edited by
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Nature and City

An Integrated Approach to Urban Biodiversity

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Preface

The volume *Nature and City. An Integrated Approach to Urban Biodiversity* is published at a pivotal moment for European and international environmental policy. Biodiversity strategies, nature restoration programmes, and the United Nations 2030 Agenda clearly indicate a common direction: ecosystem regeneration, including in urban areas, is no longer optional, but a structural prerequisite for sustainable development.

Global trends underscore the urgency of this transition. Today, more than 55% of the world's population lives in cities, and according to United Nations projections, this figure will approach 70% by 2050. Urban land expansion is occurring at a rate exceeding population growth, leading to soil sealing, habitat fragmentation, altered hydrological cycles, and significant biodiversity loss. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has warned that up to one million species are currently at risk of extinction, while the Intergovernmental Panel on Climate Change (IPCC) estimates that over 3.3 billion people live in highly climate-vulnerable contexts. Within this scenario, cities are simultaneously drivers of ecological degradation and potential laboratories for systemic solutions.

A crucial challenge concerns restoring soil functions within urban environments. Depaving asphalted surfaces, re-establishing ecological connectivity, integrating sustainable drainage systems, and designing neighbourhoods capable of regenerating natural capital rather than consuming it are fundamental actions. Rethinking urban development means creating environments where citizens can rediscover a tangible coexistence with nature, reducing urban heat islands, improving air quality, enhancing stormwater infiltration, and creating habitats for multiple species.

This book addresses this paradigm shift with scientific rigour and design-oriented vision. It proposes an integrated framework for urban biodiversity that transcends the traditional separation between planning, engineering, ecology, and governance. The chapters dedicated to Nature-based Solutions (NbS) and ecosystem restoration demonstrate that urban regeneration cannot be reduced to a set of technical interventions. Instead, it requires participatory processes, shared governance, and long-term ecological strategies. Sustainable regeneration must not merely enhance isolated ecosystem

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Roberto Bologna, Anna Lambertini, Luca Solari (edited by), *Nature and City. An Integrated Approach to Urban Biodiversity*, © 2025 Author(s), CC BY 4.0, published by Firenze University Press, ISBN 979-12-215-0966-3, DOI 10.36253/979-12-215-0966-3

services; it must restore underlying ecosystem functions, combining an ecocentric perspective with measurable social and economic benefits.

The core message of this volume — the profound interdependence between citizens' well-being and biodiversity — is strongly supported by scientific evidence. Access to green spaces has been associated with reduced cardiovascular disease incidence, improved mental health outcomes, and lower stress levels. Urban green and blue infrastructures can reduce peak temperatures by 2–4°C during extreme heat events, while sustainable drainage systems significantly enhance infiltration capacity and mitigate flood risks. Urban biodiversity should therefore be understood not as an aesthetic addition, but as critical infrastructure supporting public health, water security, climate regulation, air quality improvement, and social cohesion.

This vision is fully aligned with the One Health paradigm, which recognises the intrinsic link between ecosystem health and human health. The National Biodiversity Future Center has embraced this approach as a strategic pillar of its mission, promoting research that integrates natural sciences, engineering disciplines, social sciences, and technological innovation.

The volume is embedded within the activities of the NBFC, established under Italy's National Recovery and Resilience Plan (PNRR) – NextGenerationEU. In particular, it aligns with the research dedicated to urban biodiversity, aimed at the multilevel characterisation of ecological dynamics in cities and the development of effective and resilient Nature-based Solutions. The attention given to applied instruments, such as the NbS CataTool, reflects the commitment to translating advanced research into operational tools for public administrations, planners, and decision-makers.

Urban planning plays a decisive role in this transformation. Urban Nature Plans — currently voluntary in many contexts but increasingly central to funding frameworks and regulatory evolution — represent a paradigm shift from fragmented interventions to integrated, long-term strategies grounded in scientific evidence and continuous monitoring. This issue is even more critical in emerging countries, where rapid urbanisation often occurs in the absence of robust regulatory frameworks. In such contexts, integrating biodiversity into planning processes is essential to prevent environmental degradation, resource conflicts, climate vulnerability, and irreversible natural capital loss.

The strength of this work lies in its genuinely multidisciplinary approach. Architecture, civil and environmental engineering, ecology, circular economy, governance, and public engagement converge within a coherent framework in which biodiversity becomes a structuring principle of urban design.

