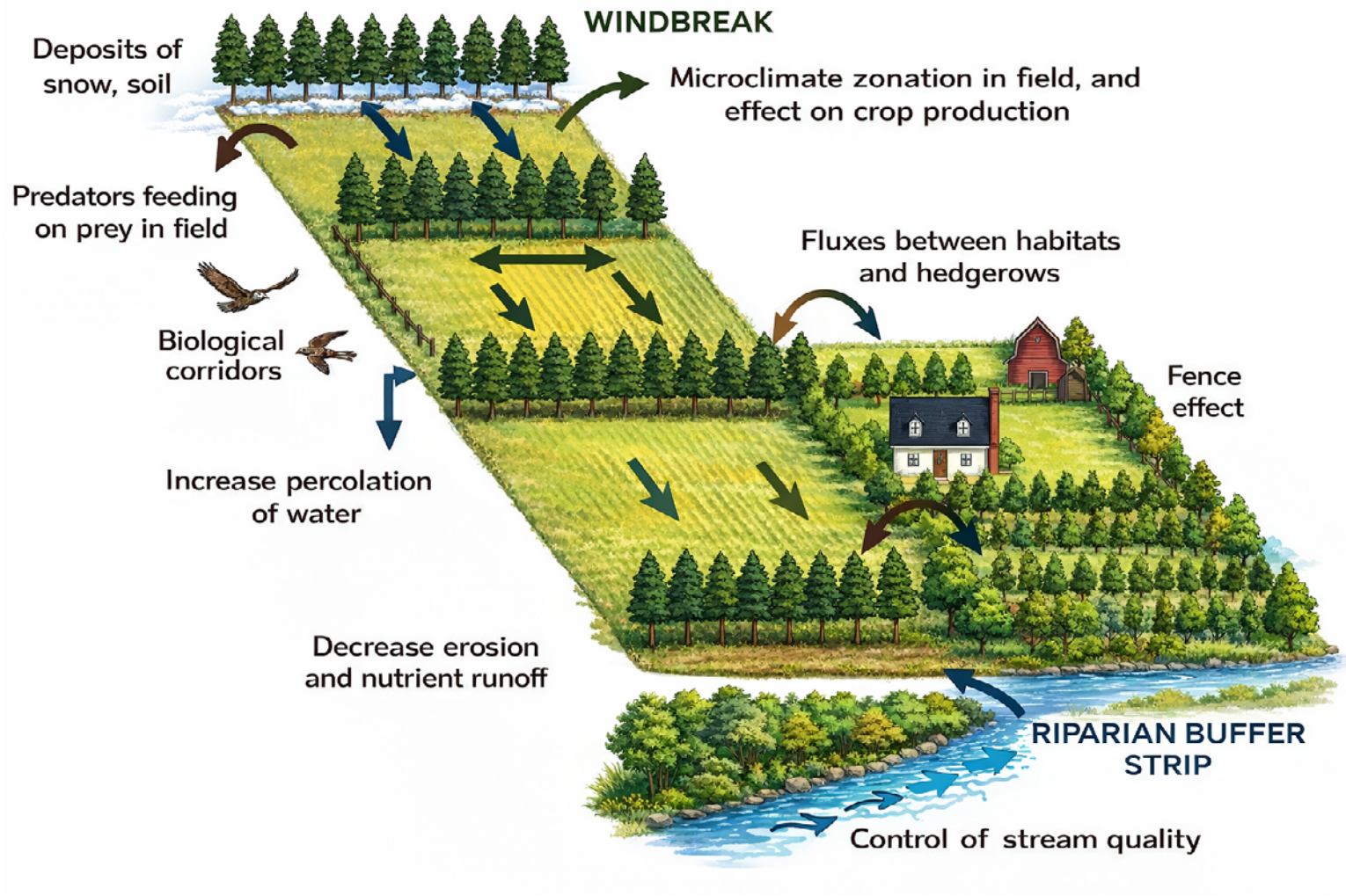

Figure 6.10. Integration of shelterbelts with other corridor systems to achieve landowner and community-based goals (own work based on Mize et al., 2008)

Building on these natural processes, green infrastructure in agricultural landscapes serves as a multifunctional system. Beyond its protective role for climate, water, soil, and habitats, it contributes to landscape connectivity, supports pollinators and other beneficial species, and helps maintain the resilience of ecosystems under changing environmental conditions. At the same time, well-managed green spaces enhance the quality of life for local communities by providing opportunities for recreation, nature-based education, and aesthetic appreciation, linking ecological benefits with social and cultural value.

Elements of green infrastructure in open landscapes include forests, water bodies, meadows, pastures, as well as hedgerows and groups of trees. Within extensive arable fields, particular importance is attributed to patches of trees, woodlots, or groves – small, often isolated woodland areas surrounded by farmland. These features serve as refuges for native flora and fauna and are interconnected by ecological corridors formed by linear hedgerows. These corridors may take the form of mid-field tree lines or vegetation accompanying watercourses, linking individual habitat patches. Such elements constitute components of ecological networks, referring to the patch–corridor matrix model developed by Forman and Godron (see Chapter 2.2).

An ecological network can be interpreted in two ways: from a species-oriented or a landscape-oriented perspective. In the species-oriented approach, the network is designed for a specific, particularly important protected species – for example, large carnivores whose populations have significantly declined over the past century. The key objective is to connect habitats within natural refuges in order to maintain migration routes for the selected species. This approach counteracts population isolation and forms the basis of contemporary nature conservation by ensuring ecological connectivity between valuable natural areas (such as national parks or regional conservation areas). However, designing such a network requires detailed knowledge of the migration requirements of the species concerned. For example, the protection of the Bengal tiger requires the preservation of continuous ecological corridors connecting protected areas. For the occurrence of this species, corridors formed by habitats of tropical moist deciduous forests dominated by sal trees (*Shorea robusta*), as well as wet marshlands, are particularly important. In India, thanks to the conservation of such ecological corridors, the tiger population has doubled since 2006 (Biswas et al., 2022).

In the landscape-oriented approach, the ecological network aims to ensure the overall proper functioning of the natural environment without focusing on a single species. Its purpose is to enable migration for various groups of organisms – plants and animals alike (including insects, amphibians, reptiles, birds, and small mammals) – within a landscape that has been significantly transformed by human activity. This involves linking relatively less anthropogenically altered habitats and creating ecological corridors that allow species to avoid crossing barriers such as roads or extensive arable fields. The objective is the holistic protection of the environment through the preservation of ecological continuity between areas of higher natural value. Such an approach is implemented, for example, in the designation of a local ecological network at the municipal level as well as at the regional scale. Usually, for a single municipality, there is no detailed information regarding the occurrence and migration of animal species. Therefore, when delineating an ecological network in such cases, the aim is not the protection of a specific species, but rather the preservation of ecological connectivity within landscapes undergoing transformation, for instance, in areas of rapid urbanization or in connection with the construction of new roads.

In such contexts, the ecological network is composed of forests, meadows, pastures, wetlands, and riparian areas, that is, all areas that remain relatively less transformed by human activity. In the case of new infrastructure projects, an important component of these connections includes wildlife crossings over (overpass) or under roads (underpass), thereby creating migration routes that eliminate ecological barriers.

Ecological connectivity networks also have significant recreational value. Educational trails, hiking paths, and cycling routes are often developed along ecological corridors. Such routes, combining recreational and ecological functions, are referred to as greenways (Ahern, 2002).

In summary, in open landscapes, green infrastructure consists of fewer anthropogenically transformed areas (forests, meadows, pastures, water bodies) connected by systems of ecological corridors. These networks may be designed either to protect selected, particularly valuable species or, from a comprehensive perspective, to ensure migration and survival opportunities for various groups of native organisms. It should be emphasized that, in addition to biological functions, ecological networks also perform climatic, hydrological, anti-erosion, and socio-cultural functions, including recreational and educational roles.

However, in predominantly agricultural regions, green infrastructure cannot be limited solely to relatively natural or semi-natural areas. Rural green infrastructure should also encompass farmland managed in ways that reinforce ecological processes and strengthen landscape connectivity. In this sense, diverse agricultural practices become instruments of green infrastructure implementation when they enhance ecosystem services while maintaining production functions. Examples include agroforestry systems that combine trees with crops or livestock, riparian buffer strips, perennial field borders and hedgerows that reduce nutrient runoff and create habitats, cover crops that protect and improve soil structure, and diversified crop rotations that support soil fertility and biodiversity (Table 6.3). Typical green infrastructure elements directly linked with agricultural land use, such as mid-field tree lines, shelterbelts, riparian buffer zones along watercourses, field margins managed for biodiversity, retention ponds, and small wetlands embedded within farmland complement larger natural patches and corridors. Together, they improve water retention, limit erosion, support pollinators and other species, and contribute to climate regulation within working landscapes (Ogwu & Kosoe, 2025).

Table 6.3. Agricultural green infrastructure practices and their ecological functions (Kujawa & Kujawa, 2018; Ogwu & Kosoe, 2025)

Practice	Features	Primary function
Cover crops	Plants grown between cropping seasons	Soil cover and nutrient cycling
Riparian buffers	Vegetated zones along waterways	Water filtration and erosion control
Agroforestry	Integrating trees with crops or livestock	Biodiversity and microclimate moderation

Table 6.3. Agricultural green infrastructure practices and their ecological functions (Kujawa & Kujawa, 2018; Ogwu & Kosoe, 2025) (cont.)

Practice	Features	Primary function
Terracing	Shaping sloped land into steps	Erosion control and water retention
Grassed waterways	Shallow, grassed linear structures to convey water	Runoff control and sediment capture
Wetlands	Constructed or natural depressions with water-tolerant plants	Water storage and biodiversity support
Hedgerows/ Windbreaks/ Shelterbelts	Linear plantings of shrubs or trees along field edges	Reduction of wind erosion Improvement of the microclimate Biodiversity enhancement Reduction of agricultural runoff pollution
Perennial field borders	Undisturbed strips of permanent vegetation along crop fields	Pollinator support and soil stabilization

The integration of such measures into everyday agricultural practice is often supported by policy instruments that provide incentives for farmers. Agri-environmental schemes under the European Union's Common Agricultural Policy (CAP), for example, compensate farmers for environmentally beneficial management practices, including biodiversity protection, soil conservation, and water quality improvement. Similar mechanisms operate in other international contexts, where conservation programs reward landowners for setting aside land for ecological purposes or adopting practices that enhance ecosystem services. Through these policy frameworks, agricultural landscapes become active and intentional components of green infrastructure systems, linking production with environmental stewardship and contributing to broader sustainability goals.

6.4.4. Comparative implications and planning considerations

Green infrastructure has emerged as a critical strategy for enhancing environmental sustainability, climate resilience, and human well-being. However, the successful planning, implementation, and maintenance of green infrastructure vary considerably across spatial contexts. Urban, suburban, and rural settings each present distinct structural, social, and governance-related challenges that influence how green infrastructure can be developed and sustained. Understanding these context-specific or setting-specific constraints is essential for designing effective and equitable green infrastructure strategies.

Across urban, suburban, and rural contexts, the challenges of green infrastructure development are shaped by spatial form, governance structures, and socio-economic conditions. While urban areas struggle with space constraints and rigid gray infrastructure, suburban regions face fragmentation and coordination issues, and rural areas contend with dispersed populations and land ownership complexity.

These differences suggest that one-size-fits-all approaches to green infrastructure are unlikely to be effective. Instead, context-sensitive planning strategies are needed – ranging from multifunctional and vertical green infrastructure solutions in dense cities, to connectivity-focused approaches in suburban landscapes, and collaborative, landscape-scale initiatives in rural areas. Recognizing and addressing these distinct challenges is a critical step toward realizing the full potential of green infrastructure across diverse settings.

Review questions:

1. What is meant by the multi-scale approach in GI planning, and why is it essential for the effective functioning of GI systems?
2. How do the roles and functions of GI differ across regional, city, neighborhood, and site scales?
3. Why is connectivity important not only within a single scale but also between different spatial scales?
4. How can multiple small-scale interventions collectively generate system-level effects within a city or region?
5. What types of elements constitute GI at different spatial scales?
6. What are the main spatial and infrastructural challenges limiting the implementation of GI in dense urban environments, and how can small-scale interventions help address these constraints?
7. What are the main spatial structures and functions of green belts?
8. Which functions of hedgerows in rural areas are important from an environmental planning perspective?

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7. SPECIFICS OF GREEN INFRASTRUCTURE DEVELOPMENT IN DIFFERENT CLIMATIC ZONES

What is this chapter about:

The specifics of green infrastructure (GI) are largely determined by climatic conditions and, similarly to climate itself, vary on a global scale. This chapter presents the classification of the Earth's climates developed by Wladimir Köppen, which is based on differences in mean air temperatures as well as the amount and seasonal distribution of precipitation. In addition, the chapter discusses the major challenges and constraints faced by GI designers in relation to different climatic zones.

This chapter provides an overview of the climatic conditions occurring in various regions of the world and the characteristics of GI associated with them. It also presents, through selected examples, methods of adapting GI to local climatic conditions, as well as the key challenges and risks that must be addressed in the process of designing GI.

What you will learn:

- The specific worldwide climatic conditions according Köppen's climate classification.
- How climatic conditions influence the types of GI.
- How climate conditions influence the landscape designing process.

7.1. HISTORY AND MAIN ASSUMPTIONS OF THE KÖPPEN'S CLIMATE CLASSIFICATION

The most widely applied classification of the Earth's climates is the system developed by the Russian-German geographer and botanist Wladimir Köppen (1846–1940). In 1884, the first map illustrating the global distribution of climatic zones was published, and in 1900, Köppen presented the first comprehensive version of his climate classification in the journal Meteorologische Zeitschrift. In the 1950s and 1960s, the German climatologist Rudolf Geiger (1894–1981), a long-term collaborator of Köppen, introduced a series of modifications to the system. Consequently, in some studies, the division of the Earth into climatic zones is referred to as the Köppen–Geiger's classification.

Subsequent revisions of Köppen's climate classification were proposed by other climatologists, primarily on the basis of increasingly precise climatological measurements from various regions of the world. Nevertheless, the fundamental assumptions of the system have remained largely unchanged to the present day.

The core principle underlying Köppen's climatic classification is the delineation of climatic boundaries, defined by specific threshold values of mean monthly air temperature and the amount and seasonal distribution of atmospheric precipitation, which correspond to the spatial distribution of natural vegetation (biomes). Köppen divided the Earth into climatic zones associated with distinct vegetation types (biomes), thereby establishing clear relationships between climatic parameters and biospheric processes. For this reason, analyses of ongoing climate change enable the anticipation of shifts in vegetation patterns, which should constitute an integral component of landscape and green infrastructure planning within a given climatic zone.

7.2. DIVISION OF THE EARTH INTO CLIMATIC ZONES

Köppen's climate classification distinguishes five principal climatic zones: tropical climates (A), arid and semi-arid climates (B), temperate climates (C), continental climates (D), and polar climates (E) (Kottek et al., 2006). All zones, with the exception of arid and semi-arid climates (B), are defined primarily on the basis of temperature criteria. In the case of dry climates, vegetation development is controlled predominantly by aridity, which is defined as the balance between moisture supply to the soil and losses resulting from evaporation. As Köppen did not have access to direct measurements of evapotranspiration, its values were estimated on the basis of air temperature, which was assumed to be the principal controlling factor. In 1966, a sixth category – highland climates – was introduced for areas situated above 1,500 m above sea level (ASL), following a modification proposed by the American climatologist Glenn Thomas Trewartha.

Each climatic zone is further subdivided into second – and third-order units. Conventionally, climate types and subtypes are described using lowercase letters of the Latin alphabet (Figure 7.1) (Lohmann et al., 1993). Climate types are distinguished based on the seasonal distribution of precipitation, whereas subtypes are defined by variations in air temperature. Exceptions include the tropical (A) and polar (E) climate zones, within which subtypes are not distinguished (Peel et al., 2007).

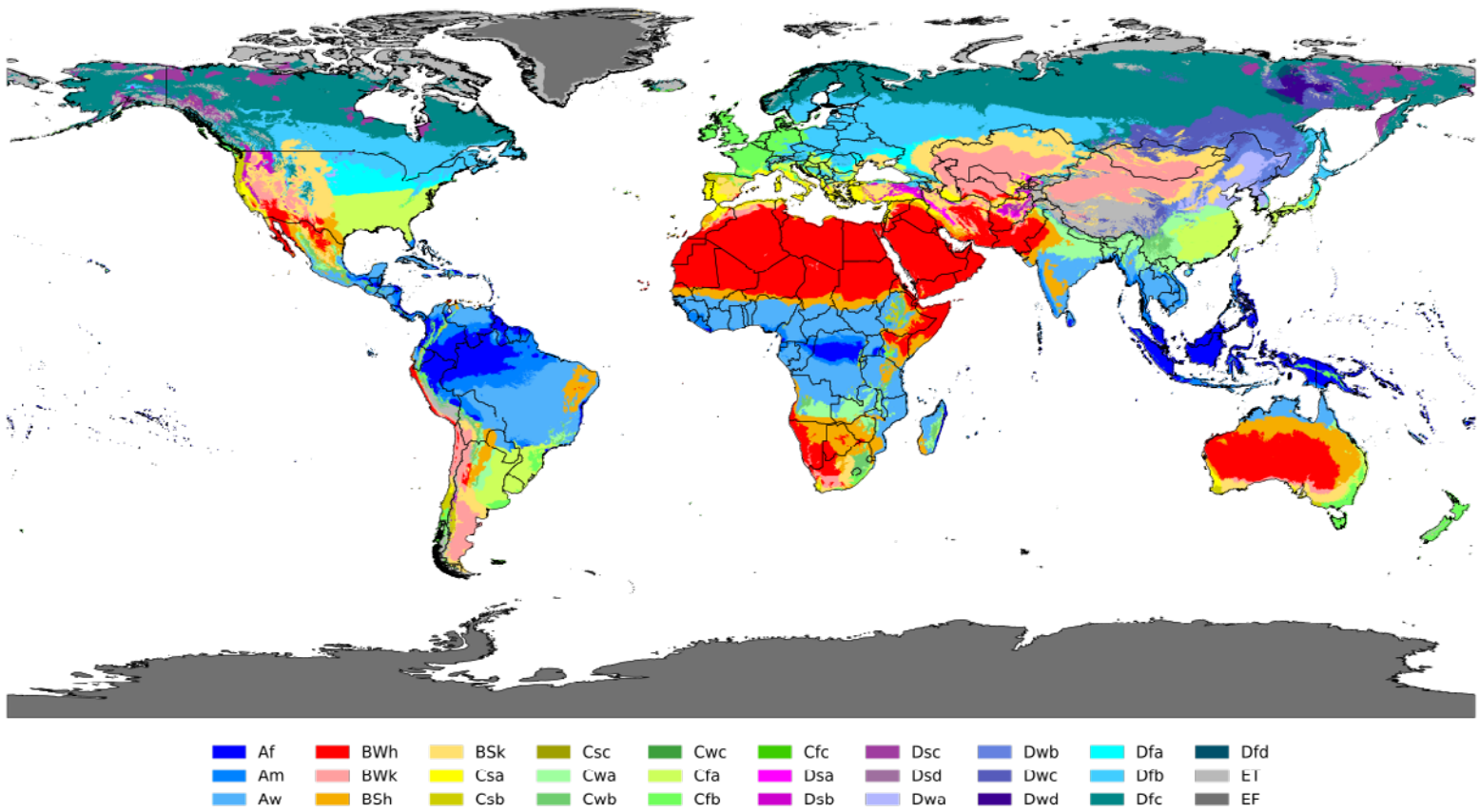

Figure 7.1. Classification of global climates according to Köppen and Geiger (Beck et al., 2023)

7.3. CHARACTERISTICS OF TROPICAL CLIMATES (A)

The tropical climate zone extends northward and southward from the equator to latitudes of approximately 15°–25° N and S. For this reason, it is often referred to as the equatorial zone. The defining feature of tropical climates is the persistence of mean monthly air temperatures exceeding 18°C throughout the year, accompanied by annual precipitation totals typically exceeding 1,500 mm. Within this zone, three climate types are distinguished based on the seasonal distribution of precipitation (Table 7.1).

The tropical rainforest climate type (Af) occurs primarily in the immediate vicinity of the equator, typically within latitudes up to 5–10°. In some regions, particularly along the eastern coasts of both Americas, it may extend as far as 25° latitude. In this climate type, atmospheric precipitation occurs throughout the entire year. Monthly variations in air temperature are relatively small, most often not exceeding 3°C, whereas diurnal temperature differences are more pronounced. Daytime temperatures may rise to approximately 32°C, while nighttime temperatures may drop to around 22°C. Due to the consistently high annual solar radiation input, the land surface undergoes intense heating, which, combined with high precipitation levels, results in very high air humidity, typically ranging from 75% to 90%. The ascent of strongly heated air masses (convection) leads to the development of low-level cloud formations, primarily cumulus and cumulonimbus. Cloud cover generally increases during the course of the day.