Through multidisciplinary research such as that developed within the NBFC, it is possible to generate Evidence-based Solutions to support urban biodiversity while simultaneously identifying technological innovations that enhance the design, implementation, monitoring, and long-term management of interventions. Advanced environmental monitoring networks, high-resolution ecological data integration, remote sensing applications, digital twins for urban ecosystems, predictive climate-risk modelling, and ecosystem service performance indicators represent enabling tools for scaling up Nature-based Solutions in a measurable and replicable manner.

Embedding biodiversity within urban systems requires robust metrics, adaptive governance frameworks, and longitudinal assessment of ecological and socio-economic outcomes. Nature-based Solutions must therefore be evaluated not only in terms of immediate co-benefits, but also in relation to ecosystem functionality, resilience thresholds, and long-term maintenance requirements. Integrating ecological science with engineering design and data-driven decision support systems is essential to ensure that urban regeneration strategies deliver quantifiable improvements in ecosystem integrity and human well-being.

In this perspective, biodiversity becomes a structural variable in urban development models, a determinant of climate adaptation capacity, public health resilience, and sustainable resource management. The transition toward biodiversity-positive cities depends on the ability to align scientific knowledge, technological innovation, and planning instruments within coherent, evidence-based frameworks.

Only by strengthening this science–policy–practice interface can urban systems evolve toward models that are ecologically functional, socially inclusive, and resilient under accelerating environmental change.

Massimo Labra
Scientific Director of
National Biodiversity Future Centre

Objectives and research methodology: adopting an interdisciplinary approach

Roberto Bologna, Anna Lambertini, Luca Solari

Funded by the Italian Ministry of University and Research (MUR) with European Union funds NextGenerationEU and in implementation of the National Recovery and Resilience Plan (PNRR)[1], the National Biodiversity Future Center (NBFC)[2] was established in 2022. It is one of the five national centers dedicated to frontier research involving institutions and companies throughout Italy.

The aim of the NBFC is to identify suitable strategies to monitor, preserve and enhance the biodiversity of species and habitats spread across various Italian territories. To develop its research activities, the Center has established an innovative model that includes a central hub and eight "spokes". Each spoke focuses on specific areas of research and development to address global challenges related to biodiversity and sustainability: Spokes 1 and 2 are dedicated to marine biodiversity; Spokes 3 and 4 deal with terrestrial biodiversity; Spoke 5 focuses on urban biodiversity; Spoke 6 addresses aspects related to health and the innovative "One Health" approach; Spokes 7 and 8 operate transversally on communication and innovation.

The main objective of Spoke 5 is the multilevel characterization of the dynamics and factors that influence biodiversity in cities in order to promote targeted forest design actions and the creation of Nature-based Solutions (NbS) suitable for different urban contexts that are effective and resilient over time (Fig. 1).

The research project was divided into seven Work Packages: Biodiversity and ecology aspects of urban forestry (WP1), Urban soil biodiversity (WP2), Urban forestry - an integrative and sustainable design (WP3), Impact of urban forestry on support-

[1] More precisely, with regards to Mission 4.3 – Investment 1.4: "Strengthening research facilities and creating national R&D champions on some Key enabling technologies"

[2] For additional information, check out the website: https://www.nbfc.it/en

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ing and regulating ecosystem services (environmental level) (WP4), Impact of urban forestry on supporting and regulating ecosystem services (biological level) (WP5), Environmental and ecological restoration (WP6). WP7 capitalizes on the results of the other activities and aims at providing innovative models and tools for the management of urban biodiversity.

Tab. 1 – Spoke 5 Strategic Research and Innovation Agenda (from www.nbfc.it).

Vision	Living in harmony with nature in an urban context
Mission	– Knowing and enhancing the environmental and biodiversity resources of the city – Developing an integrated and sustainable planning of the cities of tomorrow – Ensuring resilience to functional biodiversity and promoting biological complexity – Developing models of management and enhancement of urban biodiversity also by communication and dissemination activities – Restoring and recovering degraded areas and improving the urban ecosystem
Strategic Objectives	The research framework of spoke 5 is aimed at investigating urban biodiversity, with a multidisciplinary and transdisciplinary approach. Specifically, the team of spoke 5 is developing strategies and guidelines to realize suitable solutions to restore and/or improve the functional components of urban biodiversity, to mitigate its main abiotic and biotic stress factors. This strategy will allow a multilevel characterization of ecosystem resources and define integrative design strategies to maximize the ecosystem services and the resilience of interventions through time. The technological innovation of products and processes will sustain the realization of effective monitoring, evaluation and management of the interventions.

The third WP addresses the topic of integrated and sustainable forestry design from an urban planning perspective, through the identification of suitable NbS and the development of predictive models that are scalable and adaptable to different urban contexts in the Mediterranean area. At this stage, the general research project did not include specific in-depth analyses of the economic evaluation aspects and therefore no specialist contributions of this kind were implemented.

The University of Florence has joined those research activities developed as part of Spoke 5 on urban biodiversity, through the Departments of Architecture (DIDA), Civil and Environmental Engineering (DICEA), and Agricultural, Food, Environmental and Forestry Sciences and Technologies (DAGRI). The development of the research involved close collaboration between researchers belonging to the participating institutions, with the aim of reaching a shared result that is representative of all the necessary knowledge and skills (Fig. 2).

The specific objective which the researchers of the University of Florence contributed to is the construction of a catalogue of NbS and case studies representing good practices of NbS applications in architectural and urban regeneration processes.

The first phase involved a comparative analysis of the main existing international digital platforms dedicated to NbS. Metadata cataloging models were extracted and systematized from these platforms to develop a national digital catalog of NbS solutions. Based on this analysis, a list of NbS for the Mediterranean urban context was constructed. The list is organized according to classification criteria that include: general description and typology of the solution; urban area of application (open space and/or building); aspects related to the Societal Challenges defined by the European frameworks.

Starting from this operational framework the Mediterranean *NbS* CataTool platform was created, including the urban, land and marine domains, and made accessible on the Biodiversity Gateway of the NBFC. The development of the tool was coordinated in collaboration with the Research Institute on Terrestrial Ecosystems (IRET) of

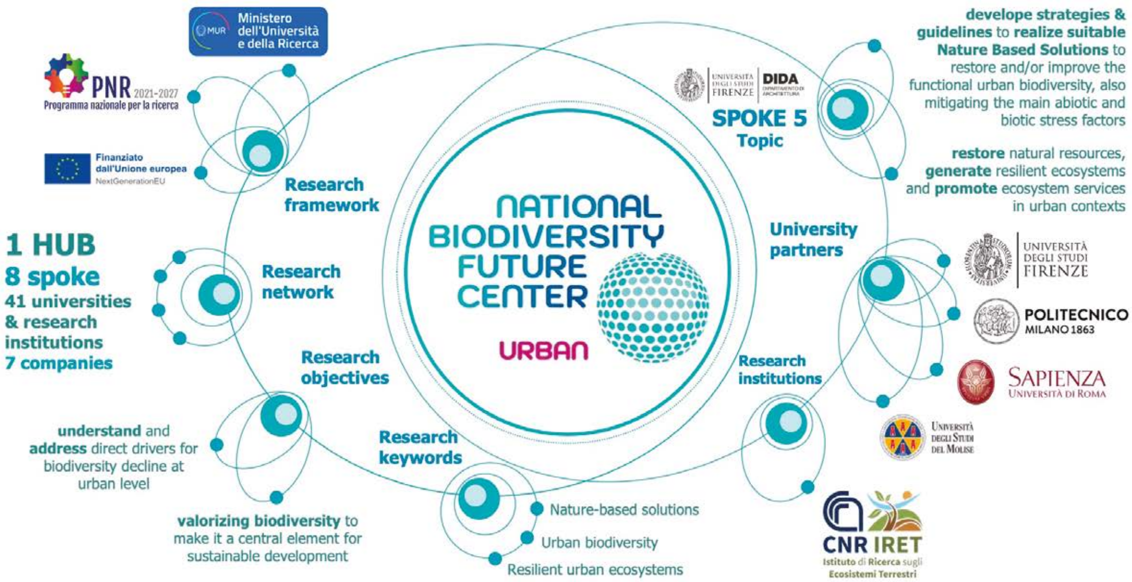

Fig. 1 – The research general plan.

the National Research Council (CNR), and with the Universities of Tuscia, Bologna, and Genova. The *NbS CataTool* is a multi-stakeholder decision support tool designed to promote the implementation of NbS in Mediterranean contexts. Some of the CataTool NbS have been integrated and explored in this publication taking into account: design, implementation and management parameters; limitations and critical issues of applicability; case studies and best practices for reference.