Table 7.1. Types of climates occurring in the tropical climate zone (own work based on Peel et al., 2007; Beck et al., 2023; Arnfield, 2026)

Symbol	Type	Characteristics	Example occurrence
Af	tropical rainforest	No dry season. The driest month has rainfall above 60 mm. Rainfall is evenly distributed throughout the year	The north-eastern Pacific coast of South and Central America (Ecuador, Costa Rica, Colombia), Amazonia (Brazil), the Congo Basin (DR Congo), Singapore, Malaysia, and Indonesia
Am	tropical monsoon	There is a distinct rainy season. The dry season is short. There is at least one month with rainfall below 60 mm. The highest air temperature occurs just before the rainy season	Florida (USA), Guyana, Suriname, the Gulf of Guinea coast (Guinea, Cameroon, Niger), southern Thailand, southern Burma, and Indonesia (Java Island)
Aw or As (winter or summer)	savanna	Summer or winter dry season (depending on the hemisphere). There are at least two months with precipitation below 60 mm (in summer or winter)	Central Brazil, Mali, South Sudan, Southeast Asia (Vietnam, Cambodia, Laos), and the northeast coast of Australia

The tropical monsoon climate (Am) occurs in regions influenced by seasonal winds known as monsoons, most notably along the coast of the Gulf of Guinea, in Southeast Asia, and along the Pacific coasts of South America and Australia. Monsoon winds change their direction seasonally: during the summer season, moist air flows from the ocean toward the land, while in the winter (dry) season, winds blow from the land toward the ocean. The total annual precipitation in this climate type is higher than in the tropical rainforest climate; however, rainfall is typically concentrated within a period of 7–9 months per year, with very low precipitation during the remaining months. This pronounced seasonal imbalance in precipitation distribution, together with annual totals that often exceed 2,000 mm, frequently leads to flooding and inundation events.

The tropical savanna climate type (Aw or As) is found closer to the Tropics of Cancer and Capricorn, generally between latitudes of 15° and 25°, and is characteristic of regions such as Africa, South Asia, northern Australia, and central Brazil. This climate is characterized by an extended dry season and a distinctly lower annual precipitation total compared to both the tropical rainforest and monsoon climates. Two distinct seasons are clearly defined: a dry season and a rainy season.

Under tropical climate conditions (A), two principal vegetation types have developed: tropical rainforests (Figure 7.2) and savannas, the latter representing a vegetation formation dominated by grass species, with the presence of scattered individual trees.



Figure 7.2. Daintree Tropical Rainforest in Queensland, Australia
(photo by Agnieszka Sosnowska, 2025)

Tropical rainforests exhibit a very high degree of diversity, not only on the global scale but also within individual regions. This vegetation formation includes tropical dry forests, tropical lowland forests, tropical montane moist forests, tropical floodplain and swamp forests, as well as mangrove forests.
The distinctive character of these forests is shaped primarily by climatic conditions, but is also influenced by elevation above sea level, soil characteristics,

and groundwater depth. Tropical rainforests are dominated by broadleaf species, often characterized by large leaves that are evergreen or semi-evergreen; during the dry season, some species may exhibit leaf discoloration or partial leaf shedding. Species richness is exceptionally high, and this biome is considered the most biodiverse on Earth. The tree layer is dominated by species such as mahoganies, ebonies, rubber trees, figs, and palms.

Tropical rainforests are typically structured into five vertical layers. The uppermost layer consists of emergent trees that rise above the general canopy and have direct access to sunlight. This layer includes the tallest and widest trees, which may reach heights of up to 50 m. Below it lies the main canopy layer, composed of trees attaining heights of approximately 30–40 m. Vegetation in this layer is relatively dense, and strong competition for light results in trees with slender trunks. The lowest tree layer consists of juvenile individuals growing under very dense conditions and typically reaching heights of 5–10 m. The fourth layer is formed by shrubs growing beneath the tree crowns, consisting mainly of young trees and shrub species. The lowest layer is the herbaceous layer, referred to as the forest floor. Due to limited solar radiation, this layer is locally devoid of vegetation; where plants do occur, they are predominantly mosses, clubmosses, and ferns.

In addition to trees, tropical rainforests support a high abundance of epiphytes and lianas. Lianas grow very rapidly, and their shoots may exceed 100 m in length. Epiphytes colonize branches, trunk bifurcations, and bark fissures, and include representatives of the Bromeliaceae and Orchidaceae families, as well as lichens, algae, and bryophytes.

A particularly important and distinctive plant community within tropical forests is mangrove forests (Figure 7.3), which occur along coastlines and in river estuaries. They are formed by deciduous tree and shrub species of varying heights and canopy densities. These plants are characterized by stilt roots that stabilize the vegetation, as well as aerial breathing roots (pneumatophores). Mangrove forests occur within the tidal zone and perform a crucial protective function for coastlines, for example, by reducing the impact of high waves generated by tsunamis or hurricanes. This protective role was particularly evident during the 2004 Indian Ocean tsunami, when mangrove forests acted as natural barriers that absorbed wave energy, thereby reducing damage and loss of life. Despite their importance, mangrove forests continue to decline at a rapid rate globally due to intensive coastal development, the expansion of shrimp farms, and the establishment of oil palm plantations. At present, mangroves cover less than 150,000 km² worldwide, primarily in Indonesia, Brazil, and Australia, and it is estimated that more than 35,000 km² have been lost over the past 30 years.



Figure 7.3. Mangrove forests in Darwin, Australia (photo by Agnieszka Sosnowska, 2025)

The principal threats to tropical rainforests include deforestation, fires, and climate change. Deforestation is driven mainly by agricultural expansion and the demand for new land for cultivation, particularly for oil palm plantations and livestock grazing. Additional drivers include industrial development, especially extractive industries, as well as infrastructure expansion. Fires in tropical rainforests are often deliberately induced, as they provide a rapid means of clearing land, for example, for grazing purposes. Climate change manifests primarily through increased air temperatures and alterations in the seasonal distribution of precipitation. In many regions, lower annual precipitation totals than those recorded in the past have been observed, leading to more frequent droughts and a consequent decline in forest conditions.

The consequences of these processes include a significant loss of biodiversity, particularly affecting endemic species that are restricted to tropical forest ecosystems. Deforestation also negatively affects the hydrological cycle, primarily by accelerating infiltration and surface runoff. Given that tropical rainforests have developed on nutrient-poor, acidic, and water-saturated lateritic soils, the removal of natural vegetation cover increases the intensity of mineral leaching and enhances water erosion processes. Another critical consequence of rainforest deforestation is the increased emission of carbon dioxide, which contributes to the intensification of the greenhouse effect and further climate change.

In tropical savanna climates, grassland communities with the presence of trees and shrubs predominate. These woody plants grow at considerable distances from one another, so their crowns do not form a closed canopy. As a result, sufficient solar radiation reaches the ground surface, enabling the development of a continuous herbaceous layer dominated primarily by grasses. This vegetation formation is referred to as a savanna (Figure 7.4).

Three main types of savanna are commonly distinguished: tree savanna, characterized by scattered trees and shrubs; shrub savanna, with dispersed shrub cover; and grass savanna, in which trees and shrubs are largely absent, and grasses dominate, such as African elephant grass. This differentiation reflects variations in the duration of the dry season – the longer the dry season, the lower the proportion of trees and shrubs and the greater the dominance of grasses. Due to the prolonged dry season, during which precipitation is minimal or absent, plant species inhabiting savanna ecosystems are largely pyrophytes, i.e., species adapted to and tolerant of fire. Typical savanna species include baobabs, acacias, and bottle trees (e.g., Pachira and Brachychiton), which possess the ability to store water in their trunks, allowing them to survive extended dry periods. In many regions of the world, savannas are used as natural grazing areas and constitute habitats for large herbivorous mammals that migrate in herds, such as zebras, giraffes, and antelopes.



Figure 7.4. Savanna in Horton Plains National Park, Sri Lanka
(photo by Agnieszka Sosnowska, 2020)

The principal threats to savanna ecosystems include climate change – particularly rising mean air temperatures, which contribute to the lengthening of the dry season – fires, which are very often human-induced and may spread uncontrollably over large areas, the expansion of invasive species introduced by humans (primarily grasses intended to increase pasture productivity), and direct human activities such as agricultural expansion, urbanization, and industrial development, especially extractive industries.

When designing GI in tropical climates, the following factors should be considered:

- persistently high air temperatures throughout the year,
- high precipitation totals and pronounced seasonal variability,
- flood protection,
- surface cooling,
- protection of exceptional biological diversity.

7.4. CHARACTERISTICS OF ARID AND SEMI-ARID CLIMATES (B)

The arid and semi-arid climate zone occurs between latitudes of approximately 20° and 35°, both north and south of the equator. In addition, it extends over large areas located in the interior of continents (e.g., in Asia and North America), where moist air masses rarely reach. The defining characteristics of this climatic zone are the dominance of potential evaporation and transpiration over atmospheric precipitation, as well as the occurrence of mean annual air temperatures exceeding 18°C. This zone is divided into four climate types based on the annual distribution of air temperature (Table 7.2).

The hot desert climate (BWh) typically occurs at lower latitudes, between approximately 20° and 33° north and south of the equator. In the vicinity of the Tropics of Cancer and Capricorn, stable subsidence of atmospheric air masses takes place, accompanied by the formation of persistent high-pressure systems. This results in hot and dry climatic conditions with intense solar radiation. Consequently, the hot desert climate is present on all continents except Antarctica. During the summer season, very high levels of insolation prevail, leading to air temperatures typically ranging from 29 to 35°C, while midday temperatures often reach 43–46°C. Absolute temperature records on Earth exceed 50°C. The hottest place on Earth is generally considered to be Death Valley (California, USA), where a record temperature of 56.7°C was

recorded. During cooler seasons, nighttime air temperatures may drop to 0°C or lower, a phenomenon driven by exceptionally high radiative heat loss under cloudless skies.

Table 7.2. Climate types occurring within the dry climate zone (own work based on Peel et al., 2007; Beck et al., 2023; Arnfield, 2026)

Symbol	Type	Characteristics	Example occurrence
BSh	warm climate of the steppes	The climate is dry, with average evaporation exceeding precipitation, but less than potential evaporation. The average temperature is above 18°	Low latitudes. North-eastern Australia, north-eastern Mexico, northern Argentina, Botswana, Zimbabwe, and central India
BSk	cold climate of the steppes	The climate is dry, with average evaporation exceeding precipitation, but less than potential evaporation. The average temperature is below 18°C	Mid-latitudes. Central United States of America, central Spain, central Turkey, southern Ukraine, northern Kazakhstan, and southern Australia.
BWh	hot desert climate	The climate is dry, with average evaporation exceeding precipitation, but less than half of the potential evaporation. The average temperature is above 18°C. Frost does not occur or occurs very rarely	Low latitudes. Northern Mexico, the Sahara Desert, the Somali Peninsula, Namibia, the Arabian Peninsula, southern Iran, southern Pakistan, and central Australia
BWk	cold desert climate	The climate is dry, with average evaporation exceeding precipitation, but less than half of the potential evaporation. The average temperature is below 18°C. In winter, air temperatures fall below 0°C	Mid-latitudes. Southern Argentina, plateaus within the Cordillera Mountains in North America, central and southern Kazakhstan, Uzbekistan, southern Mongolia, and north-western China

The cold desert climate (BWk) typically occurs in temperate zones at latitudes of approximately 30–40°. It is characterized by hot (or in some cases warm) and dry summers, as well as generally cold and dry winters. Snowfall is very rare in regions with this climate. Cold desert climates usually occur at higher latitudes than hot desert climates and are generally more arid, which is a consequence of their location within precipitation shadow zones.

Due to the very low annual precipitation in arid and semi-arid climate zones, vegetation lacking trees has developed. These are most commonly low, thorny, or shrubby plant communities dominated by grasses or shrubs, while extensive areas are completely devoid of vegetation. Under the dry conditions of steppe climates, a vegetation formation known as steppe has developed, whereas under desert climates, deserts and semi-deserts prevail.

The steppe is a multispecies vegetation formation in which grasses play the dominant role. Three types of steppe are distinguished based on the prevailing plant species: meadow steppe, feather grass (Stipa) steppe, and wormwood steppe. Meadow steppes are the most species-rich and are typically dominated by tall grasses, which may reach heights of up to 120 cm. Under this vegetation, the most fertile soils in the world – Chernozems – have developed, characterized by thick humus horizons that often exceed 1 m in depth. Due to their high fertility, these areas are primarily used for agriculture, and consequently, only small remnants of natural meadow steppes have been preserved. The second, less species-rich type is the feather grass steppe (Figure 7.5), which occurs in drier conditions than meadow steppes. As less fertile soils have developed under this vegetation, these areas are most often used for pastoral purposes. The third type, the wormwood steppe, is the most species-poor. The underlying soils are unsuitable for agricultural use, being nutrient-poor and often saline. Wormwood steppes are characterized by the lowest vegetation cover density. Grasses and perennials develop in early spring, with flowering in the Northern Hemisphere occurring in April–May, while during the summer period (July–August), plants begin to yellow and dry out as a result of low precipitation and high air temperatures. In more humid locations, grasses are dense and tall, sometimes exceeding 2 m in height, with a significant contribution of herbaceous plants; in ravines and river valleys, sparsely distributed trees may also occur. In drier areas, grasses are shorter and grow in clumps.



Figure 7.5. Feather grass steppe in eastern Turkey (photo by Agnieszka Sosnowska, 2023)

Desert vegetation formations (Figure 7.6) are dominated by xeromorphic organisms adapted to extremely arid conditions, primarily succulents, drought-resistant shrubs, and xerophytic grasses. In some areas, ephemeral plants also occur, flowering rapidly following precipitation events or moisture derived from fog. Vegetation cover in desert areas is generally sparse, reaching up to approximately 60%. Plant species occurring under desert climate conditions are adapted to high air temperatures and low or absent precipitation primarily through the development of reduced transpiration surfaces, often serving protective functions. As a result, vegetation is generally low-growing, with small leaves, woody stems, and branches terminating in spines.

Because steppes often occur on fertile soils that are intensively used for agriculture, they – like desert areas – are highly susceptible to water and wind erosion. Soils lacking continuous vegetation cover and moisture, particularly loess and clay soils, are easily eroded by wind, leading to soil degradation, loss of organic matter, or even the complete removal of the thin desert soil layer. A significant problem in both desert and steppe regions is the occurrence of dust storms.

In the 1930s, a prolonged drought affected the Great Plains of the United States of America. Combined with the intensive expansion of agriculture in prairie areas (North American steppes), this led to a major ecological disaster characterized

primarily by severe soil erosion and the widespread transport of airborne dust. This event is known as the Dust Bowl, named after the dust storms (“dusters”) that swept across the Great Plains. The disaster was primarily caused by a rapid increase in land area deprived of its natural grassland cover. Deep ploughing, the absence of crop rotation, and intensive livestock grazing, combined with prolonged drought, resulted in the erosion of the fertile topsoil from more than 100 million ha. The peak of the disaster occurred during the so-called Black Sunday on April 14, 1935, when a massive dust cloud traveled at speeds of up to 100 km/h and reached Canada and the Atlantic coast. In response, the United States government introduced soil conservation legislation and implemented a series of training programs for farmers. Unfortunately, the Dust Bowl coincided with the Great Depression, contributing to a large-scale population exodus from the affected regions. In 1938, a period of intensive rainfall began, marking the end of the era of dust storms; nevertheless, large areas of the Great Plains remain devoid of continuous steppe vegetation.

Climate change is also leading to an increased frequency of short-duration, high-intensity rainfall events occurring locally within dry climate zones. Large volumes of water reaching exposed soil surfaces intensify water erosion, resulting in the gravitational transport of unconsolidated material downslope and potentially triggering large-scale mass movements such as landslides and debris or mud flows.



Figure 7.6. Wadi Rum Desert, Jordan (photo by Agnieszka Sosnowska, 2023)

When designing GI in dry climate zones, the following factors should be considered:

- limited water availability,
- drought resistance,
- provision of shade,
- erosion control (reduction of dust emission from exposed soil surfaces).

7.5. CHARACTERISTICS OF TEMPERATE CLIMATES (C)

The temperate climate zone (C) extends between approximately 30° and 50° north and south latitude. It occurs primarily in the western and eastern parts of most continents. This climatic zone is characterized by warm, humid summers and mild winters. During the winter season, mid-latitude cyclones are the dominant weather systems, whereas convective storms prevail in the summer months. A defining feature of this zone is that the mean temperature of the coldest month exceeds −3°C (or 0°C, depending on the applied criterion) but remains below 18°C, while the mean temperature of the warmest month exceeds 10°C.

The warm temperate climate zone (C) exhibits considerable variability in both temperature and precipitation conditions and is therefore divided into eight climate types (Table 7.3).

In the humid subtropical climate (Cfa), summers are typically long, hot, and very humid. During periods of strong isolation, tropical air masses dominate, bringing frequent, intense, but short-lived convective precipitation events. Mean monthly winter temperatures are generally mild. Precipitation reaches its maximum during summer, when thunderstorms are common due to intense surface heating. Tropical cyclones may also occur in this climate type. Winter is generally the drier season.

The oceanic temperate or subtropical highland climate (Cfb) occurs primarily along the western coasts of continents located at higher mid-latitudes. It is characterized by warm summers and cool or mild winters, relatively small annual temperature ranges, and a low frequency of extreme temperature events. Climatically similar types include the subpolar oceanic climate (Cfc) and the cold subtropical highland and subpolar oceanic climate influenced by monsoons (Cwc), which are generally situated closer to polar regions. Winters in these climates are long but relatively mild, while summers are short and cool. Snowfall is more frequent than in other oceanic climate types.

Table 7.3. Types of climates occurring in the temperate zone (own work based on Peel et al., 2007; Beck et al., 2023; Arnfield, 2026)

Symbol	Type	Characteristics	Example occurrence
Cfa	humid subtropical	The coldest month with an average temperature above 0°C or −3°C. At least one month with an average temperature above 22°C and at least four months with an average temperature above 10°C. No significant differences in precipitation between seasons	The southeastern coast of the United States of America, eastern Argentina, southern Brazil, northern Italy, southeastern China, and eastern Australia
Cfb	oceanic temperate or subtropical highland	The coldest month with an average temperature above 0°C or −3°C. All months with an average temperature below 22°C and at least four months with an average temperature above 10°C. No significant differences in precipitation between seasons	Northern France, Great Britain, Belgium, the Netherlands, western Germany, the highlands of Colombia, Chile, and Argentina, southeastern Australia, and New Zealand
Cfc	subpolar oceanic	The coldest month with an average temperature above 0°C −3°C, and 1–3 months with an average temperature above 10°C. No significant differences in precipitation between seasons	The coast of Iceland, the coast of Norway, the west coast of Canada, southern Chile, and southern Argentina
Cwa	subtropical humid monsoon	The coldest month with an average temperature above 0°C −3°C. At least one month with an average temperature above 22°C and at least four months with an average temperature above 10°C. At least ten times more precipitation in the wettest month of summer than in the driest month of winter	Northern India, Bangladesh, Myanmar, northern Vietnam, northern Mexico, western Argentina, southern Angola, and western Zambia

Table 7.3. Types of climates occurring in the temperate zone (own work based on Peel et al., 2007; Beck et al., 2023; Arnfield, 2026) (cont.)

Symbol	Type	Characteristics	Example occurrence
Cwb	subtropical mountainous or oceanic temperate influenced by monsoons	The coldest month with an average temperature above 0°C or −3°C. All months with an average temperature below 22°C and at least four months with an average temperature above 10°C. At least ten times more precipitation occurs in the wettest month of summer than in the driest month of winter	The eastern foothills of the Andes in Bolivia, Peru, and Argentina, central Mexico, eastern Madagascar, southeastern South Africa, Sichuan in China, and Nepal
Cwc	cold subtropical highland or subpolar oceanic influenced by monsoons	The coldest month with an average temperature above 0°C or −3°C, and 1–3 months with an average temperature above 10°C. At least ten times more precipitation occurs in the wettest month of summer than in the driest month of winter	Southeastern Mexico, northeastern South Africa, the High Atlas Mountains, the mountains of southern Europe, the southern Appalachians, and the Western Ghats in India
Csa	mediterranean typical	Hot summer. Coldest month with an average temperature above 0°C or −3°C. At least one month with an average temperature above 22°C and at least four months with an average temperature above 10°C. At least three times more precipitation in the wettest month of winter than in the driest month of summer, and the driest month of summer has less than 40 mm of precipitation	The Mediterranean basin (southern Spain, southern Italy, Albania, Greece, western Turkey, Lebanon, Israel, northern Algeria, northern Morocco, California, and southwestern Australia

Table 7.3. Types of climates occurring in the temperate zone (own work based on Peel et al., 2007; Beck et al., 2023; Arnfield, 2026) (cont.)

Symbol	Type	Characteristics	Example occurrence
Csb	mediterranean warm	The coldest month with an average temperature above 0°C or −3°C. All months with an average temperature below 22°C and at least four months with an average temperature above 10°C. At least three times more precipitation in the wettest month of winter than in the driest month of summer, and the driest month of summer has less than 40 mm	The northwestern coast of the United States of America, the central part of the coast of Chile, northern Portugal, northwestern Spain, and southeastern Australia
Csc	mediterranean with cool summers	The coldest month with an average temperature above 0°C or −3°C, and 1–3 months with an average temperature above 10°C. At least three times more precipitation in the wettest month of winter than in the driest month of summer, and the driest month of summer has less than 40 mm of precipitation	Fragments of mountain ranges located in the central Cordillera, the central part of the Andes, and Corsica

The typical Mediterranean climate (Csa) is characterized by hot, and occasionally extremely hot, dry summers. Winters are usually mild, cool, or slightly frosty. In some locations, particularly at higher elevations, occasional snowfall may occur during winter. The warm-summer Mediterranean climate (Csb) occurs less frequently and is characterized by warm, dry summers. In contrast, the cool-summer Mediterranean climate (Csc) is very rare and typically occurs at high elevations above sea level; it is characterized by cool and dry summers.

Traditionally, a monsoon was defined as a seasonal wind system with a periodically reversing direction, accompanied by corresponding changes in precipitation. Today, the term refers more broadly to seasonal changes in atmospheric circulation and precipitation occurring between the equator

and the boundaries of the Intertropical Convergence Zone (ITCZ) in both the Northern and Southern Hemispheres. These oscillations result in two distinct seasons: a dry season and a rainy season.

Under warm temperate climates (C), two main types of vegetation formations have developed: deciduous broadleaf forests and hard-leaved vegetation (maquis).

Deciduous forests, in which trees shed their leaves during winter, occur in regions where the growing season lasts from four to six months, and annual precipitation exceeds 700 mm. They are found primarily in western and central Europe, eastern Asia, and along the eastern coast of North America in temperate latitudes. These forests are relatively species-rich, dominated by deciduous tree species that lose their leaves each winter. This is one of the most widespread biomes on Earth, covering nearly 10% of the planet's surface. Typical tree species in the Northern Hemisphere include oak (*Quercus*), maple (*Acer*), linden (*Tilia*), beech (*Fagus*), and elm (*Ulmus*), while in the Southern Hemisphere they are mainly represented by southern beeches (*Nothofagus*).

Due to strong seasonal variability in climatic conditions, trees have developed adaptive strategies such as leaf shedding during the transition from autumn to winter, which is a response to reduced solar radiation and low mean daily air temperatures. Winter thus represents a dormant period during which plants conserve energy and reduce water loss. Before leaf fall, leaves change color to various shades of red, yellow, and orange as a result of chlorophyll degradation and the formation of pigments such as anthocyanins, carotene, and xanthophyll.

Deciduous forests have developed on relatively fertile soils. The decomposition of leaf litter contributes to high levels of organic matter and nutrient availability, resulting primarily in Cambisols (brown soils) and Luvisols. The high productivity of these soils makes them particularly suitable for agriculture; consequently, large areas within temperate climate zones have been converted into agricultural land. It is estimated that more than 50% of deciduous forest areas in this zone have been fragmented into smaller forest patches surrounded by agricultural and urban landscapes, which hampers animal migration and leads to a decline in biodiversity. On poorer soils under these climatic conditions, mixed or coniferous forests have developed, particularly on acidic sandy soils such as Podzols.

Among the most widespread types of deciduous forests in Europe are beech forests (Figure 7.7). These stands are characterized by strong shading and a relatively poorly developed shrub and herb layer. The dominant species is the European beech (*Fagus sylvatica*).

A significant component of Central European forests is formed by oak–hornbeam forests (*Carpinion betuli*), which are multispecies stands with a high proportion of oak, maple, linden, hornbeam, and ash. The shrub layer is well developed,

and the herb layer is particularly rich, especially in spring during the so-called spring aspect, when various geophytes flower before the emergence of tree leaves.



Figure 7.7. Beech forest in Müritz National Park, Germany (photo by Agnieszka Sosnowska, 2005)

Along watercourses, riparian forests occur, including willow, elm–ash, or alder communities. These vegetation types are highly species-rich, not only in the tree layer but also in the shrub and herb layers. In waterlogged areas, alder forests develop, characterized by a distinctive tuft-and-hollow microtopography. Trees and grasses grow on elevated tufts, while depressions are occupied by standing water for much of the year, often covered by duckweed (Figure 7.8).

Deciduous forests are characterized by a three-layered structure. The uppermost layer consists of trees forming one to three vertical strata, either composed of several species or dominated by a single species with others as admixtures. The second layer is the shrub layer, whose development depends on the vegetation type. The ground layer consists mainly of perennials, occasionally with dwarf shrubs and bryophytes. Epiphytes are limited to mosses and lichens.



Figure 7.8. Alder forest in the Kampinos Forest, Poland (photo by Agnieszka Sosnowska, 2012)

Deciduous forests are exposed to numerous disturbance factors and are generally resilient to them. However, they face increasing threats from extreme weather events such as heavy snowfall, storms, and strong winds, which can cause tree breakage or uprooting. Other abiotic disturbances include droughts, flooding, and fires, while biotic factors include fungal pathogens and outbreaks of bark beetles or other insects. In recent decades, climate change has led to rising temperatures and increased drought frequency in temperate deciduous forests.

Hard-leaved vegetation occurs primarily in the typical Mediterranean climate (Csa) and the warm-summer Mediterranean climate (Csb). In Europe, these vegetation types are referred to as maquis, in California as chaparral, and in South Africa as fynbos.

Maquis (Figure 7.9) is a secondary vegetation formation that developed in areas formerly covered by sclerophyllous forests, mainly oak forests. Due to prolonged land use, which led to soil erosion, as well as prevailing climatic conditions – especially hot and dry summers – the recovery of natural vegetation communities in these areas is highly constrained.

Hard-leaved vegetation may occur in loose assemblages or in dense formations. In many areas, small trees accompany shrub vegetation. Dominant species are evergreen shrubs that can reach heights of up to 2.5 m. Owing to prolonged

summer drought, these plants exhibit various adaptations, including reduced transpiration (sclerophytism), small leathery leaves, and the presence of spines or thorns. In some locations, vegetation forms extremely dense stands that are difficult to penetrate due to the hard-leaved nature of the species. An important feature is the production of essential oils, which can increase flammability and lead to spontaneous ignition during periods of extreme heat.



Figure 7.9. Maquis near Athens, Greece (photo by Agnieszka Sosnowska, 2019)

Many plant species occurring in sclerophyllous communities are fire-dependent, with seed germination stimulated by fire. Additionally, fires increase light availability at the ground surface and enhance access to soil nutrients, facilitating rapid post-fire regeneration. Historically, fires occurred every several to several dozen years and constituted a natural process supporting ecosystem renewal. However, fragmentation of maquis vegetation due to urban development and fire suppression has led to the accumulation of large amounts of flammable biomass. During periods of extreme heat, this material may ignite spontaneously, resulting in fires that are difficult to control and pose significant threats to human settlements.

When designing GI in temperate climate zones, the following factors should be considered:

- seasonal variability,
- high environmental heterogeneity within climate zones,
- extreme weather events.

7.6. CHARACTERISTICS OF CONTINENTAL CLIMATES (D)

Continental climates (D) are characterized by a mean air temperature of the warmest month above 10°C and a mean air temperature of the coldest month below −3°C. Both summer and winter are distinctly pronounced. These climates occur at latitudes similar to those of temperate climates (C) but are located farther inland, where moist air masses reach less frequently. In the Southern Hemisphere, due to the limited extent of land at these latitudes, continental climates are virtually absent.

Within continental climates, three main types are distinguished: humid continental (Df), subarctic with summer precipitation (Dw), and subarctic with winter precipitation (Ds). These are further subdivided into a total of twelve subtypes based on the mean temperature of the warmest month, including climates with hot summers, warm summers, cool summers, and extremely cold summers (extreme continental climates). The characteristics of these subtypes are presented in Table 7.4.

Table 7.4. Types of climates occurring within the continental climate zone (own work based on Peel et al., 2007; Beck et al., 2023; Arnfield, 2026)

Symbol	Type	Characteristics	Example occurrence
Dfa	continental humid with hot summers	The coldest month has an average air temperature below 0°C or −3°C, at least one month has an average temperature above 22°C, and at least four months have an average temperature above 10°C. There are no significant differences in precipitation between seasons	The north-eastern part of the United States of America, eastern Hungary, southern Romania, eastern Ukraine, Transcaucasia, and central Japan

Table 7.4. Types of climates occurring within the continental climate zone (own work based on Peel et al., 2007; Beck et al., 2023; Arnfield, 2026) (cont.)

Symbol	Type	Characteristics	Example occurrence
Dfb	continental humid with warm summers	The coldest month with an average air temperature below 0°C or −3°C, all months with an average temperature below 22°C, and at least four months with an average temperature above 10°C. No significant differences in precipitation between seasons	Southern and south-eastern Canada, Poland, the Czech Republic, southern Sweden, Belarus, Lithuania, Latvia, western and central Ukraine, and western Russia
Dfc	continental humid with cool summers	The coldest month with an average air temperature below 0°C or −3°C. 1–3 months with an average temperature above 10°C. No significant differences in precipitation between seasons	Northern Canada, northern Scandinavia, and northern Russia (including Siberia)
Dfd	distinctly continental humid	The coldest month with an average temperature below −38°C, and 1–3 months with an average temperature above 10°C. There is no significant difference in precipitation between seasons	Eastern Siberia in Russia
Dwa or Dsa	continental subarctic with hot summers and precipitation in summer (Dw) or winter (Ds	The coldest month with an average air temperature below 0°C or −3°C, at least one month with an average temperature above 22°C, and at least four months with an average temperature above 10°C. At least ten times more precipitation in the wettest month of summer than in the driest month of winter (Dwa), or precipitation in the wettest month of winter is at least three times greater than in the driest month of summer, and in the driest month of summer, it is less than 30 mm (Dsa)	North-eastern China, North Korea, and South Korea

Table 7.4. Types of climates occurring within the continental climate zone (own work based on Peel et al., 2007; Beck et al., 2023; Arnfield, 2026) (cont.)

Symbol	Type	Characteristics	Example occurrence
Dwb or Dsb	continental subarctic with warm summers and precipitation in summer (Dw) or winter (Ds)	The coldest month with an average air temperature below 0°C, or 1–3 months with an average temperature above 10°C. At least ten times more precipitation in the wettest month of summer than in the driest month of winter (Dwb), or precipitation in the wettest month of winter is at least three times greater than in the driest month of summer, and in the driest month of summer, it is less than 30 mm (Dsb)	The Primorsky Krai in south-eastern Russia
Dwc or Dsc	continental subarctic with cool summers and precipitation in summer (Dw) or winter (Ds)	The coldest month with an average air temperature below 0°C or –3°C, and 1–3 months with an average temperature above 10°C. In the wettest month of summer, rainfall is at least ten times greater than in the driest month of winter (Dwc), or rainfall in the wettest month of winter is at least three times greater than in the driest month of summer, and in the driest month of summer, it is less than 30 mm (Dsc)	The southern part of the Alaska Peninsula, northern Mongolia, south-eastern Russia, and western China
Dwd or Dsd	continental subarctic, extremely cold with precipitation in summer (Dw) or winter (Ds)	The coldest month with an average air temperature below –38°C, and 1–3 months with an average temperature above 10°C. In the wettest month of summer, rainfall is at least ten times greater than in the driest month of winter (Dwd), or rainfall in the wettest month of winter is at least three times greater than in the driest month of summer, and in the driest month of summer, it is less than 30 mm (Dsc)	The Far East of Russia

The humid continental climate (Df) is characterized by four distinct seasons and large seasonal temperature contrasts, with warm to hot (often humid) summers and cold (sometimes extremely cold in northern regions) winters, marked by snow. Precipitation generally occurs throughout the year. In contrast, the subarctic continental climate is characterized by long, intensely cold periods with short, often clear days, relatively low precipitation (mainly as snow), and low humidity. Mean monthly temperatures remain below freezing for six to eight months, the frost-free period lasts only 50–90 days per year, and snow cover persists for many months. Summers are short and mild, with long daylight hours. Subarctic continental climates exhibit the largest annual air temperature amplitudes on Earth, reaching approximately 30°C over most areas and exceeding 60°C in central Siberia.

The settlement of Tomtor (eastern Siberia, Russia) lies within a frigid continental climate. In January 2004, a record-low air temperature of −72.2°C was recorded there. The previous record was measured in Oymyakon, located approximately 40 km northwest, where −71.2°C was recorded in January 1926. Oymyakon also recorded the largest annual temperature amplitude of 104°C, with a maximum summer temperature of 33°C.

Within the continental climate zone, deciduous forests that shed their leaves in winter, mixed forests, and coniferous forests all occur. Deciduous and mixed forests are characteristic of the warmest and most humid climate types within this zone, namely Dfa and Dfb climates. Coniferous forests, referred to as taiga or boreal forests, occur in the colder and drier climate types.

The taiga (Figure 7.10) is found exclusively in the Northern Hemisphere, primarily in Siberia (Russia), Manchuria (northeastern China), Alaska, Canada, and northern Scandinavia. These regions are characterized by short, warm summers and long, cold, snowy winters. Permafrost is commonly present in the substrate and thaws during summer, which contributes to the formation of wetlands, as both evaporation and surface runoff are very limited. Boreal forests cover approximately 17 million km², representing about 11.5% of the Earth's land surface.

The taiga is dominated mainly by spruce, pine, Swiss pine, Siberian fir, and larch species, often accompanied by deciduous species such as birch, aspen, alder, and rowan. Deciduous trees are more common along forest margins, riverbanks, and wetland areas, and they also appear as successional species on burned sites. The shrub layer in boreal forests is very poorly developed, whereas the ground layer is highly developed. Coniferous tree species are well adapted to harsh climatic conditions. Thick, waxy needle coatings protect against excessive transpiration and frost. Forest stands are generally single-layered, with trees growing in dense canopies, resulting in dark forest interiors. At higher latitudes, near the boundary with the next vegetation zone – the tundra – the taiga becomes

more open. Trees are narrower and more slender, as narrow and tall crowns allow more efficient use of solar radiation under low sun angles. Additionally, this crown structure increases resistance to damage caused by snow loading (wet, heavy snow accumulation). Trees growing in the taiga typically have shallow, plate-like root systems, enabling them to absorb nutrients over large surface areas; the presence of permafrost does not pose a major limitation. The conical shape of the trees facilitates the shedding of snow accumulating on branches during winter.



Figure 7.10. Taiga along the Shumak River in the Eastern Sayan Mountains, Siberia, Russia (photo by Agnieszka Sosnowska, 2008)

Two types of taiga are distinguished: dark taiga and light taiga. Dark taiga occurs mainly in Europe and Western Siberia and is composed of taller, more densely growing species such as Siberian spruce, Siberian fir, and Siberian Swiss pine. The ground vegetation is relatively rich and dominated by dwarf shrubs. Light taiga, in contrast, occurs in Eastern Siberia and is formed primarily by shorter, more sparsely growing species such as Dahurian larch and Scots pine. The ground layer is usually poor and dominated by reindeer lichens.

The structure and functioning of the taiga are strongly influenced by natural disturbances, including windthrow, snow loading, and wildfires. Many coniferous tree species exhibit pyrophytic traits, most notably thick, exfoliating cork bark, as well as the production of substantial amounts of essential oils. Fire is one of the most important factors shaping boreal forest development; the formation of extensive treeless areas promotes intensive development of ground and understory vegetation, leading to forest stand regeneration.

As a result of climate change, a significant increase in air temperature has been recorded in the continental climate zone, affecting winter periods more strongly than summer. This leads primarily to a shortening of the winter season, faster snowmelt, and consequently substantial loss of soil moisture. Since summer temperatures are also rising, the taiga has begun to experience drought stress. Additionally, accelerated thawing of permafrost promotes increased insect activity, which during summer attacks drought-weakened trees, leading to widespread tree mortality. Under such conditions, the occurrence of fire results in faster spread and affects much larger areas.

When designing GI in continental climatic zones, the following factors should be considered:

- very large annual air temperature fluctuations,
- freeze–thaw cycles of the soil,
- snow loads during the cold season,
- management of snowmelt,
- seasonal planning of plantings.

7.7. CHARACTERISTICS OF POLAR CLIMATES (E)

Polar climates (E) are characterized by low air temperatures throughout the year. They occur in the northern coastal regions of North America, Europe, and Asia, as well as in Greenland and Antarctica, collectively covering more than 20% of the Earth's land surface. These areas are located near the poles and therefore represent the least populated regions of the planet. Polar climates are defined by the absence of warm summers. In the warmest month, mean temperatures remain below 10°C, and winter conditions vary in intensity. A key feature is the extreme variation in day length: during winter, days are very short or polar night prevails, while in summer, days are very long, and although the sun remains low above the horizon, it may shine continuously for 24 hours. Two types of polar climates are distinguished: tundra climate (ET) and ice cap climate (EF) (Table 7.5).

Table 7.5 Types of polar climates (own work based on Peel et al., 2007; Beck et al., 2023; Arnfield, 2026)

Symbol	Type	Characteristics	Example occurrence
ET	tundra	At least one month with an average air temperature above 0°C, but no month with an average air temperature exceeding 10°C	The islands of northern Canada, Spitsbergen, Iceland, Novaya Zemlya, and the northern reaches of Siberia in Russia
EF	ice sheet	The average monthly air temperature throughout the year does not exceed 0°C	Fragments of Antarctica and Greenland

The tundra climate is one of the coldest climate types occurring on Earth. Significantly lower air temperatures are recorded in some continental climates (Dfd, Dwd, Dsd). However, in those climates warmer periods do occur, whereas in the tundra climate they are virtually absent. Summers are short and relatively cold, while winters are diverse in character: they may be mild, with mean air temperatures around 0°C along sea and ocean coasts, but can be quite severe in continental interiors. The winter season lasts longer than summer (6–9 months). Due to the location within the circumpolar zone of solar illumination, the input of solar radiation is limited to a very short period, sometimes not exceeding several dozen days per year. Precipitation, both rainfall and snowfall, is generally low (approx. 250 mm annually) as a result of low water vapour pressure in the cold atmosphere. However, because potential evapotranspiration is extremely low, extensive wetlands, bogs, and peatlands can develop.

The ice sheet climate (EF) is characterized by the complete absence of summer. Throughout all twelve months of the year, mean air temperatures remain below 0°C. Atmospheric precipitation exceeds potential evapotranspiration. The climate is shaped by the constant presence of Arctic or Antarctic air masses, and the cold conditions are further intensified by the permanent ice cover. The ice cap climate is the coldest climate on Earth, as it records both the lowest absolute air temperatures and the lowest mean annual temperatures. At Vostok Station in Antarctica, considered the coldest place on Earth, the mean annual air temperature is −55.2°C, and the lowest recorded air temperature of −89.2°C was measured there. It should be noted that this area is not permanently inhabited by humans.

Because polar climates are characterized by cool summers and very cold winters – and, in the case of the ice sheet climate, by the complete absence of summer – either tundra vegetation develops in these regions, or vegetation cover is absent, resulting in polar ice deserts.

Tundra is a treeless formation with very low vegetation cover, dominated by dwarf shrubs, mosses, and lichens (Figure 7.11). Due to climatic conditions, particularly very low evapotranspiration, permafrost occurs in the substrate, similarly to the taiga. As a result, soils are well supplied with moisture during the warmer season. However, because of the long winter period, they are shallow, stony, and often take the form of polygonal soils. The growing season lasts from approximately 1.5 to 3.5 months. Within this short period, vegetation completes its entire life cycle from germination to seed production, although some species are aperiodic, meaning they can develop over many years and interrupt growth at any stage.

Tundra vegetation is characterized by low species diversity. It is estimated that the entire tundra zone contains approximately 300 species of vascular plants. Perennial species with dwarf growth forms and cushion-like habits dominate. Annual plants are very rare, and bulbous and rhizomatous plants are absent. In contrast, mosses and lichens exhibit high diversity, with more than 800 species occurring in tundra ecosystems. Unfavourable climatic conditions particularly soil freezing and strong winds have led to the development of thick, storage roots in many species. Plants are generally very low-growing, often prostrate, and long-lived, with some species capable of surviving for 100–200 years. In spring, plants flower almost simultaneously due to the short growing season; consequently, flowers are often conspicuous and brightly coloured, which enhances pollinator attraction.



Figure 7.11. Tundra beyond the Arctic Circle in northern Norway (photo by Agnieszka Sosnowska, 2009)

Four types of tundra are distinguished: forest tundra, shrub tundra, moss–lichen tundra, and Arctic tundra. The term proper tundra is commonly applied to shrub tundra and moss–lichen tundra.