The book collects the contributions of the group of scholars who participated in the research in the area of integrated and sustainable design for the urban context. In addition to the people from the University of Florence, a researcher from the CNR at the Institute for Research on Terrestrial Ecosystems (IRET) also contributed with her own chapter.

The research involved a large number of researchers representing a wide range of skills and approaches. For this reason, each author has used the most appropriate language and terminology to effectively communicate the meaning and specificity of their contribution. The transdisciplinary dimension is therefore the aspect that most characterizes the cultural approach to the theme of urban regeneration and the application of NbS for the restoration of biodiversity, the increase in resilience to climate change, the improvement of the quality and usability of urban spaces and the conditions of well-being of citizens.

The research topics and the results acquired are therefore an expression of an integration between:
- technological and environmental/spatial, architectural and urban design;
- landscape architecture, urban landscape planning and management;
- urban planning and governance;
- environmental engineering;
- environmental physics;
- agricultural, environmental and forestry science.

Active collaboration between different scientific skills allows for the strengthening of transdisciplinary integration and the development of participatory and inclusive methodologies and techniques for co-design and co-management. Particular emphasis has been placed on the planning, design, construction and management of ecological connections as infrastructures of urban and sub-urban areas, in order to reduce anthropogenic pressure on ecosystems, communities and populations and contribute to the consolidation of the overall resilience of environmental systems.

The aim of the publication is to provide theoretical, methodological and instrumental references for urban regeneration through the application of solutions that highlight the role of open spaces, widespread naturalness and plant formations in increasing biodiversity, combating climate change and improving the well-being and health of citizens.

The research group intended to scientifically and instrumentally support this objective in order to guarantee the operation required by the general program of the NBFC for the aspects concerning urban planning, trying to integrate, through the skills represented by the members of the group:

- adaptive design processes;
- architectural, urban and landscape regeneration criteria focused on the quality and usability of spaces;
- assessment of the effectiveness and energy-environmental efficiency of NbS and integration with spatial and technological devices;
- assessment of intervention alternatives consistent and compatible with further transformation and redevelopment objectives within the framework of local and national regulations, defining and quantifying spatial-technological-energy quality indicators.

The authors' contributions are organized into three main sections which respectively describe the theoretical, methodological and instrumental approaches of the research. Each section is divided into chapters.

In the 1st section the contributions, in the form of critical essays with a broad cultural scope, deal with the key themes of the research, the scientific framework of the problem and the theoretical foundations underlying the development and innovation of knowledge.

Starting from the illustration of the meaning of NbS and the role of nature in the urban domain, the chapter 1.1 proposes a reinterpretation of the relationship between nature and artifice and illustrates an holistic approach considering the collaborative relationship between the forms of natural, artificial and collective intelligence that can guide the coexistence of living beings in the built environment and lead to adaptation and mitigation scenarios capable of counteracting the drastic changes on our planet (Bologna).

The chapter 1.2 introduces the concept of Landscape-based Solutions for Urban Biodiversity, proposing to move from the paradigm of greenery to that of open space systems in their different and multiple characterizations (ecological, environmental, socio-symbolic, historical, expressive, aesthetic). Landscape-based Solutions indicate that every plan choice and transformation project should prove "landscape-sensitive" at different scales of intervention (spatial and temporal). This means that in the landscape concerned and in the open spaces that belong to it, basic indications should be found to guide and define specific choices. Choices that are attentive to different contexts (in the broadest sense of the term) and conscious regarding ecological-environmental, historical-cultural, socio-symbolic, and aesthetic issues. (Lambertini).

Biodiversity issues in historic urban landscape are illustrated in chapter 1.3, especially focusing on layered landscape features composing heritage places, as historic gardens, parks and open spaces sequences. Exploring the concept of biological diversity, the chapter proposes the introduction of the term *temporal diversity*, to be considered as a variety of historical phases, evolutionary sequences, chronological documentation, visible or invisible, present or even just perceptible in a given open space or landscape context (Matteini).

The chapter 1.4 analyses the current state of urban biodiversity to highlight the importance of a strategic planning and management of urban green spaces. The authors propose strategies, like habitat diversification, native planting, and lower maintenance schedules, that can greatly increase biodiversity in alignment with sustainability and public health goals. Moreover, the authors show the most widely used indicators for assessing biodiversity, useful tools for integrating biodiversity into urban development policies (Ferrini, Lo Piccolo).