The greatest threat to tundra ecosystems is climate change. An increase in mean annual air temperature leads to thawing of permafrost, which increases soil water content and accelerates erosion processes, potentially causing negative impacts on technical infrastructure. Climate change also results in transformations of natural vegetation, particularly the expansion of woody species and a reduction in the proportion of dwarf shrubs and grasses. Another significant issue is the increased release of carbon dioxide stored in wetland and peatland areas, which, once emitted into the atmosphere, contributes to the intensification of the greenhouse effect.

When designing GI in polar climate zones, the following factors should be considered:

- exposure to storms, salt spray fog, and sea-level rise,
- freeze–thaw cycles of the soil,
- dune stabilization,
- creation of wetland buffer zones,
- protection against wind erosion.

7.8. CHARACTERISTICS OF HIGHLAND CLIMATES (H)

The highland climate zone (H) was introduced in the 1960s by Glenn Thomas Trewartha to describe areas situated at elevations above 1,500 m ASL. High-mountain areas occur on all continents and occupy approximately 8% of the Earth's land surface. Climatic conditions vary depending on the location of a mountain range within a given climatic zone (A–E). However, a key common feature is the change in climatic parameters with increasing altitude. Under humid continental climates with warm summers (Dfb), air temperature decreases on average by 0.6°C per 100 m of elevation; under drier conditions, the decrease is approximately 1°C, while in the Himalayas it can reach up to 1.5°C. With increasing altitude, solar radiation also increases by an average of about 1% per 100 m. Annual precipitation totals generally increase as well, although usually only up to the altitude at which the atmosphere becomes fully saturated with water vapour.

Vertical variability of climatic conditions – particularly air temperature (the aerothermal gradient) – also leads to changes in other components of the natural environment. This phenomenon is referred to as the law of altitudinal zonation and represents one of the fundamental principles of organizing natural processes on Earth. With increasing elevation, the intensity and character of erosion and accumulation processes change, physical weathering becomes more dominant at the expense of chemical weathering, soil thickness decreases, and plant and animal ecosystems change, forming so-called climatic–vegetation belts.

The arrangement of climatic–vegetation (landscape) belts in individual mountain ranges depends primarily on latitude, the orientation of the mountain massif, and the local exposure of its slopes. This determines the occurrence of four principal landscape boundaries in mountains: the upper and lower limits of glaciation, the lower limit of permanent snow, the upper treeline, and the lower forest limit (also referred to as the upper limit of aridity). The upper limit of glaciation occurs above approximately 7,200 m ASL (Himalayas and Karakoram). Above this elevation, persistently negative temperatures reduce the potential for firn to transform into glacial ice.

Plant species occurring in mountainous regions have adapted to the prevailing climatic conditions. The main challenges include a short growing season, large air temperature fluctuations both seasonally and diurnally, excessive solar radiation, and strong winds. Flowers of alpine plant species often exhibit intense colours, produce strong scents, and generate large quantities of nectar to attract insects within the short growing season. Leaves are frequently evergreen, succulent, and covered with a waxy layer. Plants at higher elevations often adopt dwarf or cushion growth forms. Many species are also capable of spreading their development over several growing seasons. Flowers may be covered with hairs or dense pubescence, which provides thermal insulation and reduces water loss through transpiration. Some plant species exhibit pseudo-vivipary, whereby vegetative propagules develop instead of flowers and fruits and root directly into the soil, giving rise to new individuals.

Due to global population growth, mountain areas are subject to increasing pressure. At present, several percent of the world’s population live in mountainous regions, but projections suggest that this proportion may rise to as much as 10% in the near future. This trend is largely driven by climate change, expansion of agricultural land, increased extraction of mineral resources, growing environmental degradation in lowland areas, and the inherent natural attractiveness of mountain regions, which leads to changes in land use (e.g., conversion from agricultural to recreational and tourism functions). Intensified development of mountain areas contributes to the acceleration of erosion processes, particularly the occurrence of large landslides and debris flows.

When designing GI in mountainous areas, the following factors should be considered:

- steep terrain,
- altitudinal climatic zonation and microclimatic variability,
- prevention of erosion and landslides,
- management of surface and subsurface runoff,
- slope stabilization,
- hazards related to avalanches and sudden outbursts of lakes and water reservoirs.

Review questions:

1. How many climate zones are distinguished in the Köppen–Geiger's classification?
2. What criteria were used to divide the Earth's climates in this classification?
3. In which climate types are Poland and Indonesia located?
4. What are the main differences between plant communities occurring in Poland and Indonesia?

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8. GLOBAL CASE STUDIES OF GREEN INFRASTRUCTURE PRACTICES

What is this chapter about:
In the face of growing challenges related to climate change, urbanization, and the degradation of the natural environment, virtually all countries are confronted with the need to implement solutions based on long-term, systemic spatial planning. A key factor in decision-making is the analysis of projects that have proven effective in practice, delivering measurable environmental, social, and economic outcomes. Case studies constitute a research tool that enables the identification of success mechanisms, the assessment of their durability, and the evaluation of their potential adaptability to different spatial, climatic, and cultural conditions.

This chapter presents nine examples of solutions implemented across different climatic zones, continents, and spatial scales.

The Great Green Wall in Africa and the Mesoamerican Biological Corridor in Central America represent a supra-regional and transnational approach, in which ecological continuity and the scale of impact are of critical importance. Both projects demonstrate that combating environmental degradation and biodiversity loss requires actions that transcend administrative boundaries and should be grounded in international cooperation and the active involvement of local communities in landscape management. In this context, the landscape becomes a tool for climate stabilization, the protection of natural resources, and the improvement of living conditions in areas particularly vulnerable to the impacts of climate change.

The sponge city concept and the revitalization of Wadi Hanifah in Riyadh focus on water as a structuring element of space. Both examples demonstrate that restoring natural hydrological processes – such as retention, infiltration, and self-purification – constitutes an effective alternative to conventional, technical water drainage systems. This approach not only reduces the risks of flooding and drought but also improves the microclimate, the quality of public spaces, and residents' relationships with the landscape, making water an integral component

of the urban structure. Las Kabacki (forest park and woods nature reserve named in honor of Stefan Starzyński) in Warsaw and the Ontario's Greenbelt highlight the importance of strategic protection and planned development of large-scale green areas within and around cities. In both cases, long-term spatial policy plays a crucial role by treating green areas as a barrier against uncontrolled urban sprawl, an element of ecological connectivity, and a foundation for recreation and improved quality of life.
These examples demonstrate that preserving existing ecosystems often generates greater and more durable benefits than their subsequent restoration following periods of degradation.

In contrast, the agricultural park Gardens of Stene in Ostend, the system of green streets and stormwater management in Portland, and the historically developed irrigation system and tree-lined avenues in Mendoza illustrate diverse models for integrating greenery, water, and social functions into the urban fabric. Their common feature is the treatment of green infrastructure (GI) as a spatial component responsible for climate security, urban system resilience, and the enhancement of residents' quality of life.
The analysis of these projects highlights the importance of planning consistency, interdisciplinary collaboration, and institutional support in achieving long-term outcomes.

What you will learn:

- Regardless of scale – from global landscape initiatives to local urban strategies – the integration of environmental, social, and spatial objectives within a single, coherent development vision is of fundamental importance.
- Presented case studies confirm that GI plays a key role in increasing the resilience of cities and regions to climate change, while simultaneously strengthening place identity and social well-being.
- Learning from examples enables the identification of universal planning principles that may serve as a foundation for contemporary strategies in shaping the landscapes of the future.

8.1. LARGE-SCALE GREEN INFRASTRUCTURE SYSTEMS

8.1.1. Metropolitan open space systems – Ontario's Greenbelt (Canada)

Province of Ontario is characterized by a humid continental climate with warm summers (Dfb). This is the fastest-growing region in Canada in both economic and demographic terms. The green spaces system surrounding Toronto (Ontario's

Greenbelt) constitute an extensive, open, and undeveloped area comprising agricultural land, forests, and wetlands, which provide a wide range of ecosystem services to the region's inhabitants, including food production and access to clean water and air.

Toronto is situated within the so-called Golden Horseshoe, a region forming the south-eastern edge of the province. This area is home to more than 9.8 million inhabitants, accounting for approximately 26.5% of Canada's total population (Ali, 2008). One of the key drivers of the Golden Horseshoe's development has historically been food production. It should be emphasized that only 3.2% of soils in Canada are suitable for cultivation. Therefore, the fertile soils of this region – among the most productive in the country – are of particular importance. The problem of the loss of high-quality agricultural soils in this part of Canada was already observed between 1995 and 2001, when nearly 16% of the best soils (Class I) were converted to built-up areas (Byers, 2013). This led to the emergence of the concept of introducing a planning instrument around Toronto to control urban sprawl.

In 2005, the Greenbelt Protection Act was adopted, enabling the designation of undeveloped areas covering nearly approximately 800,000 ha (2 million acres) (Figure 8.1). These areas surround Toronto but also extend over the Oak Ridges Moraine and along the Niagara Escarpment – a narrow (4–10 km wide) geological formation stretching approximately 750 km in length. The primary objective of establishing development-free areas (the Ontario's Greenbelt) was to protect the region from rapidly expanding urbanization, particularly on agricultural lands and environmentally valuable areas, as well as areas critical for the protection and replenishment of water resources. Consequently, the Ontario's Greenbelt encompasses not only agricultural land but also natural areas, a system of regional parks with significant recreational value, as well as rural settlements (47) and individual farms (4,800). Although the Ontario's Greenbelt was introduced as a top-down initiative by the provincial authorities, responsibility for its implementation lies with the municipalities within whose boundaries it is located.

Municipalities are tasked with designating agricultural land and identifying key elements of natural heritage. They are therefore obliged not only to implement local plans but also to comply with the provisions of the Ontario's Greenbelt Plan. Every 10 years, this plan is reviewed, during which time all municipalities are required to maintain the Ontario's Greenbelt to an unchanged spatial extent.

In the most recent Ontario's Greenbelt Plan (MMAH Ontario, 2017), conservation objectives were slightly revised, defining the green belt as a system of lands that:

- are permanently protected from conversion and fragmentation of agricultural land, with agriculture remaining the dominant land use within its boundaries,

- provide long-term protection of natural heritage and water resources that sustain environmental quality and ensure favourable health conditions for regional residents,
- form an environmental framework around which regional development is concentrated,
- strengthen economic and social linkages between local communities and agricultural, tourism, recreational functions, as well as natural environmental resources,
- enhance resilience and mitigate the impacts of climate change.

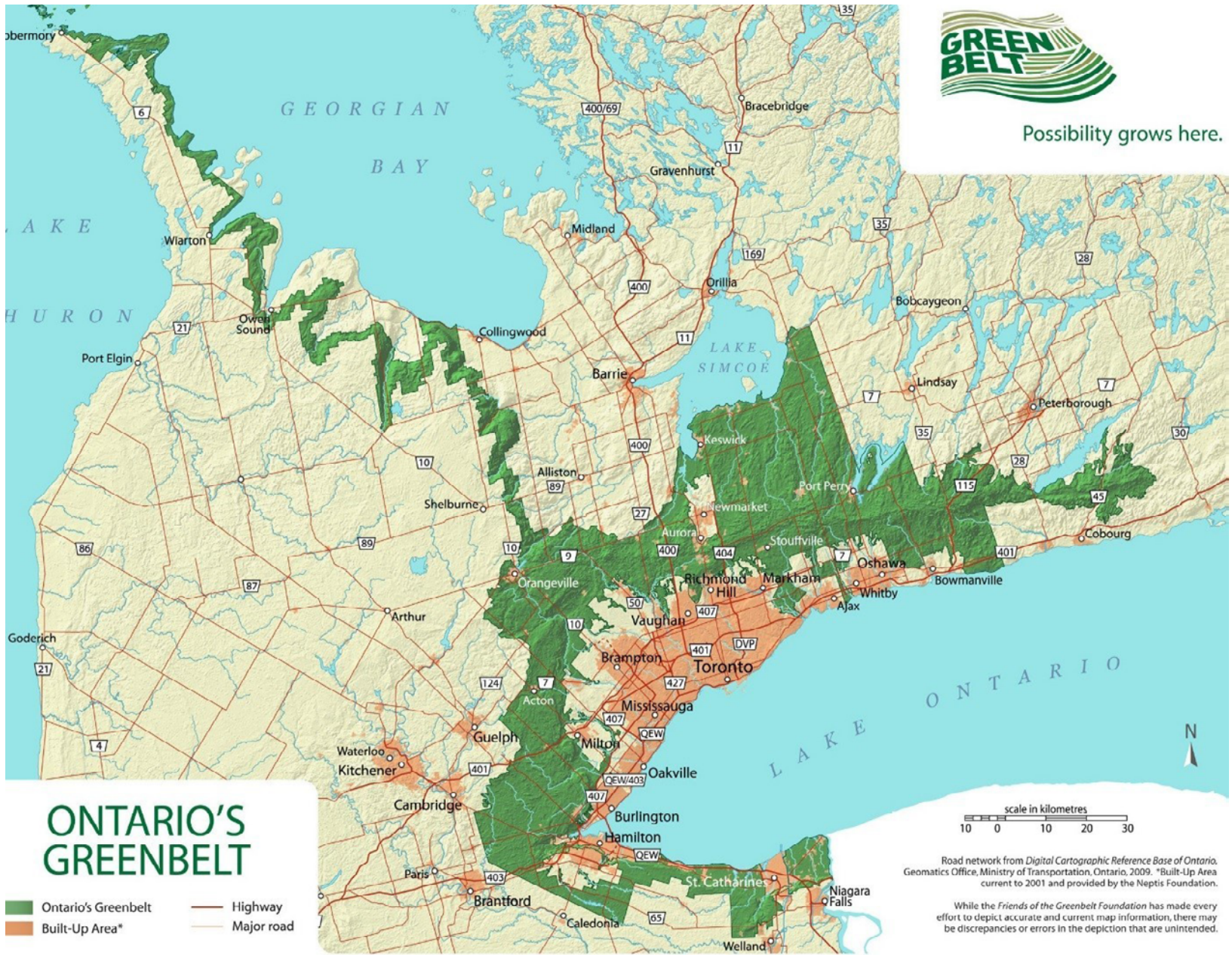

Figure 8.1. Ontario's Greenbelt: dark green – green belt area; light green – undeveloped areas outside the green belt; brown – urbanized regions (Greenbelt Foundation, 2025b)

The concept of protecting open land around Toronto is based on top-down financing mechanisms and strong political support for the Ontario's Greenbelt, which has significantly contributed to its durability and effectiveness.
Of particular importance is the broad inclusion of stakeholders residents, developers, environmental organizations, and farmers in the planning and implementation process.

The activities of two organizations supported the implementation of the green belt around Toronto. One of these was the Greenbelt Council, an advisory body providing expert guidance, while the other was the Friends of the Greenbelt Foundation, a non-governmental organization promoting the green belt concept. The Greenbelt Foundation aims, on the one hand, to popularize the concept among residents by raising awareness of its importance in everyday life, and on the other hand, to operate as a research-oriented institution initiating and supervising studies on the Ontario's Greenbelt, its ecological functioning, and its economic performance, particularly in the context of sustainable agriculture and recreation. In addition, the Greenbelt Foundation provides financial support for solutions facilitating the implementation of the Greenbelt Plan, including spatial development plans and sectoral policies. It also carries out extensive information and educational activities (Figure 8.2), organising public events, television programmes, and initiatives targeted at children and local communities.



Figure 8.2. Information board at the entrance to the Ontario's Greenbelt at Toronto (Greenbelt Foundation, 2025a)

As a result of the activities of these two organizations, public support for the Ontario's Greenbelt is very high. According to surveys conducted in 2016, nearly 80% of Ontario's residents supported the provincial development plan with a restrictive policy regarding the Ontario's Greenbelt. Furthermore, 88% of respondents believed that new development should be concentrated within already urbanized areas, while 73% expressed criticism of low-density suburban sprawl. As many as 84% of respondents declared a YIMBY (Yes in My Back Yard)

attitude, accepting protection measures even within their immediate surroundings. These results underscore the importance of long-term education and bottom-up public engagement, particularly given that many municipalities initially feared development restrictions, negative impacts on agriculture, and rising land prices.

According to the provisions of the Ontario's Greenbelt Plan, development is prohibited in:

- areas forming part of the natural heritage system, i.e., environmentally valuable areas and those critical for water resources,
- areas designated for specialty crops and the highest-quality agricultural land.
- Regulations governing rural areas include:
- restrictions on non-agricultural functions and new development,
- regulations concerning infrastructure development (stormwater management, wastewater, water, and energy resources),
- limitations on the subdivision of new building plots.

The minimum size of a new farm is required to be 16 ha (40 acres) in specialty crop areas or 40 ha (100 acres) on prime agricultural land (Figure 8.3). Small plots are permitted within existing settlements, provided that they do not lead to further fragmentation of environmentally valuable areas or areas critical for water resource protection. In environmentally sensitive areas, development is allowed exclusively for nature conservation purposes or public uses. The Ontario's Greenbelt Plan also introduces buffer zones around wetlands and areas with high infiltration capacity, as well as along streams, lakes, and valuable forest complexes and other vegetation. These buffer zones must be at least 30 m wide for general human activity and at least 120 m wide for development.



Figure 8.3. Agricultural landscape of the Ontario's Greenbelt (Greenbelt Foundation, 2025c)

Operating in parallel with the Ontario's Greenbelt Plan is the growth plan for the Greater Golden Horseshoe, which covers the entire metropolitan area, including Toronto, the zone between the city boundary and the Ontario's Greenbelt, and areas located outside this zone. A key principle of the growth plan is the designation of boundaries for urban and settlement development that accommodate growth needs while assuming a minimum density of 80 inhabitants per 1 ha. Both documents are prepared concurrently and are therefore complementary.

8.1.2. Ecological corridors and biodiversity networks – Mesoamerican Biological Corridor (Belize, Columbia, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Costa Rica, Panama)

The Mesoamerican Biological Corridor aims to protect and sustainably manage the environment in more than half of Central America. It was established to reduce ecosystem fragmentation, particularly in cross-border areas (Dettman, 2006). This area acts as a natural land bridge connecting North and South America, allowing many plant and animal species to migrate between these areas. Due to the nature of the area, the narrow strip of land between the Pacific Ocean to the west and the Gulf of Mexico and the Caribbean Sea to the east has a humid climate. The dominant climates are tropical rainforest (Af), tropical monsoon (Am), and savannah (Aw). On higher altitudes, there is a humid subtropical climate (Cfa) and a subtropical highland climate (Cfb). Due to climatic conditions, but also limited human pressure in this area, there are several unique habitats for about 7–10% of the world's known terrestrial species.

The Mesoamerican Biological Corridor is in the Inter-American region of Central America, covering the south-western part of North America, from the Isthmus of Tehuantepec to the Isthmus of Darien, located in the northern part of South America. The main physical-geographical regions included in its composition are the Northern Cordillera and Southern Cordillera of Central America and the Nicaraguan Lowlands. According to the political division, the Mesoamerican Biological Corridor is in the southern states of Mexico (Campeche, Chiapas, Quintana Roo, and Tabasco), Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama, and the north-western part of Colombia (Isthmus of Darién) (Figure 8.4). The entire area covers 768,990 km² and is inhabited by over 30 million people, with a population growth rate exceeding 2% per annum.



Figure 8.4. Location of the Mesoamerican Biological Corridor (CI & CABS, 2025)

The Mesoamerican Biological Corridor is located at the junction of two floristic regions: Holarctic (Holoarctis) and Neotropical (Neotropics). Most of the corridor's area (approx. 57%) is covered by natural vegetation. The main types of vegetation include humid equatorial forests, equatorial mountain forests (Figure 8.5), subequatorial forests that lose their leaves during the dry season, savannah, and high-altitude volcanic vegetation. The corridor has 6,600 km of diverse coastline rich in mangrove forests, coral reefs, and other types of coastal and marine ecosystems. In mountainous areas, the vegetation changes with altitude. On the highest peak in Central America, Tajumulco (4,220 m ASL, Guatemala), the vegetation zones are as follows: up to 600 m ASL, humid equatorial forests (tierra caliente); 600–2,000 m ASL: mountain forests with an increased number of conifers (tierra templada), 2,000–4,000 m ASL: cloud forests with oak trees (tierra fria), and above 4,000 m ASL: grassy vegetation with a large proportion of mosses and lichens (tierra helada). The vegetation of Costa Rica is characterized by the greatest species richness (over 20,000 species), with a significant proportion of endemic species occurring in a limited area (particularly in Guatemala and Panama).



Figure 8.5. Equatorial mountain forests in Panama (photo by Wojciech Lewandowski, 2014)

In 1992, the Central American System of Protected Areas was established, followed in 1997 by the official creation of the Mesoamerican Biological Corridor, which strengthened the integration of nature conservation policies in the region (IEG, 2011). The main objective of the Mesoamerican Biological Corridor was to improve the connectivity of protected areas on a regional scale, while improving the living conditions of local people. According to the assumptions, the movement of animals along the American continent should take place without disrupting civilization development and land use, while promoting sustainable development. The Mesoamerican Biological Corridor is defined as a spatial planning system that encompasses core natural areas, buffer zones, multifunctional zones, and ecological corridors, which are under various administrative provisions (Miller et al., 2001). These are organized and consolidated in a way that provides environmental benefits and services to Central America and the world at large.