The chapter 1.5 focuses on NbS as a holistic and resilient approach, integrating ecological processes with engineered systems to manage water risks more sustainably. A shift from solely grey infrastructure to hybrid "blue-green" systems demonstrates how certain infrastructures can evolve into NbS, while others may remain conventional. This blended paradigm enhances resilience by aligning risk reduction with environmental restoration (Solari, Carbonari).

The chapter 1.6 examines the evolution of policies concerning urban and riverine biodiversity at the global, European and national scales, particularly the Italian context. The study highlights how cities and surface watercourses are not merely sites of environmental impacts, but also spaces of opportunity for the implementation of Nature-based Solutions (NbS), capable of enhancing climate resilience, quality of life and social cohesion. The paper underscores the need to strengthen multilevel governance and participatory processes, promoting place-based approaches capable of adapting global and European objectives to local specificities (Hasanaj, Carbonari, Nofroni).

The 2nd section deals with the criteria, methodologies and approaches to environmental and technological, architectural and urban, and landscape design for urban regeneration.

The chapter 2.1 advances an evolutionary reading of NbS towards Nature and Culture-based Solutions (NCBS), conceived as bio-technological and cultural devices that trigger systemic processes of urban regeneration. The challenge is to govern hybrid systems in which humans are active and co-responsible components. This entails moving beyond the paradigm of ecological transition towards that of ecological conversion, grounded in reciprocity between society and the environment. The author also introduces the figure of the reflective *ecotechnician*, a professional who combines technical competence with ethical responsibility (De Luca).

The chapter 2.2 illustrates a method as a useful and effective tool for environmental, urban/architectural, energy and integrated NbS design, applied at small and large scale, i.e. respectively, to the complex building-plant system and its surroundings (built, unbuilt and/or green system), and building, building stock, district and urban-built-up and/or green areas. The simple method proposed, links applied thermodynamics to physics-informed modelling of urban built-up and green areas, and allows the quantification of the energy sustainability of green ecosystem services and/or NbS in any urban area and their areal distribution in different built-up zones (Balocco).

The chapter 2.3 explores urban transition processes according to the principles of regenerative design, enhancing the role of nature and the recycling of local resources for the transformation of critical areas into ecosystems characterised by the circularity of material and immaterial resource flows. The author focuses on the concept that it is crucial to rethink architecture as a discipline capable of following the same logic as nature, balancing the construction economic with the production ecology and regenerating the life cycles of resources, and that the integration of natural solutions and circular economy principles can support urban regeneration, improving citizens' well-being and health (Moretti).

The chapter 2.4 analyses the interrelations between biodiversity, urban resilience, and human well-being through three European case studies: the Emscher Restoration (Germany), Lyon Confluence (France), and the North–South Ecological Corridor in Berlin. The study adopts a critical and interdisciplinary approach, assessing how biodiversity can serve as an operational parameter for adaptive design and climate mitigation. The analysis shows that the most effective strategies are those able to integrate ecological, climatic, and social dimensions within a systemic and multiscale framework. The examined cases illustrate diverse models of ecological regeneration and multi-species cohabitation, where urban planning acts as an active ecological infrastructure. (Carbonari, Hasanaj, Nofroni).

The chapter 2.5 illustrates a method of public engagement (PE) to raise public awareness and empower local authorities on natural hazards, urban resilience and NbS, assuming that co-creation process can be adopted to test new synergies between biophilic urban regeneration and emergency preparedness. The experience of the project Code4Risk is presented as a participatory initiative in which knowledge sharing, co-design and self-construction activate the community as a collective architect who can imagine shared future scenarios for nature-based urban regeneration (Arnetoli).

The 3rd section deals with the application tools (NbS catalogue) for nature restoration in urban areas.

In the chapter 3.1 the author present the *NbS CataTool*, a multi-stakeholder Decision Support System (DSS) designed to promote the implementation of NbS in Mediterranean contexts. The tool integrates three main components: an NbS selection tool, a Learning tool, and a Case Study Finder. The *NbS CataTool* is based on two interconnected databases – the NbS Database (NbS DB) and the Case Study Database (CS DB) – containing theoretical solutions and georeferenced case studies across Italy. By combining taxonomic organisation, interactive exploration, and spatial mapping, the *NbS CataTool* enhances knowledge sharing, decision-making, and collaborative planning among diverse stakeholders (Catalano).

In the chapter 3.2 the authors analyse and present NbS for the building system with a specific focus on their indicators towards biodiversity enhancement and other societal challenges, considering that the integration of NbS in roofs and walls offers multiple ecosystem benefits and are fundamental tools for increasing biodiversity, climate adaptation and ecological integration of the built environment, contributing to the transition towards more resilient and liveable cities (Catalano, Hasanaj).

The chapter 3.3 analyzes specific NbS that contribute to the strategy of enhancing vegetation in open spaces within urban, suburban, and peri-urban areas: afforestation, tree rows, vegetation cluster, tree plantation on paved surface, hedgerows and shrub strips, flower meadows (Nofroni).

The chapter 3.4 describe the water-related NbS that include interventions within the riverscape, functionally connected to the river, and sustainable urban drainage solutions, based on natural retention and infiltration processes designed to reduce flooding, increase water storage capacity, and improve water quality. NbS for water management, within the "working with nature" approach, encompass actions and measures aimed at reducing water-related risks while preserving and restoring river and wetland ecosystems (Carbonari).

The book concludes with a reflection on the results achieved, the limitations and the prospects for development of the research, also in relation to the program of activities envisaged by the NBFC.

SECTION 1

Scientific framework and research issues

Nature and Artifice. An holistic approach to environmental and technological design

Roberto Bologna

Abstract: After a brief introduction to the conditions that make it necessary to resort to natural solutions, the chapter illustrates the meaning of Nature-based Solutions (NbS), a concept that has evolved over time and has now reached a widely shared formulation. The *Catalogue of NbS and Case Studies* of the National Biodiversity Future Center (NBFC), developed within the research project to which the University of Florence group contributed with specific reference to applications in urban areas, also refers to this "umbrella concept". The chapter proposes a reinterpretation of the relationship between nature and artifice, which today can no longer be understood as antithetical, but must instead take into account their interaction in order to absorb increasingly pervasive technological innovations. This is especially relevant at a time when the boundaries between nature and artifice are becoming increasingly blurred, and creativity and innovation are now the result of shared, collaborative and multidisciplinary processes. The mediation between nature and artifice becomes even more necessary in urban spaces, where artefacts, but also critical issues, are most concentrated, and where it is essential to combine the objectives of reintegrating nature with ordinary planning processes. The chapter presents a holistic approach based on the collaborative relationship between forms of natural, artificial and collective intelligence. These forms of intelligence can guide the coexistence of living beings in the built environment and lead to adaptation and mitigation scenarios capable of counteracting the drastic changes that are putting the survival of our planet at risk. Therefore, the theme of dwelling and urban life cannot be addressed through natural elements alone, however fundamental they may be, but must also act on the artificial and technological components, including AI, and on the ideational capacity expressed by communities in response to complex problems. In rethinking the built environment, the role of architectural and urban designers also changes, as do the skills required to address new scenarios that outline a new approach to the use of available resources, inspired by biophilic design and circular design.

Keywords: Nature, Artifice, NbS, Architectural and urban regeneration, Environmental and technological design.

1. The context of the research

In reports investigating the state of health of our planet, the use of nature is identified as one of the priority areas of intervention across all ecosystems—marine, terrestrial and urban—in an effort to counteract negative forecasts for the future (IPBES 2019; IPCC 2023).

Recognising the complexity and dynamism of socio-ecological systems, the sustainable use of nature has been proposed at both practical and political levels as a means of addressing societal challenges. Nature-based Solutions (NbS) have the capacity to generate benefits for both people and the environment by addressing the risks to which our habitat is increasingly exposed. They focus attention on human beings by associating biodiversity conservation and management aspects with social factors such as people's well-being, poverty reduction, socio-economic development and governance principles (Eggermont et al. 2015).

The urban environment, particularly that of large cities, is where the effects of the Anthropocene produce some of the most catastrophic consequences, since cities are

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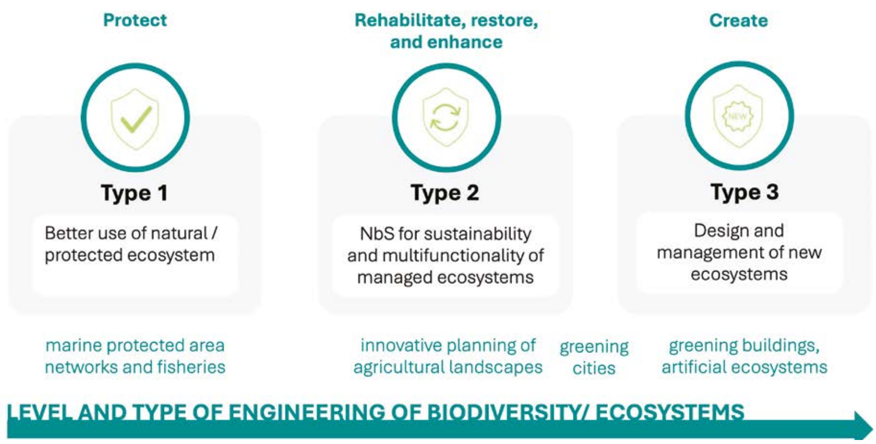