Four zones have been designated within the corridor, each of which is characterised by a different level of accessibility for human activities. These are: the core zone, comprising protected areas whose purpose is to promote and maintain biodiversity in these areas and to provide ecosystem services for the local people; a buffer zone covering areas surrounding the core zones,

corridor zones (also known as connectivity zones) connecting water and land passages, enabling the movement of plants and animals within the corridor, and multifunctional zones, i.e. areas with diverse uses, separating natural and protected areas from agricultural land used for animal husbandry, forestry and other areas directly affected by human activity, mainly urbanization and mining (Figure 8.6).

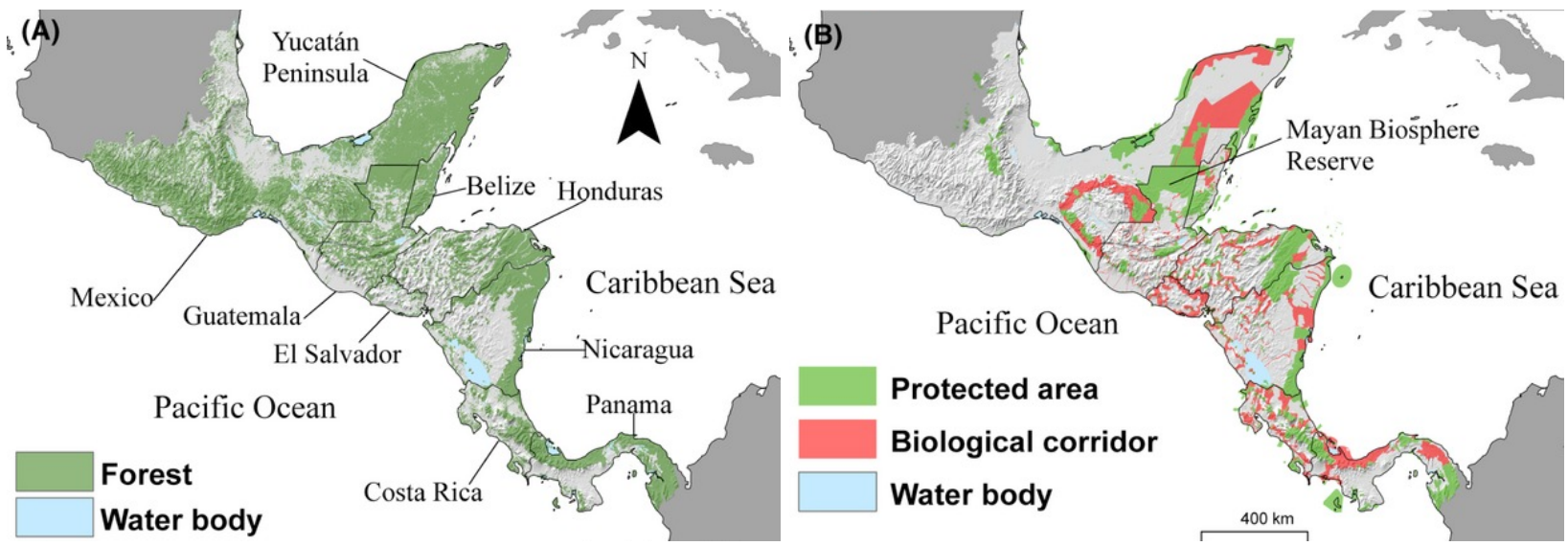

Figure 8.6. Extent of forest and location (A) of protected areas and corridor zones within the Mesoamerican Biological Corridor (B) (Imbach et al., 2013)

Since its creation, the corridor has attracted considerable interest from many government institutions and international cooperation agencies. It seems that several decades of concrete action are still needed to see significant results from its operation. Unfortunately, the current management model has ended. Individual countries are unable to effectively manage all protected areas as they have done so far. Despite considerable efforts, the isolation of protected areas remains high, which threatens the functioning of the entire corridor (Magliocca et al., 2024).

Only about 10.7% of the Mesoamerican Biological Corridor is currently covered by some form of environmental protection. This is clearly insufficient to preserve biodiversity. Natural vegetation should also be effectively protected outside national parks and reserves, as these forms of protection are often isolated from other natural areas, and their maintenance is too costly and often quite controversial from the perspective of local communities. Therefore, a key element for the functioning of this system is to further strengthen cooperation with residents so that they can fully benefit from the ecosystem services offered by the corridor. It is important that local communities become the main actors responsible for managing protected areas and maintaining the functioning of the corridor, but also the ones who benefit from its functioning. As agricultural production is an important part of the economy of all countries in the region, great emphasis should be placed on implementing sustainable agricultural practices, reducing habitat fragmentation, and the rate of further deforestation.

8.1.3. Wetland restoration – Wadi Hanifah (Saudi Arabia)

The Wadi Hanifah restoration is one of the most instructive examples in aridregion (climate BWh) green infrastructure, where stormwater management, constructed wetland processes, and creation of a continuous ecological corridor were combined at the watershed scale to deliver multiple environmental and social benefits.

Wadi Hanifah (Hanifa Valley) is the green spine of the Green Riyadh Project, which is a part of Saudi Arabia's Vision 2030 and the Saudi Green Initiative. These initiatives have launched transformative programs aimed at enhancing climate resilience. The valley (wadi) has historically served as the city's natural drainage system, comprising five distinct sections: bed, floodplain, horizontal alluvial terraces, valleys, and branches. It runs from northwest to southeast, traversing the western edge of Riyadh in its central part (Figure 8.7). From this midpoint, the valley features a continuous watercourse resulting from the daily discharge of approximately 650,000 m^3 of treated and untreated water.
This continuous flow of water has created a unique phenomenon of year-round lush areas in an arid environment. Rapid urban expansion and industrial activity threatened this function: floodplains were filled, effluents were dumped, and riparian habitats were fragmented (Rędzińska & Dreksler, 2025).

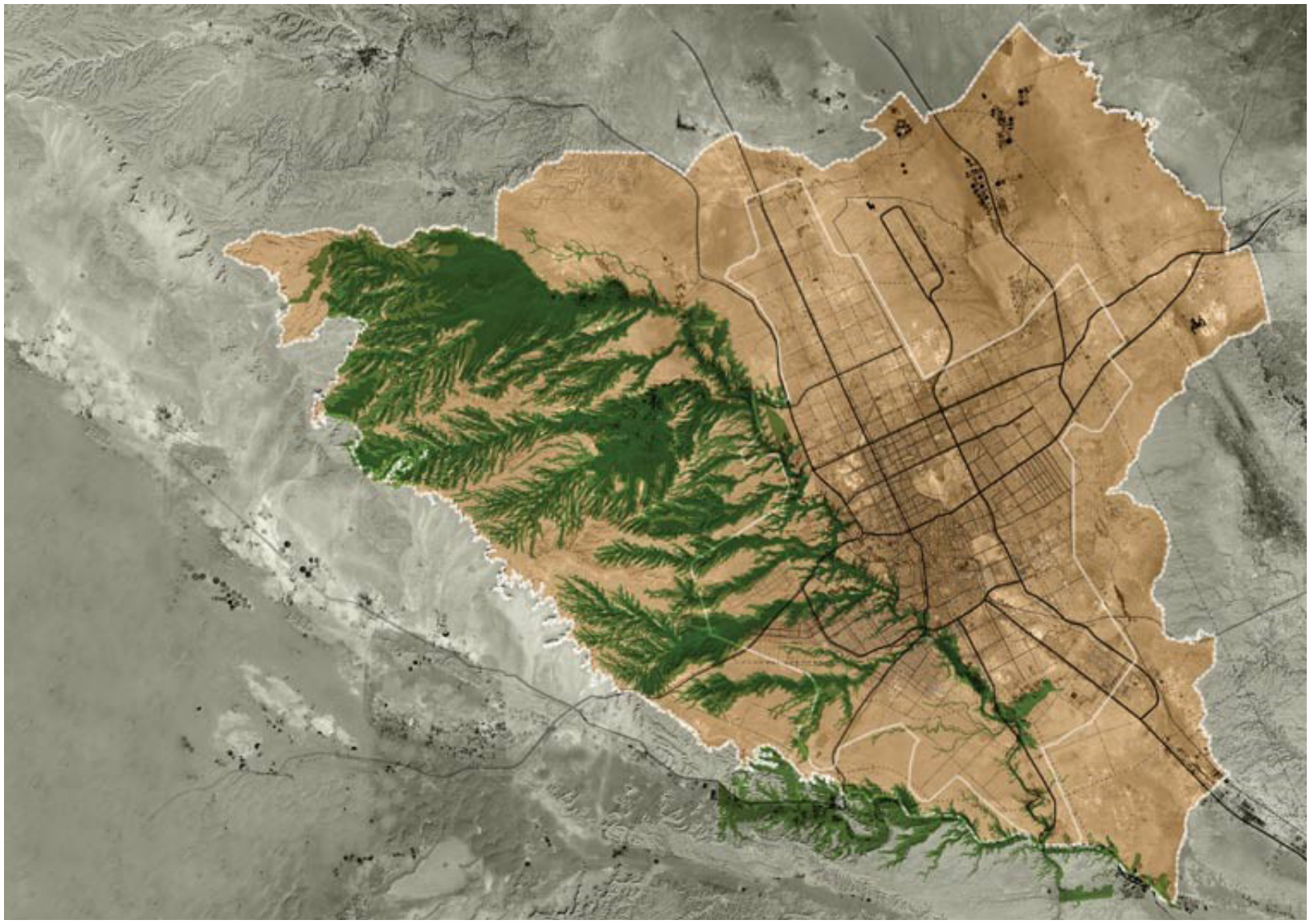

Figure 8.7. Wadi Hanifah is in the middle of the Najd Plateau, stretching roughly 120 km across a 4,000–4,500 km^2 watershed. It is fed by more than 40 tributaries and groundwater seepage (RCRC, 2025)

From the outset, planners and engineers took a systems view: this was not merely a riverside park but a comprehensive flood management and environmental rehabilitation project. The Wadi Hanifah Comprehensive Development Plan (early 2000s) and later interventions led by the Arriyadh Development Authority and the Royal Commission for Riyadh City married hydraulic engineering (HEC-RAS, TUFLOW, and 2D/3D LiDAR modeling) with landscape design and ecology (BuroHappold, 2010; Alrabe, 2013; Figure 8.8). The river channel was re-profiled to restore conveyance while maintaining meanders, riffles, and pools that slow the flow and encourage infiltration. Seasonal flood channels and upstream check dams reduce peak flows, development controls, and mapped floodplains prevent further encroachment.



Figure 8.8. Redesigned river channel (courtesy of Moriyama & Teshima Planners 2010; Trottier & Eidick, 2015)

Central to the valley's ecological revival is the bioremediation facility and a series of wetlandlike features. Rather than depending on energyintensive mechanical treatment alone, designers installed a chain of roughly 140 biocells, weirs, pools, and riffles, a living treatment train that raises dissolved oxygen, encourages periphyton and benthic activity, traps sediment, and reduces nutrients and coliform loads (Figure 8.9). Downstream lakes and reconfigured natural basins act as detention and polishing ponds, providing habitat and amenity as they store and slow stormwater. These constructed wetland processes are especially appropriate in a dry climate where

base flows often derive from treated effluent and groundwater seepage. By using water as a resource for habitat and recreation, the project reframed wastewater as an ecosystem input rather than simply a pollutant (Wescoat, 2015).

Wadi Hanifah is a prime example of how the proper management and treatment of municipal wastewater can help rebuild the relationship between a city and its surrounding natural environment. Thanks to careful water resource management and modern ecological solutions, the negative impact of urbanization on the valley has been reduced, and it has been transformed into a valuable natural and recreational space. Consequently, Wadi Hanifah now serves as an important ecological corridor and a recreational area where residents can enjoy contact with nature, generating numerous social, environmental, and landscape benefits for the entire city. The 50 km-long corridor includes nine large parks, five lakes, and over 7 km of waterfront promenades.



Figure 8.9. Main bioremediation facility (AKDN, 2014)

As part of the project, key native species characteristic of different sections of the valley were identified. Cuttings and seeds were collected from the least degraded areas of the valley and then propagated in newly established greenhouses and nurseries. These plants were installed in 35 different configurations of planting cells that were constructed by the thousands along the valley bed. The cells consist of gravel-topped planting beds that become local incubators for seed propagation between cells. Extensive riparian planting

with native and droughttolerant species, reintroduced palm groves, and restored wetlands have increased habitat connectivity. 30,000 shade trees, 6,000 date palm trees, 2,000 large acacia trees, and 50,000 shrubs were planted or transplanted. As a result, the valley now supports greater numbers of aquatic invertebrates, fish, and migratory birds that use the lakes and pools as stopover and breeding sites. Trails, promenades, and public spaces along the banks encourage human stewardship, which helps deter illegal dumping and reduces landscape degradation – an essential social co-benefit.

Outcomes from the Wadi Hanifah interventions are multiple and mutually reinforcing. Flood risk has been reduced through improved conveyance, upstream detention measures, and enforced floodplain controls. Water quality has improved because of the bioremediation facility and the wetlands' polishing functions; treated water is reused for irrigation and to sustain perennial flows. Biodiversity metrics have improved where habitat was restored, and the green corridor now offers recreational and cultural services to Riyadh's residents. Equally important, the project illustrates governance lessons: success depended on master planning at the catchment scale, technical modeling, continued monitoring, and an institutional framework that enforced landuse controls and coordinated agencies.



Figure 8.10. A total of 1,805 planting cells were installed in 35 distinct configurations adapted to riverbed microclimate condition (Trottier & Eidick, 2015)

Despite these achievements, challenges remain. Longterm management of constructed wetlands and lakes requires ongoing maintenance to prevent siltation, invasive species, and algal blooms, particularly as the city's water demand and climate variability shift hydrological regimes. Continued funding, adaptive monitoring, and engagement with local communities are essential to sustain ecological functions. Wadi Hanifah offers three clear lessons: design green infrastructure at the watershed scale; prioritize multifunctional naturebased treatment systems; and embed governance, maintenance, and community access in project design.

8.1.4. Restoration of degraded landscapes on a supra-regional scale – Great Green Wall (Burkina Faso, Chad, Djibouti, Eritrea, Ethiopia, Mali, Mauritania, Niger, Nigeria, Senegal, Sudan)

The Great Green Wall (GGW) initiative is one of the environmental and social programs operating in Africa. Its main objectives are to decrease desertification, restore degraded ecosystems, and strengthen the climate resilience of the population living in the Sahel region, which is characterized by a hot desert climate (BWh) and a warm steppe climate (BSh).

Initially, the project was to take the form of a green belt approximately 15 km wide and 8,000 km long, stretching across the entire African continent, from Senegal in the west to Djibouti in the east (Figure 8.11). However, in recent years,

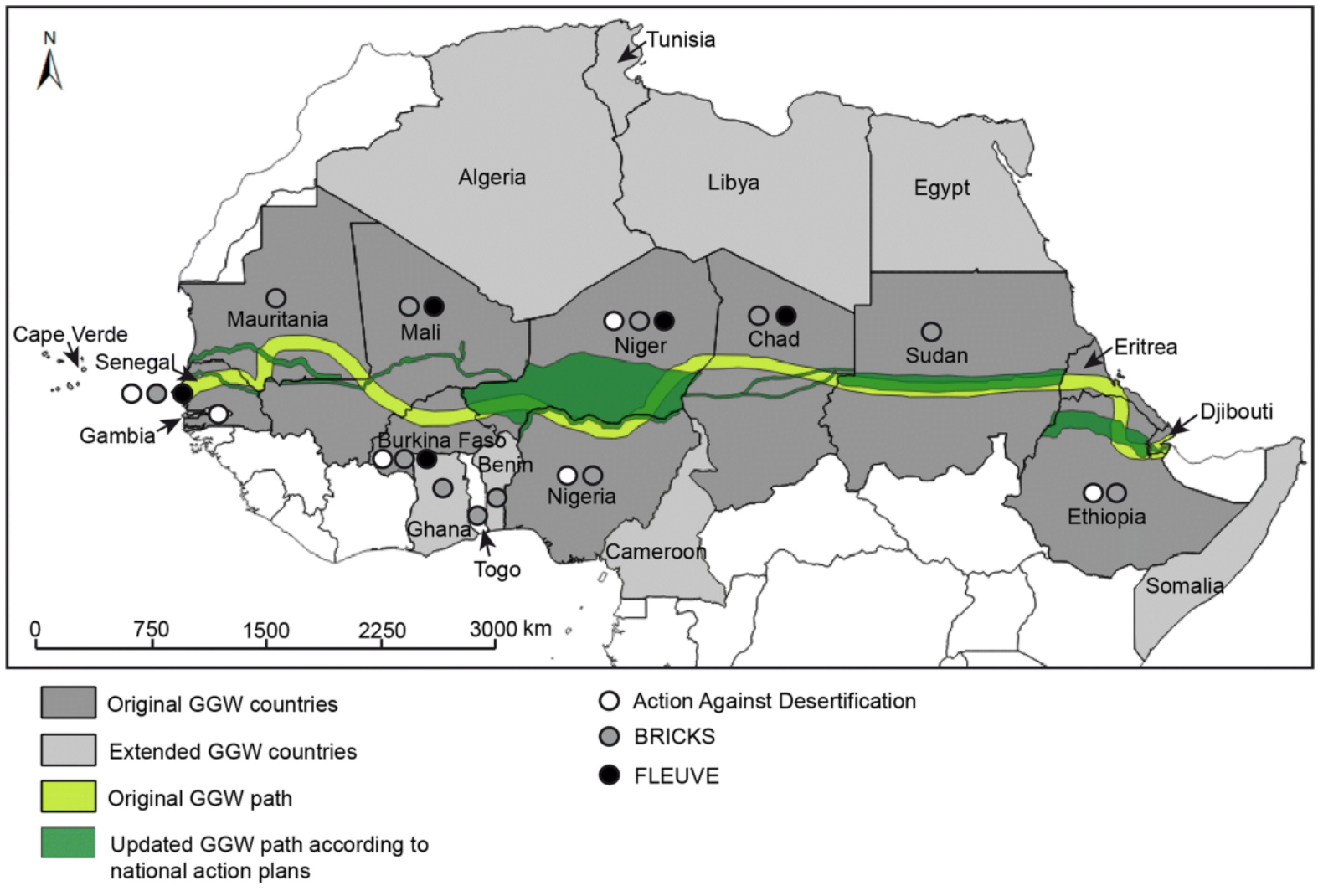

Figure 8.11. Location of the Great Green Wall (Goffner et al., 2019)

this vision has evolved into an integrated approach to sustainable environmental management, aiming to create a mosaic of different land uses, regenerate natural vegetation, and improve water retention and conservation. The total area of the Great Green Wall initiative is 156 million ha, with the largest areas located in Niger, Mali, Ethiopia, and Eritrea.

According to data from the United Nations Convention to Combat Desertification (UNCCD), the overarching goal is to rehabilitate 100 million ha of degraded land, create 10 million “green” jobs, and sequester 250 million ton of carbon dioxide by 2030.

The idea of building the Great Green Wall first emerged in the 1980s. However, it was not until 2007 that the African Union, with the support of the UNCCD, initiated a decision that gave it political and institutional shape. The first years of implementation, however, were characterized by scattered activities and a lack of coordinated monitoring. Individual countries carried out their own afforestation projects without common progress indicators or stable funding. In 2010, all Sahel countries established the Pan-African Agency of the Great Green Wall (PA-GGW) to coordinate the implementation of this initiative and support the mobilization of resources. In 2020, the “Great Green Wall Implementation Status and Way Ahead to 2030” report was published, which was the first comprehensive assessment of the project’s implementation status. The report shows, among other things, that thanks to the activities carried out between 2007 and 2018, almost 20 million ha of land were reclaimed (Figure 8.12) and approximately 90 million USD in revenue was generated. This initiative has a number of environmental and socio-economic benefits, such as providing employment opportunities for rural residents, which contributes to poverty reduction. The project has created over 350,000 jobs and trained approximately 220,000 people in sustainable agricultural and pastoral production.



Figure 8.12. Reclaimed areas under the Great Green Wall initiative (UNCCD, 2021)

In 2021, the Great Green Wall Accelerator program was established, led by the UNCCD, to monitor the financing and results of this initiative. In 2023, the Great Green Wall Observatory was established as a monitoring and evaluation system to provide information for local, national, and regional programs. In 2024, the African Union Commission (AUC, 2024) adopted a new Great Green Wall Initiative Strategy and Ten-Year Implementation Framework (2024–2034), which combines environmental actions with social and economic objectives under Agenda 2063, a long-term vision for the integration and development of the continent. The updated Great Green Wall Initiative Strategy extends the scope of activities beyond the original 11 countries and integrates the initiative into the framework of the United Africa continental environmental policy.

The contemporary functioning of the Great Green Wall is based on a variety of activities, ranging from local agroforestry techniques to the use of advanced scientific and financial tools. Traditional knowledge is of great importance in the Sahel region. For decades, farmers have been using soil restoration and water retention techniques such as zaï, small pits filled with organic matter, half-moons, semi-circular depressions with a diameter of about 2 m, with the “open side” facing the slope (Figure 8.13, Figure 8.14), and stone lines, which slow down surface runoff (Figure 8.15). In the case of half-moons, the soil excavated from the pit forms a ridge that retains runoff water, allowing it to infiltrate deep into the soil. Compost or manure is placed in the depressions, and then plants, including trees, are planted. This simple, low-cost technique significantly improves soil moisture and productivity.

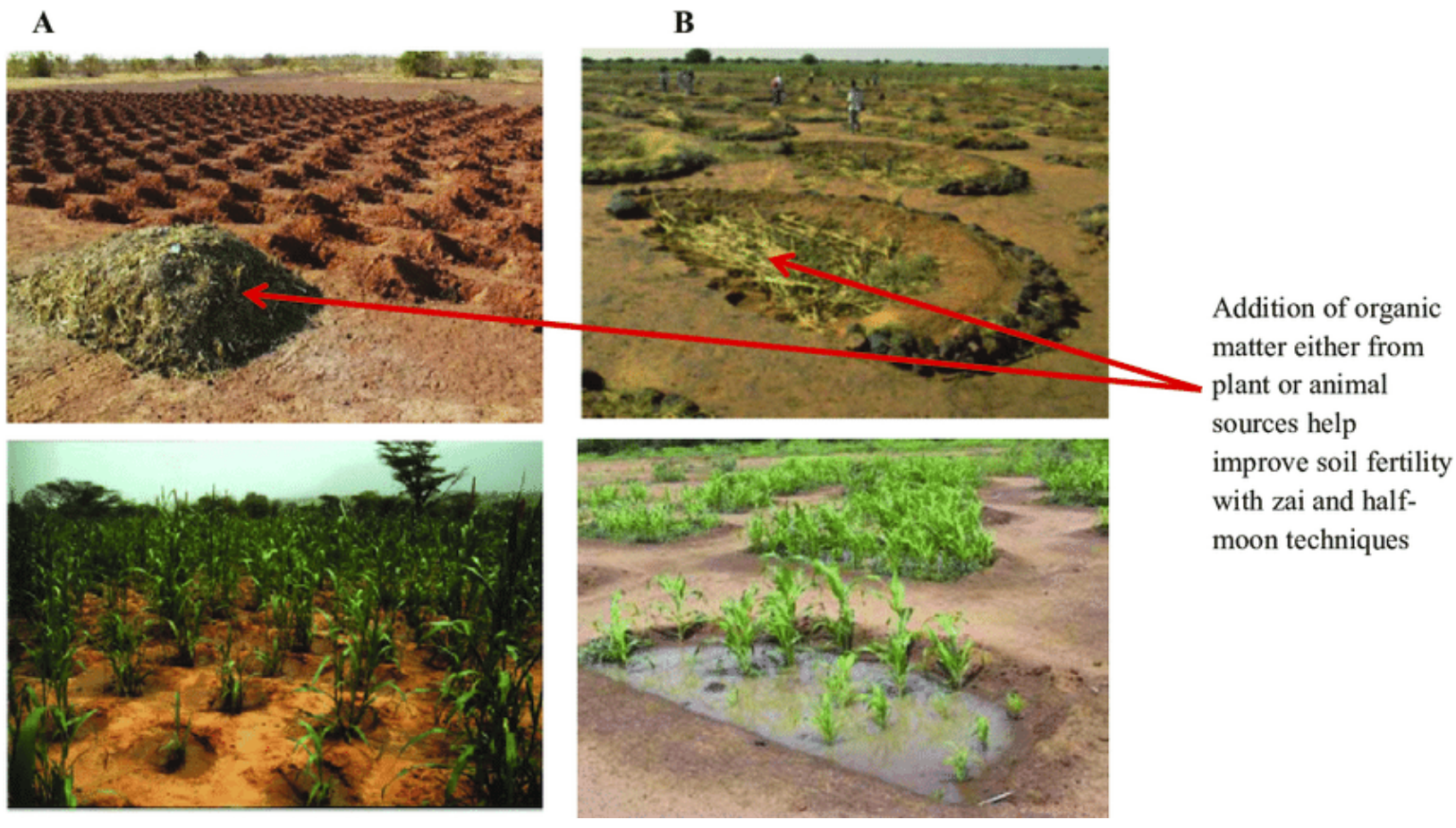

Figure 8.13. Zaï (A) and half-moons (B) (Partey et al., 2018)

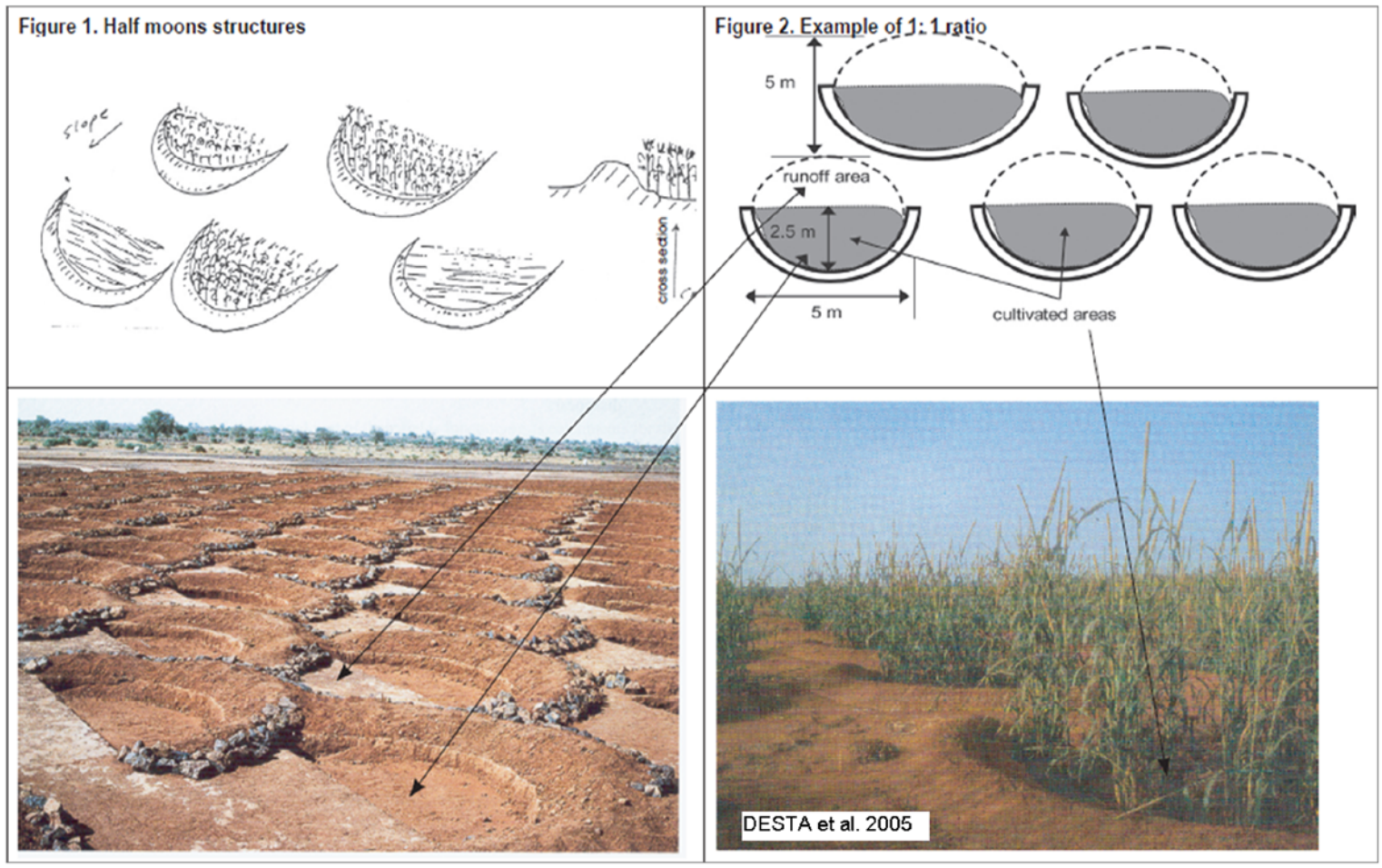

Figure 8.14. Half-moons (Desta et al., 2005)

In addition to traditional solutions, natural tree regeneration systems are also used. At the same time, scientific research and monitoring are carried out using remote sensing data. Based on observations of land cover type, vegetation index, precipitation intensity, and land surface temperature, a slow reduction in desertification has been observed.

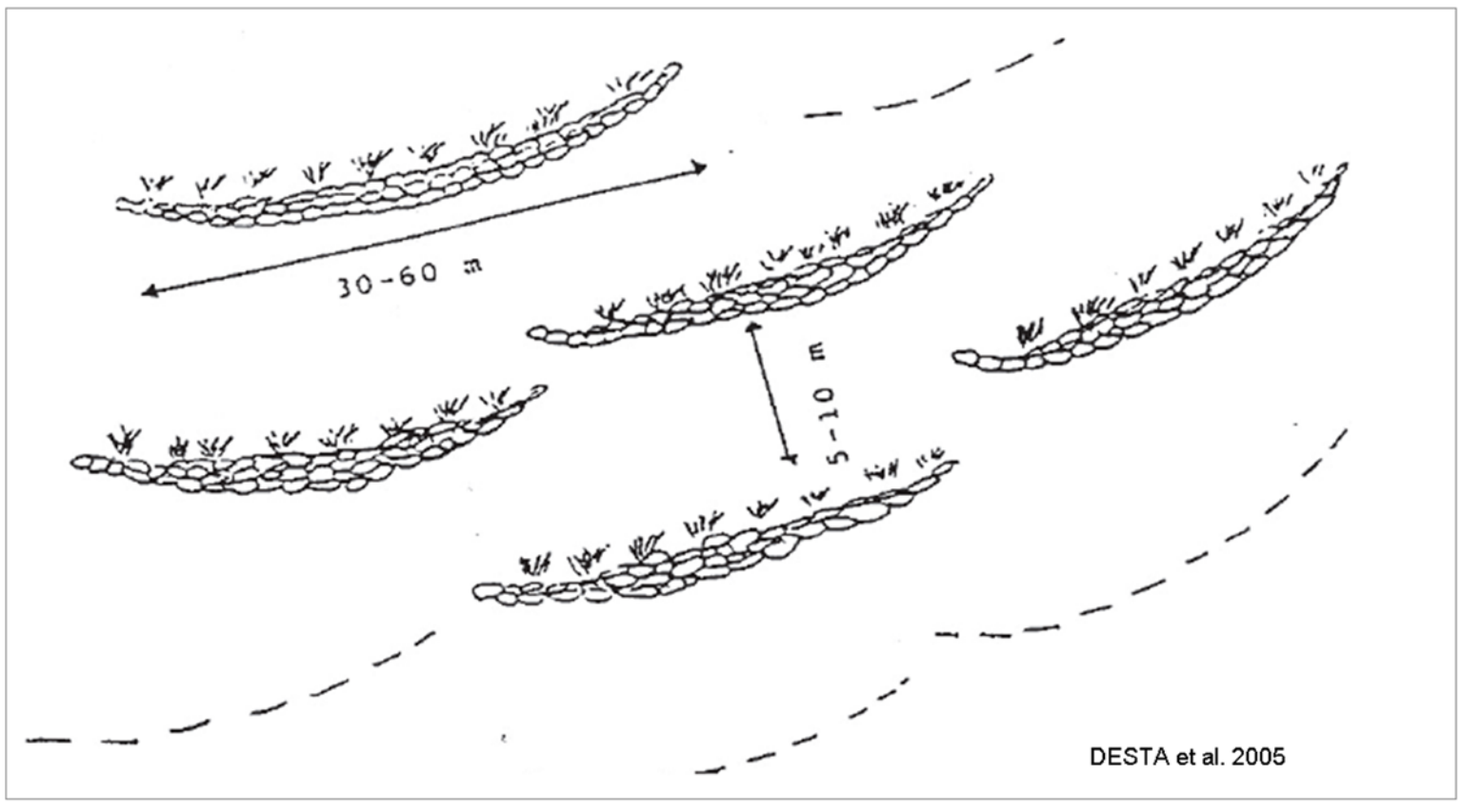

Figure 8.15. Stone lines located parallel to the slope of the terrain (Desta et al., 2005)

The Great Green Wall combines two strategic objectives, namely socio-ecological adaptation to climate change and mitigation of greenhouse gas emissions. In terms of adaptation, the initiative strengthens the resilience of landscapes and communities to drought, erosion, and climate instability. The restoration of vegetation improves water retention, reduces erosion, and improves soil fertility. The creation of green jobs (Figure 8.16), the development of the bioeconomy, and the involvement of local communities in resource management promote social resilience to crises. This reduces the risk of having to abandon areas subject to desertification. Analysis of regional climate model data (RegCM version 4.3) demonstrates the positive changes brought about by the Great Green Wall initiative. The vegetation of the green belt has contributed to a 9% increase in the number of rainy days, an increase in the intensity of heavy rainfall, and a 4% reduction in the duration of extreme droughts (Saley et al., 2019).



Figure 8.16. Local community working on the creation of half-moons (photo by Anneli Sundin, 2013)

In terms of mitigation, the Great Green Wall contributes to the absorption and reduction of carbon dioxide emissions and increases the capacity of soils to store organic carbon.

Despite the visible effects of the Great Green Wall initiative, the pace of the project's implementation is significantly affected by, among other things, insufficient and varied funding in the countries, political tensions in the region, and changing climatic conditions. Nevertheless, the Great Green Wall remains a symbol of cooperation and integration among African countries, a project that combines traditional knowledge, science, politics, and economics in the pursuit of landscape restoration and increased climate resilience.

8.2. URBAN GREEN INFRASTRUCTURE SYSTEMS

8.2.1. Restoration of degraded landscapes on a city scale – sponge cities (China)

Ongoing urbanization leads to serious disturbances in the natural environment, especially in the water cycle. Urban development is associated with the loss of open, vegetated areas and an increase in the proportion of impermeable surfaces. Due to climate change, there has been an increase in the frequency of droughts and flash floods in urban areas. In response to these challenges, the urban concept called sponge city, which acts like sponge, has been developed, which assumes that the city will function as a kind of sponge by imitating natural hydrological processes. Its main objective is to increase the resilience of cities to floods and water shortages by absorbing, storing, and reusing rainwater. The sponge city concept is an example of the comprehensive implementation of green infrastructure on an urban scale. It allows urban, hydrological, and ecological solutions to be combined. This concept is an example of sustainable water management, which is the foundation for climate resilience and improving the quality of life of residents.

The foundations of the sponge city concept date back to 1997, when Kongjian Yu and his team began researching the functioning of urban water systems. At that time, the metaphor of a sponge was used for the first time to describe the ability of ecosystems to store and regulate water, pointing out that natural wetlands along rivers act like sponges, retaining water during floods and replenishing water resources during droughts (Figure 8.17). In 2001, Yu and his colleagues published the "Ten Strategies for Building Ecological Infrastructure in Cities", which was one of the first comprehensive studies on stormwater management. The strategy emphasizes the importance of protecting natural rivers, coastlines, and wetlands, identifying them as key elements in providing cities with ecosystem services ranging from water purification and flood mitigation to improving aesthetics and quality of life for residents. The document criticized the widespread phenomenon of river concreting and wetland degradation as a result of urbanization. In 2004, the strategy was incorporated into China's national ecological planning system and has been used in projects for Beijing, Dongying,

Heze, Taizhou, and Weihai, as well as in the ecological plans of some 200 other Chinese cities. The first examples of the application of the sponge city concept include projects in Qian'an (2010), Suining (2011), and Xixian New Area (2013) (Figure 8.18).



Figure 8.17. Yanweizhou Riverside Park in Jinhua City, which combines recreational functions with natural flood protection (Zhejiang Province, China) (Turenscape, 2014)

Kongjian Yu's first projects served as laboratories for developing the concept of a sponge city. The Zhongguancun Life Science Park in Beijing (2000) introduced a system of "earth life cells" – artificial wetlands for collecting and purifying rainwater. A breakthrough in promoting the concept was the 2012 flood in Beijing, which led to the deaths of 79 residents. The tragic consequences of this flood were widely reported in the media and provoked a strong public reaction, prompting policymakers to reassess the sponge city concept. In 2013, the Chinese government recognized the potential of Kongjian Yu's concept as a tool for improving the safety and resilience of cities to climate change. As a result, the concept was incorporated into the national urban policy strategy, which is considered a breakthrough and confirmed the practical effectiveness of the concept and opened up new opportunities for solving problems related to water management, environmental degradation, and quality of life in cities.

The sponge city has become a systemic approach to stormwater management, flood control, water purification, reclamation of degraded areas, restoration of natural habitats, and shaping of the urban microclimate.



Figure 8.18. Sanlihe River Ecological Corridor in Qian'an City (Hebei Province, China) (Turenscape, 2013)

In 2015, pilot sponge city projects were launched in 16 cities, and in 2016, another 14 centers were included in the program. The location of the pilot cities was not random. Their selection reflects the country's climatic and hydrological diversity, allowing solutions to be tested in different environmental conditions, primarily in conditions of water surplus or deficit. The selected cities are in cold desert (BWk), humid tropical (Cfa), subtropical highland (Cfb), and continental subarctic (Dwa and Dwb) climates. Most of the pilot cities are in the more humid eastern and southern regions of China (Figure 8.19).

According to the concept, by 2020, approximately 20% of built-up urban areas were to have the capacity to infiltrate and store rainwater, and the long-term goal is that by 2030, as much as 80% of urban built-up areas will become permeable surfaces capable of retaining and utilising 70% of local rainfall.

The success of China's sponge cities has contributed to global interest in this concept. In Russia, the first phase of the Chinese-inspired Kaban Lake project in Kazan was completed in 2018. A year later, Vancouver (Canada) launched its rain city strategy, based on natural infrastructure and ecological processes to reduce urban flooding, improve water quality, and increase biodiversity. In Montreal, there are plans to build 30 "sponge parks" and 400 "sponge sidewalks" to slow down rainwater runoff and relieve the burden on the sewer system. In Toronto, the requirement to create green roofs in new developments was introduced as early as 2009. In Amsterdam, blue-green roof projects are being developed, and Los Angeles is testing so-called "sponge streets" with green strips along the streets. In India, where flash floods are becoming more frequent, cities such as Ahmedabad and Chennai are implementing the principles of the concept by building retention parks, infiltration systems, and a flood warning network.