Fig. 1 – Schematic representation of the range of approaches to NbS (Author's elaboration adapted from Eggermont et al. 2015).

exposed to the greatest risks: they are densely populated, housing, services and infrastructure are highly concentrated, and they constitute the fulcrum of social relations and economic activities. Interventions aimed at restoring ecosystems, improving the health and well-being of living beings and increasing biodiversity—specifically through the application of NbS—can play a decisive role in enhancing the resilience of human settlements and supporting their transition towards a sustainable future.

The *Catalogue of NbS and Case Studies* developed within the National Biodiversity Future Centre—the NbS CataTool/NBFC—with the contribution of researchers from the University of Florence, is configured as a Decision Support System designed to provide users across the national territory with up-to-date and evidence-based knowledge on NbS.

2. What are NbS?

The term NbS became widespread in the early 2000s, and its meaning and definition have evolved over time, incorporating both the scientific guidelines emerging from research and the political-strategic orientations of major international institutions.

The acronym NbS was initially used in the search for new solutions for mitigating and adapting to the effects of climate change, while at the same time protecting biodiversity and improving sustainable living conditions. The International Union for Conservation of Nature (IUCN) used the term NbS with reference to the fight against climate change (IUCN 2009), after which it was adopted in policy contexts to indicate an innovative means of creating jobs and growth within a green economy system (EC 2015).

In view of the multiple meanings associated with the role and significance of NbS, Eggermont et al. (2015) propose a characterisation of NbS according to three types:

Type 1: consists of no or minimal intervention in ecosystems, with the objective of maintaining or improving the delivery of a range of ecosystem services both within and beyond these preserved ecosystems;

Type 2: corresponds to the definition and implementation of management approaches that develop sustainable and multifunctional ecosystems and landscapes, whether extensively or intensively managed, improving the delivery of selected ecosystem services compared with what would be obtained through more conventional interventions;

Type 3: consists of managing ecosystems in highly intrusive ways or even creating new ecosystems, such as artificial ecosystems with new assemblages of organisms for green roofs and walls designed to mitigate urban warming and clean polluted air.

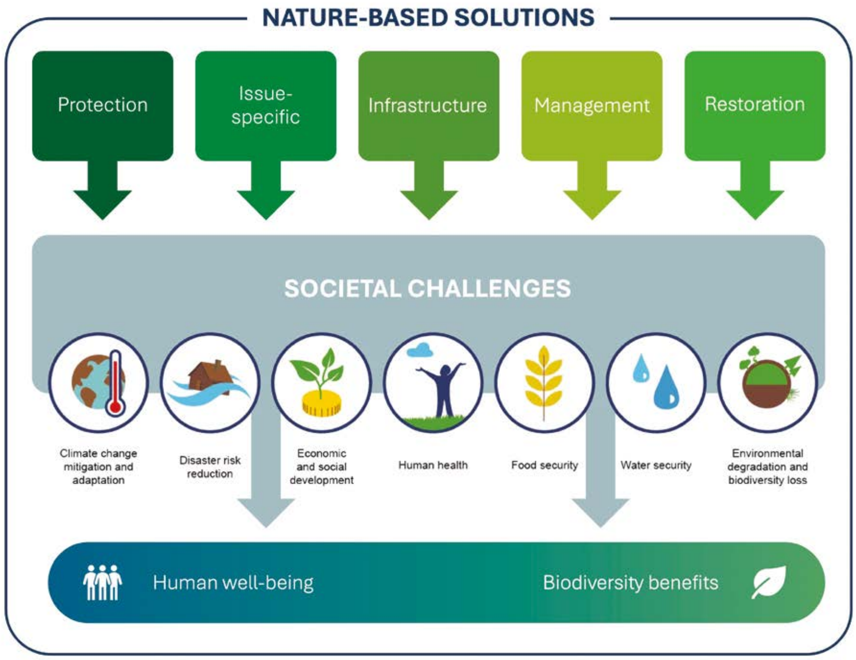

Fig. 2 – The definition scheme of NbS (Author's elaboration adapted from IUCN 2020)

The three types take into account two gradients: the degree to which biodiversity and ecosystem engineering are involved in NbS; and the number of ecosystem services and stakeholders targeted by a given NbS (Eggermont et al. 2015) (see Fig. 1).