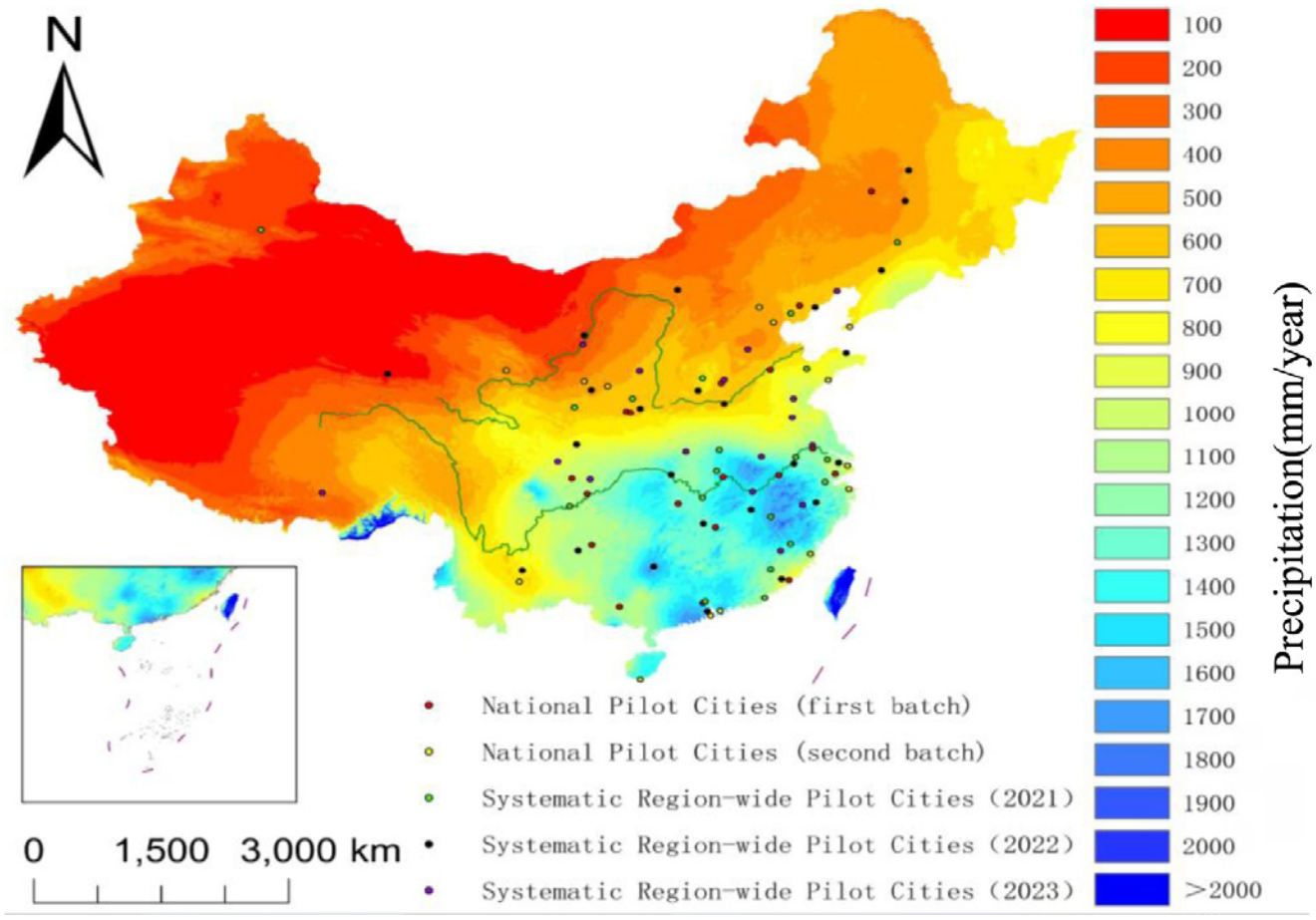

Figure 8.19. Location of pilot cities participating in the Sponge City Program in China against the background of average annual precipitation [mm] (Shi et al., 2023)

In practice, the sponge city model is based on creating an integrated water circulation system in urban areas. The city functions as a hydrological ecosystem in which infrastructure and natural processes interact, and water becomes a closed-loop resource. Instead of quickly draining precipitation into the sewer system, this system allows for local retention, infiltration, purification, and reuse.

The basis for the functioning of the sponge city is a network of blue-green infrastructure, integrating natural and designed elements. These include permeable surfaces, green roofs, rain gardens, infiltration basins, retention

reservoirs, as well as urban wetlands and bioretention channels. Each of these elements performs a specific function in the city's water cycle. First and foremost, these elements slow down surface runoff, allow water to infiltrate the ground, improve its quality through biological filtration processes, and allow it to be reused, e.g., for irrigating urban greenery or for municipal purposes.

The effectiveness of the sponge city requires action on three interrelated scales (Figure 8.20):

- microscale – solutions are applied at the level of individual plots and buildings, e.g., through rainwater harvesting systems and green roofs,
- mesoscale (neighborhood or district scale) – these elements are connected in a network, creating retention and infiltration systems serving a larger area.
- macroscale – the concept permeates the planning of the entire city or catchment area, where hydrological, landscape, and urban functions are integrated.

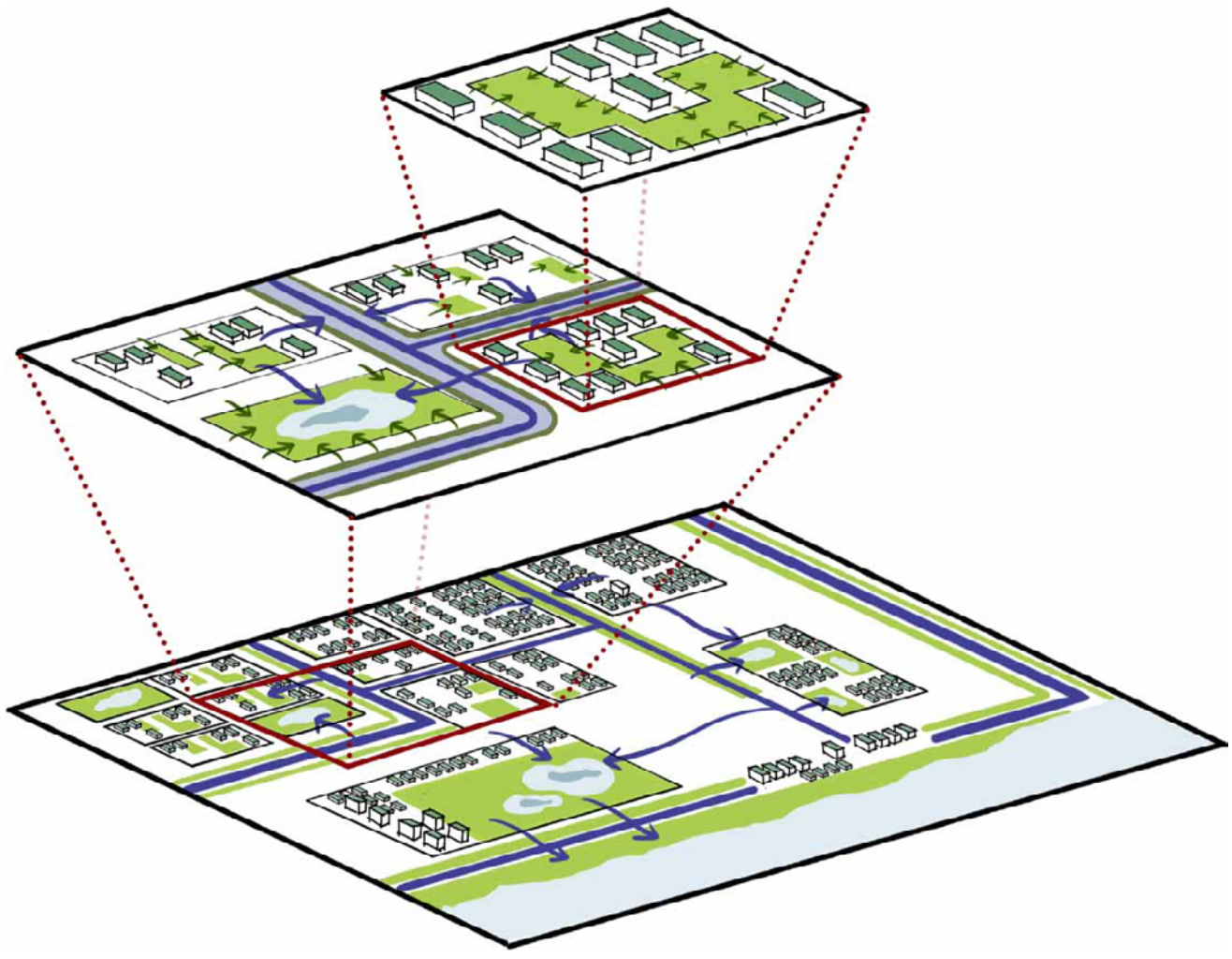

Figure 8.20. Large-scale connectivity models in the sponge city concept (Shi et al., 2023)

Designing at different interconnected scales allows for maintaining a balance between water runoff and retention, thus reducing the risk of flash floods and counteracting the effects of drought. In the concept of sponge city, rainwater is no longer treated as waste, but becomes part of urban ecosystem services, supporting biodiversity, improving the microclimate, and the quality of life of residents.

The concept is also based on the principle of ecological compensation, which assumes that the benefits of regulatory ecosystem services (e.g., retention, purification, or cooling) should be balanced and taken into account in the management and financing of urban infrastructure. Only the integration of ecological, spatial, and economic aspects can maintain the long-term effectiveness of this system. As a result, sponge city is not just a technical solution, but a new paradigm for urban planning, in which the landscape structure, water management, and social needs create a coherent, climate-resilient functional system.

Due to the interaction of technical and natural infrastructure in the sponge city, self-regulating and climate-resilient cities are being built. This is due to the slowing down of runoff, increased rainwater retention, and reduced risk of flash floods or mitigation of the effects of drought, but also to lower air temperatures, which reduces the vulnerability of residents to heat waves and overheating of the city. At the level of direct mitigation, increasing the biologically active area promotes carbon sequestration through vegetation growth, thereby improving the city's energy balance by supporting natural carbon dioxide absorption and air pollution reduction processes. Although the microclimate cooling effect is primarily an adaptive measure, it also has an indirect mitigation effect. Lower air temperatures in urban areas reduce energy consumption for air conditioning, which in turn leads to a decrease in carbon dioxide emissions from the energy sector. Blue-green infrastructure mitigates the effects of climate change and indirectly reduces its causes. The effectiveness of adaptation and mitigation processes depends on the integration of spatial planning, water management, and environmental policy.

8.2.2. Urban agriculture – agricultural park Gardens of Stene in Ostend (Belgium)

The Gardens of Stene represent a new type of urban park in which food production becomes a key function of public space. The park was developed as part of the Groen Lint (Green Ribbon) masterplan – a 35-kilometre cycling route encircling Ostend, designed as a new suburban public space intended to activate productive areas surrounding the city. The Gardens of Stene (Figure 8.21) constitute a significant project within the European FoodSHIFT Accelerator Labs initiative, under which Ostend tested new planning models for so-called "edible cities".

Ostend is a compact city covering an area of 37 km² and is located within the temperate oceanic climate zone (Cfb). Despite its high population density, the city offers relatively good access to green spaces, with as many as 85% of residents living within 400 m of green areas. Historically, Ostend benefited from the expertise of distinguished landscape architects such as Charles Girault, Henri Maquet, and Elie Lainé, who were invited by King Leopold II to contribute to the city's spatial development.



Figure 8.21. Part of the Gardens of Stene in proximity to Basisschool Stene (Landezine Award, 2022)

Approximately 10 years ago, the city authorities began to focus on the urban fringe and the potential of the green belt. As part of this process, 15 landscape types were identified, each intended to play a role in climate change mitigation and adaptation, primarily through nature conservation, energy production, water management, food production, and heat regulation.

One of the designated areas was the agricultural park known as the Gardens of Stene, located in previously inaccessible and little-known areas of the village of Stene (Figure 8.22). The design process lasted two years and involved experts, farmers, non-governmental organizations, students, politicians, and residents. The City of Ostend acquired 16 of the 35 ha covered by the project to ensure the implementation of public objectives. Construction was carried out between 2018 and 2019, with a total cost of approximately 2.5 million EUR.

The agricultural park of the Gardens of Stene was divided into four functional zones (Figure 8.23):

1. polder garden – an area specialising in vegetable production,
2. water meadows – an area dedicated to extensive grazing and the development of natural functions,
3. test fields – an area focusing on innovative cultivation methods,
4. food platform – an area dedicated to food storage and distribution.



Figure 8.22. Zone of ecological ornamental plant production (FoodSHIFT2030, 2023)



Figure 8.23. Land-use plan of the Gardens of Stene (Landezine Award, 2022)

The Gardens of Stene function as a multifunctional 21st-century food park based on targeted interventions in suburban areas. The project involved the transformation of watercourses, deepening of retention canals, removal of approximately 22,000 m^3 of soil, and the creation of a coherent network of pedestrian and cycling paths with three main park entrances. Additional measures included the drainage of agricultural fields, the establishment of an orchard, and the construction of supporting infrastructure such as footbridges, picnic areas, an outdoor classroom, and an edible pergola.

The agricultural park operates through its users (Figure 8.24), including members of Community Supported Agriculture schemes, walkers, tourists, farmers, and volunteers. A trained group of guides leads visitors through the “productive gardens of the 21st century”, turning the site into an educational tool promoting the concept of “from landscape to plate”. A crucial role is also played by institutions adjacent to the park, including the Sint Andreasschool (with an outdoor classroom and a rainwater harvesting system for irrigation), the Boldershof residential community, and a planned housing development with a local food store. Owing to these local linkages, the area functions as a social ecosystem rather than merely a spatial structure.



Figure 8.24. Outdoor educational meeting in the agricultural park (Landezine Award, 2022)

An important aspect of the Gardens of Stene is social justice, which frames access to healthy food as a component of urban resilience. Initiatives aimed at redistributing food surpluses and supporting socially vulnerable groups strengthen the city’s capacity to respond to climatic and economic crises. Among other outcomes, the operation of the park enabled the nearby municipal central kitchen to reduce food waste by approximately 40%, resulting in financial savings of around 50,000 GBP and a reduction of carbon dioxide emissions

by approximately 112 ton. This example demonstrates that organizational changes within public food systems can simultaneously deliver economic and environmental benefits.

The agricultural park also fulfils climate change adaptation objectives through an integrated approach in which water systems, food production, biodiversity, and social functions form interrelated components of suburban infrastructure. Adaptation measures focused on restoring and deepening watercourses, constructing new canals, and implementing water level regulation systems, which significantly increased the retention capacity of the area. These actions reduced flood risk, decreased soil salinisation, and stabilized conditions for agricultural activity.

Climate change mitigation is pursued primarily through the strengthening of local food systems and the reduction of emissions associated with food transport and processing. The agricultural park supports local food production characterized by short supply chains, while the development of an edible forest contributes to reducing the carbon footprint of the food system. In addition, the expansion of biologically active surfaces, the development of permanent grasslands, and the planting of trees and shrubs promote carbon sequestration and improve the city's overall energy balance. A further important dimension of mitigation is behavioural change. The City of Ostend has implemented a food strategy in which the Gardens of Stene play a central role in supporting shifts in consumption patterns towards healthier and more plant-based diets. These actions include food waste prevention, cooperation with the gastronomy sector, and support for short food supply chains.

8.2.3. Urban forests and green streets program – irrigation system and tree-lined avenues in Mendoza (Argentina)

Mendoza is the capital of the province of the same name, located in Argentina. The city itself lies in the north-central part of the province, in a region at the foothills and high plateaus on the eastern part of the great Andean mountain system. The city currently has a population of over 127,000 inhabitants. Mendoza is situated in a dry climate zone, classified as a cold desert climate (BWk), characterized by hot, humid summers and cool, dry winters. The average annual precipitation in Mendoza is approximately 220 mm. For this reason, extensive agriculture throughout the province is possible only thanks to an irrigation system. Water is supplied from the main rivers of the region, which originate in the Andes, and comes primarily from melting snow.

The city was founded in the 16th century by Spanish conquistadors in the valley of the Mendoza River. During an earthquake in the second half of the 19th century, it was largely destroyed and subsequently rebuilt according to a completely new urban plan. Mendoza gained, above all, a network of wide streets intersecting at right angles, as well as a system of urban parks and other green spaces.

An important aspect was also the construction of water supply systems, sewage systems, an irrigation network, and the planting of numerous trees, which had a positive impact on the quality of life of residents and the city's aesthetic value.

In the urban plan, green infrastructure played a key role. In the western part of the city, General San Martín Park was established, covering an area of over 400 ha and currently housing, among other facilities, a zoo, a football stadium, recreational areas, and the campus of the National University of Cuyo. General San Martín Park was designed by the French-Argentine landscape architect Carlos Thays. The design followed the principles of 19th-century garden planning in force at the time, including promenades with sculptures, a rose garden, and numerous fountains.

Despite the extremely dry climate, Mendoza has an extensive artificial irrigation system that enables the development and preservation of greenery throughout the city, as well as the cultivation of grapevines in the province and the production of world-famous wine, mainly the Malbec variety, along with the production of olives and olive oil. A characteristic feature of this irrigation system is the open stone channels (Figure 8.25) running along both sides of the streets, supplying water to thousands of trees. The constant flow of water is controlled by a system of sluices that are opened depending on water allocation and by the terrain's topography, as gravity causes the water to move through the channels.



Figure 8.25. Irrigation channels in Mendoza (IWSN, 2019)

Currently, about 50,000 street trees grow in Mendoza (Figure 8.26). They play a crucial role in regulating the urban climate, primarily by mitigating the urban heat island effect and improving the thermal comfort of residents, especially in the summer. Thanks to the significant shading of streets and buildings, the demand for electricity needed to cool homes is noticeably reduced. Street trees in Mendoza also contribute to improved air quality, a significant increase in air humidity, noise reduction, and greater biodiversity within the city. The irrigation system also plays a major role in regulating water flow during heavy rainfall, thereby limiting the negative effects of flash floods.

The trees growing in the city are mainly plain trees, acacias, and rosewoods along wide avenues, while narrower streets are dominated by mulberries, ashes, plums, sweetgums, ornamental jacarandas, and pepper trees. A characteristic element of the landscape on the outskirts of the city and in its immediate surroundings is rows of tall poplars planted along transport routes. These provide shelter that mitigates the effects of wind erosion, stabilizes the soil, offers protection against flash floods, and provides shade. They also supply raw material for the construction of structures used to regulate and divert water, such as sluices, small dams, and retaining walls.



Figure 8.26. Plane trees growing along one of the streets in Mendoza (photo by Wojciech Lewandowski, 2016)

8.2.4. Stormwater management in the city – green streets in Portland (USA)

The problem of stormwater drainage in cities arises primarily from the dominance of impervious surfaces, which significantly limit infiltration. In urban areas, stormwater is typically conveyed through sewer networks that often operate as combined sewer systems, collecting both sanitary wastewater and stormwater. With the increasing frequency of intense rainfall events, sewer systems in large cities are becoming increasingly inefficient, leading to surface flooding that affects not only streets but entire neighborhoods.

In Europe, including Poland, an average moderate single rainfall event amounts to 10–15 mm; however, contemporary precipitation events increasingly reach intensities of 100–120 mm (100–120 l/m²). Under such conditions, it is not feasible to design sufficiently efficient gray infrastructure (centralized sewer networks), particularly given the growing extent of sealed surfaces in cities. In urbanized areas with more varied topography, extreme rainfall results in very rapid runoff into sewer systems. Consequently, intensive surface runoff over impervious surfaces causes excessive loading of combined sewer systems, leading to combined sewer overflows. These, in turn, result in flooding, reduced efficiency of wastewater treatment plants, and – during heavy rainfall – the discharge of untreated mixed wastewater directly into rivers, lakes, or seas. Such discharges pose a threat to drinking water sources and negatively affect human health and environmental quality.

Stormwater management has therefore become one of the key challenges of urban spatial planning, with blue-green infrastructure emerging as a principal response. One city that has systematically addressed this challenge for over three decades is Portland (population approx. 650,000), located in the state of Oregon, USA.

Portland lies within the warm-summer Mediterranean climate zone (Csb), with an average annual air temperature of approximately 11°C and the highest annual precipitation reaching around 1,000 mm. These climatic conditions have long led to flash floods and local flooding. The intensity of these phenomena increased significantly in the second half of the 20th century, when the city’s population grew severalfold, accompanied by a rapid expansion of impervious surfaces.

In the 1990s, severe flooding events and direct discharges of wastewater into rivers occurred as frequently as 57 times per year. In response to these threats, a comprehensive project integrating the expansion of both gray and green infrastructure was initiated in 1991. The gray infrastructure component comprised the so-called “Big Pipe” project, which involved the construction – completed by 2011 – of three interceptor pipes with diameters exceeding

6.5 m and a total length of more than 20 km. These massive tunnels were constructed along the Willamette and Columbia rivers and function by slowing stormwater conveyance, intercepting runoff, and gradually directing excess flows to wastewater treatment plants before discharge into the rivers.

The second component of the project focused on the design and implementation of green infrastructure, aimed at capturing stormwater to reduce inflows into the sewer system and, wherever possible, promote direct infiltration into the ground within courtyards, gardens, and streetscapes (McPhillips & Matsler, 2018).

Initial measures involved disconnecting the roof downspouts and conveying clean rainwater from the combined sewer system. In total, 56,000 downspouts were disconnected, resulting in a reduction of approximately 4.5 million m^3 of stormwater discharged into the sewer network. This water was redirected into small-scale solutions installed along streets, such as rain gardens, vegetated swales, infiltration basins, and drywells. The first pilot green infrastructure projects were implemented both in public spaces – near schools and museums – and on private properties.

The introduction of green infrastructure elements was carried out gradually, initially by public authorities such as the Portland Bureau of Environmental Services, and subsequently by private developers. This systemic approach required extensive preparation and training to ensure that appropriate spatial provisions were made at the planning stage and to familiarize developers with new stormwater management solutions. In this way, the concept of green streets was developed (Figure 8.27), supported by a range of grant programs incentivising the implementation of various types of green infrastructure.

Within the grant program, private property owners were offered fee reductions of 35% for retaining stormwater on-site and avoiding discharge to the sewer system, and up to 67% if green infrastructure solutions were installed.
The development of green roofs – referred to locally as eco-roofs – was also supported, both for new construction and retrofits, including commercial buildings such as a Walmart supermarket in the southern part of the city. In 2021, Portland introduced a new policy requiring eco-roofs on all developments exceeding 1,858 m^2, with up to 40% of the roof area permitted for alternative uses, such as photovoltaic panels.

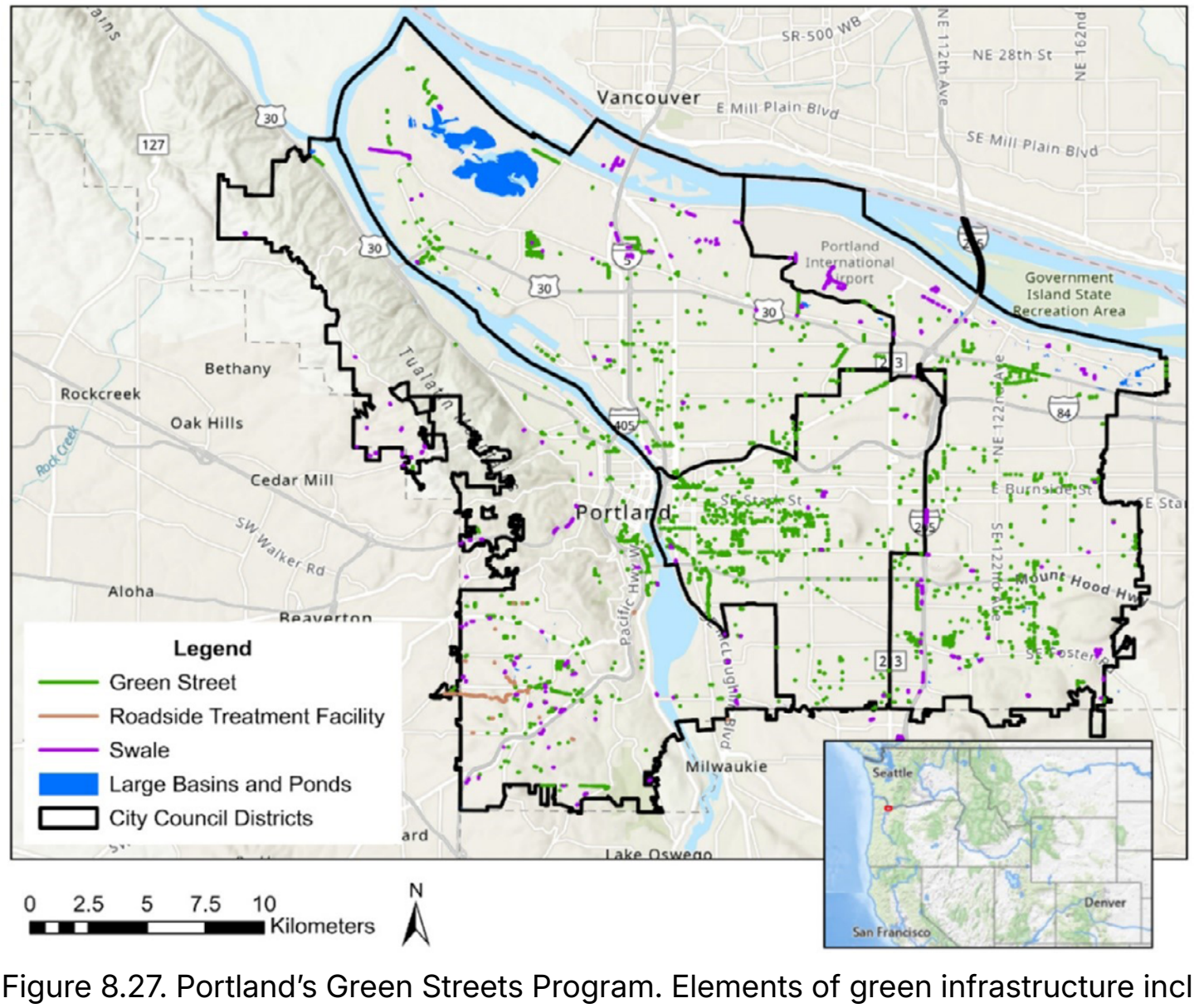

Figure 8.27. Portland’s Green Streets Program. Elements of green infrastructure include approximately 2,950 streetscape installations, mainly rain gardens, as well as 70 roadside wastewater treatment facilities, 350 infiltration basins, and 200 large infiltration depressions and ponds (City of Portland, 2026)

A particularly important aspect of the Portland’s Green Streets Program has been the long-term monitoring of the performance of implemented solutions, both in terms of stormwater retention and water quality improvement. Monitoring has enabled the optimisation of plant species selection for rain gardens, the adjustment of soil substrates, and the refinement of technical design solutions.

One of the key tools supporting the implementation of the Portland’s Green Streets Program is the “Stormwater Management Manual”, first published in 1999, with the most recent edition released in 2025 (City of Portland, 2007; City of Portland, 2025). The manual sets out detailed requirements that must be met by all new developments and redevelopment projects; any modification involving more than 46 m^2 of impervious surface requires approval by the Portland Bureau of Environmental Services. These requirements address not only the size and location of stormwater facilities, but also water treatment standards and plant species selection. Pollutant removal capacity is flow-based and assumes a treatment flow rate of 0.48 mm/h and a runoff coefficient of 0.90.

Currently, Portland has more than 3,000 green infrastructure elements located along streets and adjacent to parking areas. The majority are so-called micro-interventions, whose cumulative effectiveness is achieved through a scale effect. These include pocket rain gardens (Figure 8.28, Figure 8.29), small infiltration basins (Figure 8.30), and drywells with depths of approximately 9 m and diameters of 1.2 m, featuring perforated side walls that enable gradual infiltration of stormwater into the ground.



Figure 8.28. Pocket rain garden in the city center (photo by Agata Cieszewska, 2025)

At present, approximately 29% of green infrastructure installations are implemented by the City of Portland, 33% by private developers, and 38% through projects led by various institutions, including environmental, housing, and energy organizations.



Figure 8.29. Pocket rain garden in a residential neighborhood
(photo by Agata Cieszewska, 2025)



Figure 8.30. Vegetated infiltration basin conveying excess water from a public square
(photo by Agata Cieszewska, 2025)

Portland is widely regarded as a global pioneer in the systemic implementation of Green Streets Program (McPhillips & Matsler, 2018). The program has dramatically reduced the negative effects of sewer system overloading, including rapid stormwater conveyance and the frequency of flooding events. Beyond reducing the risk of street and basement flooding, the initiative has generated multiple co-benefits for local communities. These include improved protection of river water quality through the elimination of up to 90% of pollutants carried by stormwater, replenishment of groundwater resources, reduced vulnerability to drought, increased carbon dioxide absorption, and improved air quality – collectively contributing to enhanced quality of life.

Additionally, the expansion of biologically active surfaces and vegetation cover has reduced the risk of heatwaves, mitigated the urban heat island effect, and improved pedestrian and cyclist safety by calming traffic through the reallocation of road space to green infrastructure.

8.2.5. Large-scale urban parks – Las Kabacki in Warsaw (Poland)

Urban areas are characterized by a high degree of human impact on the landscape. In particular, the increasing number of anthropogenic elements leads to a reduction in natural areas, resulting in a decline in native species and an increase in non-native species, including many invasive ones. The process of urbanization contributes to the transformation of the natural environment, largely through the fragmentation of open spaces. A key objective is therefore the preservation of all forest areas located within city boundaries, which can be achieved through legal protection and their integration into spatial planning processes. At the same time, it is essential to thoroughly assess the recreational potential of these areas, identify existing recreational infrastructure, and understand the needs and preferences of users.

Urban forests constitute large-scale parks and are among the most valuable green spaces in cities. They play a crucial role in shaping urban ecological networks, supporting the conservation of natural habitats and biodiversity, and providing psychological and recreational benefits that positively affect human well-being. Urban forests primarily serve as spaces for everyday recreation, both during commuting and leisure time. They deliver a wide range of ecosystem services, including ecological benefits (e.g., wildlife habitats and ecological connectivity), economic benefits (e.g., reduced hospital recovery times and lower crime rates), carbon dioxide sequestration, air pollution removal, noise reduction, local climate regulation, health benefits, cultural values, aesthetic qualities, and functional uses.

Within the urban landscape, forest parks play an important role as recreational spaces for residents, offering opportunities for relaxation and wildlife observation. Thanks to appropriately designed infrastructure, they facilitate physical activity and contribute to both mental and physical well-being. In some cases, they also serve as sources of inspiration for artists.

In Warsaw, the capital of Poland, urban forests occupy nearly 15% of the city's area (approx. 7,250 ha). They are mainly distributed along the city's periphery in 27 forest complexes, 15 of which are managed by the City of Warsaw.

An example of an urban forest is Las Kabacki (forest park and woods nature reserve named in honor of Stefan Starzyński), located in the southern part of Warsaw, within the Ursynów District (Figure 8.31). The forest extends over a length of approximately 4–5 km and a width of 2.5–3 km, covering an area of 924.72 ha. It borders the municipalities of Piaseczno and Konstancin-Jeziorna to the south, the Ursynów housing estates to the north, and the development along Puławska street to the west. Las Kabacki is one of the most valuable

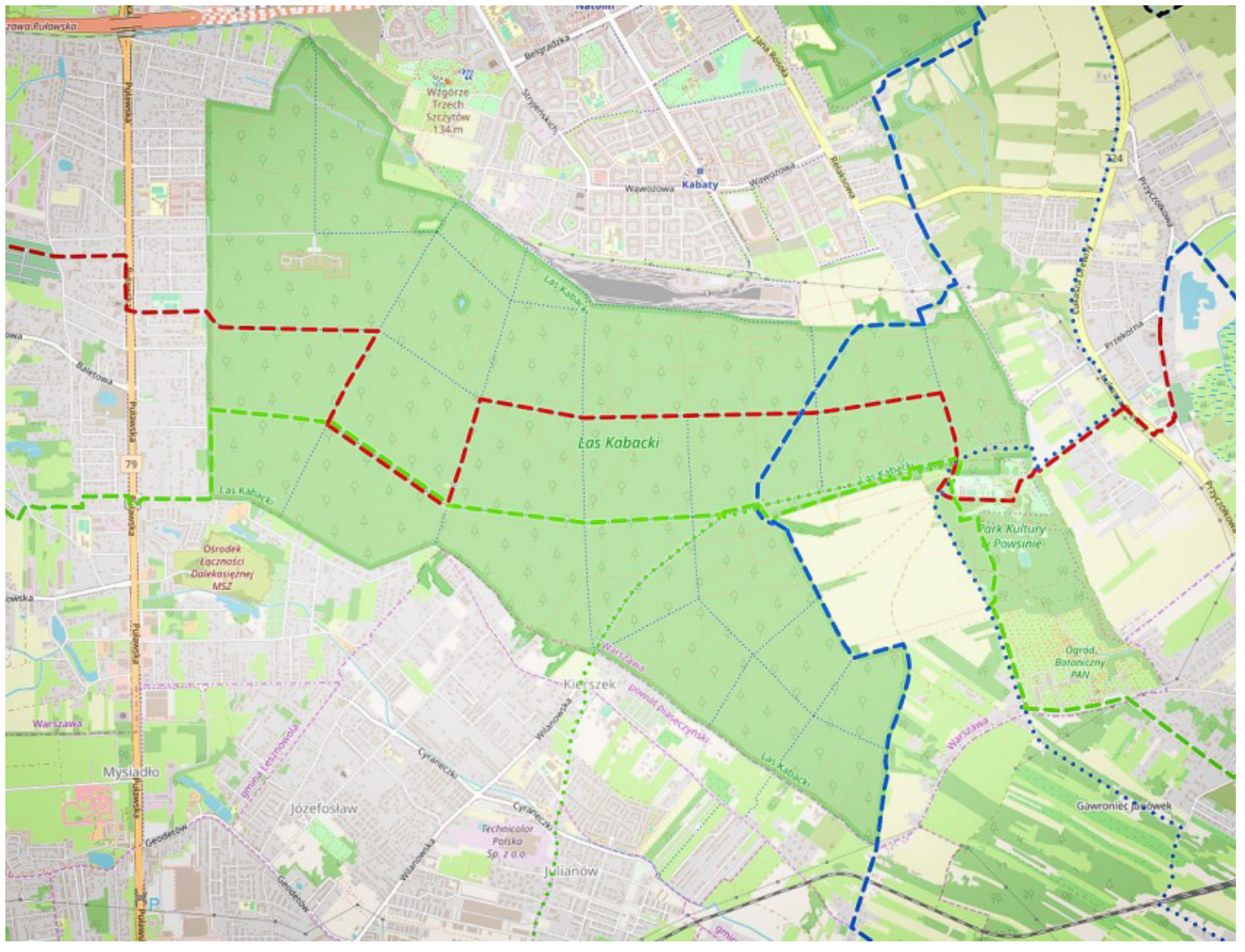

Figure 8.31. Location of Las Kabacki in relation to its surroundings and tourist trails (Mapa Turystyczna, 2025)

natural areas in the city; consequently, it was designated a nature reserve on August 11, 1980. It is also the largest forest complex within the municipal forests of Warsaw and the largest nature reserve in the Mazowieckie Voivodeship.

From a natural perspective, Las Kabacki constitutes a fragment of the old Mazovian natural forest, dominated by poor subcontinental oak–hornbeam forest (Figure 8.32), which developed under humid continental climatic conditions with warm summers (Dfb). The forest occupies a postglacial moraine plateau and part of the Warsaw Escarpment, a distinct landform marking the boundary of the Vistula river valley. A total of 623 species of vascular plants have been identified within the reserve, including 62 species of trees and shrubs. Thirteen natural monuments are located within the forest, represented by trees of exceptional dimensions, such as a Norway spruce with a trunk circumference of 160 cm and a height of 32 m, and a red oak with a circumference of 145 cm. The presence of 22 mammal species has been recorded, including roe deer, wild boar, raccoon dogs, and badgers. Numerous protected bird species are also common. One of the main threats to wildlife is the increasing isolation of the forest, as adjacent areas are gradually urbanized. This limits animal movement, potentially leading to weakened populations due to inbreeding and, ultimately, local extinction.



Figure 8.32. Oak–hornbeam forest stand in Las Kabacki (photo by Agata Cieszewska, 2024)

Historically, the area of Las Kabacki formed part of the Wilanów estates in the 17th and 18th centuries, which changed ownership over time – from King John III Sobieski of Poland to the Branicki family. In 1892, the forest became an independent forestry administration, managed until 1923 by Wiktor Stephan. Shortly before the outbreak of the Second World War, in December 1938, the forest was purchased by the City of Warsaw. The initiative was led by the then commissioner mayor of Warsaw, Stefan Starzyński, whose name the forest bears to this day. At the time of purchase, Las Kabacki lay outside the city boundaries. The primary objective was to provide recreational space for Warsaw's residents, a function it continues to fulfil today. The acquisition of over 900 ha of forest land situated between agricultural areas ensured its preservation in an unchanged form, as it was not subdivided for development. Consequently, the forest became a natural southern boundary for the expansion of Warsaw as the city gradually developed southwards.

From the outset, the forest was intensively used by residents. Due to increasing recreational pressure, it was designated as a nature reserve in order to preserve the social and landscape values of the natural environment. Protection measures excluded the entire area from commercial forestry, halted clear-cutting practices, and introduced forest stand conversion. This process reduced the dominance of pine in favour of deciduous species typical of oak–hornbeam habitats. Today, old pine stands growing on brown and podzolic soils, with a significant share of larch and oak, and reaching ages of up to 130 years, represent some of the most valuable plant communities in the area.

Las Kabacki plays a vital role for the residents of Warsaw and the surrounding municipalities. It is a traditional destination for leisure and recreation, offering tourist trails, walking paths, cycling routes, and fitness trails. In winter, the forest is particularly popular for cross-country skiing due to its relatively wide and orthogonally arranged paths. Visitors preferring passive recreation can use numerous shelters, benches, and forest playgrounds for children (Figure 8.33). In the southern part of the forest, near a historic wooden forester's lodge dating from 1890, there is a large recreational clearing where visitors can light campfires, play ball games, or sunbathe. This area is a popular site for full-day family picnics. An important aspect of the forest's functioning is its proximity to the Culture and Leisure Park in Powsin and the Botanical Garden of the Polish Academy of Sciences, which together encourage long and diverse recreational routes.

The forest also contains elements of historical and cultural heritage. These include numerous graves and memorials commemorating, among others, sites of Nazi crimes during the Second World War, the former location of the secret "Wicher" unit involved in deciphering German military codes of the famous Enigma machine, as well as the site of a passenger aircraft crash in 1987.



Figure 8.33. Tourist shelters in Las Kabacki (photo by Agnieszka Sosnowska, 2009)

Review questions:

1. What spatial problems was the introduction of the green belt around Toronto intended to address?
2. What were the main objectives behind the establishment of the Mesoamerican Biological Corridor?
3. Which nature-based solutions were applied in the restoration of Wadi Hanifah in Riyadh?
4. How does the implementation of the Great Green Wall in Africa contribute to climate change adaptation and mitigation?
5. What is the core concept of the sponge city approach?
6. How does the irrigation system in Mendoza support urban greenery in a dry climate, and what other functions does it have besides providing water?
7. What is the difference between gray infrastructure and green infrastructure in Portland's stormwater management system, and why does combining them work well?
8. Why is Las Kabacki important for nature protection and the spatial structure of Warsaw?
9. What features do all the discussed projects have in common, and what general planning principles can be learned from them?

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9. CONCLUDING REMARKS

The historical evolution of green infrastructure demonstrates that it is not a sudden innovation, but the outcome of a long intellectual and practical trajectory. From 19th-century social reform movements that emphasized the restorative power of urban parks, through the emergence of ecological planning and network-based thinking, to contemporary concepts of ecosystem services and resilience, each stage has expanded the understanding of the relationship between nature and the city. What began as a response to the health crises of industrial urbanization has matured into a systemic framework integrating ecological processes with spatial planning and socio-economic development. Recognizing these foundations clarifies that green infrastructure is both historically rooted and forward-looking – anchored in environmental ethics while oriented toward adaptive and regenerative futures.

Green infrastructure can be interpreted through diverse yet complementary lenses: as a spatial network, as a hydrological system, as an integrated socio-ecological framework, and ultimately as an emerging planning paradigm. Each perspective highlights specific functions and operational logic, from connectivity and water management to governance and implementation practices. The comparison of conceptualization across national contexts further reveals that green infrastructure is shaped by cultural, institutional, and environmental conditions. Rather than representing a single rigid model, it constitutes a flexible conceptual framework capable of adapting to local realities. Understanding these multiple perspectives enables a more nuanced and context-sensitive application of green infrastructure principles in research and practice.

Translating the concept of green infrastructure into practice requires supportive policy frameworks, effective planning instruments, and clearly articulated design principles. International agendas and regulatory mechanisms provide strategic direction, while implementation tools – ranging from spatial planning instruments to financial incentives – facilitate on-the-ground realization. At the same time, the guiding principles of connectivity, multifunctionality, inclusivity, and long-term sustainability ensure coherence between theory and practice. Operationalization is therefore not merely a technical process but a governance challenge that demands coordination across sectors and scales. The effectiveness of green infrastructure ultimately depends on its integration into mainstream planning and decision-making systems.

Green infrastructure plays a critical role in strengthening environmental resilience while simultaneously enhancing the quality of life. Its multifunctional character

allows it to deliver ecosystem services that mitigate climate risks, improve environmental conditions, and support social cohesion. Beyond physical benefits, such as air purification or flood mitigation, green spaces contribute significantly to mental health, stress reduction, and overall human well-being.
By linking ecological performance with social value, green infrastructure becomes a cornerstone of sustainable development. Its significance lies precisely in this integrative capacity – bridging environmental protection, public health, and long-term socio-economic stability.

The effectiveness of green infrastructure depends on its alignment with spatial scale and territorial context. From regional ecological networks to site-specific design interventions, each scale requires tailored strategies and governance arrangements. Urban, suburban, and rural areas present distinct structural conditions, pressures, and opportunities, influencing both priorities and implementation challenges. A multi-scale perspective ensures functional continuity and ecological connectivity, while also addressing local needs. Recognizing scale as a fundamental dimension of planning enables more coherent, efficient, and context-responsive green infrastructure systems.

Climatic conditions fundamentally shape the design, performance, and maintenance of green infrastructure. The diversity of global climate zones – from tropical and arid regions to temperate, continental, polar, and highland environments – requires differentiated strategies rooted in local ecological processes. Water availability, temperature extremes, vegetation patterns, and seasonal variability influence both risks and opportunities. Applying climate-sensitive design principles enhances the adaptive capacity of landscapes and ensures long-term functionality. Integrating climatic knowledge into green infrastructure planning reinforces its resilience and underscores the importance of context-specific solutions in a changing global climate.

The case studies presented in this book illustrate the versatility and transformative potential of green infrastructure across scales and regions. From large-scale ecological corridors and landscape restoration initiatives to urban stormwater systems and multifunctional parks, these examples demonstrate how theoretical principles can be translated into tangible spatial outcomes. They reveal that successful implementation depends not only on technical design, but also on governance structures, stakeholder engagement, and long-term commitment. Collectively, the cases confirm that green infrastructure is a dynamic and adaptable framework capable of addressing environmental degradation, climate challenges, and social needs. By learning from diverse global experiences, planners and designers can refine strategies that are innovative, resilient, and responsive to local contexts.

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