NbS have gradually acquired a broader value, extending their meaning to a set of actions aimed at providing environmental, social and economic benefits. The European Commission and, subsequently, the IUCN identify NbS as a combination of different types of intervention: not only solutions "based" on nature, but also solutions "inspired" by nature and solutions "derived" from nature, in order to move towards a sustainable and low-carbon future. While nature-based solutions harness the power of functioning ecosystems as infrastructure to provide natural services for the benefit of society and the environment, nature-derived solutions operate through production methods derived from natural sources. Nature-inspired solutions include the innovative design and manufacture of materials, structures and systems that are modelled on biological processes and inspired by nature (EC 2015; IUCN 2020).

The meaning of NbS thus becomes a general "umbrella concept" under which different approaches to environmental sustainability and ecosystem management are integrated (see Fig. 2).

To be considered an NbS, an intervention must address one or more societal challenges in an integrated way. The IUCN identified a list of societal challenges (IUCN 2020), later updated according to *The NetworkNature EU Roadmap to 2030* (El Harrak and Lemaître 2023): 1) Climate resilience, 2) Water management, 3) Food security, 4) Social justice and social cohesion, 5) New economic opportunities and green jobs, 6) Participatory planning and governance, 7) Natural and climate hazards, 8) Health, well-being and air quality, 9) Green space management, 10) Place regeneration, 11) Knowledge and social capacity building for sustainable urban transformation, 12) Biodiversity enhancement.

Following growing interest in NbS, the IUCN deemed it necessary to define a standard allowing practitioners to regulate the design and application of each NbS according to the principles established in 2016 (see Tab. 1). This provides a common basis for understanding what can be considered an NbS and for contributing to change by improving NbS practice and supporting NbS-related development policies (IUCN 2016; IUCN 2020).

Tab. 1 – NbS principles according to the NbS definition (Author's adaptation from IUCN 2016).

Principle 1	NbS embrace nature conservation norms and principles
Principle 2	NbS can be implemented alone or in an integrated manner with other solutions to societal challenges (e.g. technological and engineering solutions)
Principle 3	NbS are determined by site-specific natural and cultural contexts that include traditional, local and scientific knowledge
Principle 4	NbS produce societal benefits in a fair and equitable way in a manner that promotes transparency and broad participation
Principle 5	NbS maintain biological and cultural diversity and the ability of ecosystems to evolve over time
Principle 6	NbS are applied at a landscape scale
Principle 7	NbS recognize and address the trade-offs between the production of a few immediate economic benefits for development, and future options for the production of the full range of ecosystems services
Principle 8	NbS are an integral part of the overall design of policies, and measures or actions, to address a specific challenge

The Standard consists of eight Criteria, each of which is divided into a series of Indicators (see Tab. 2).

Tab. 2 – Criteria and Indicators of the IUCN Global Standard for NbS (Author's adaptation from: IUCN 2020).

	Indicatori
Criterion 1 NbS effectively address societal challenges	C- 1.1 The most pressing societal challenge(s) for rights-holders and beneficiaries are prioritised
	C-1.2 The societal challenge(s) addressed are clearly understood and documented
	C-1.3 Human well-being outcomes arising from the NbS are identified, benchmarked and periodically assessed
Criterion 2 Design of NbS is informed by scale	C-2.1 The design of the NbS recognises and responds to the interactions between the economy, society and ecosystems
	C-2.2 The design of the NbS is integrated with other complementary interventions and seeks synergies across sectors
	C-2.3 The design of the NbS incorporates risk identification and risk management beyond the intervention site
Criterion 3 NbS result in a net gain to biodiversity and ecosystem integrity	C-3.1 The NbS actions directly respond to evidence-based assessment of the current state of the ecosystem and prevailing drivers of degradation and loss
	C-3.2 Clear and measurable biodiversity conservation outcomes are identified, benchmarked and periodically assessed
	C-3.3 Monitoring includes periodic assessments of unintended adverse consequences on nature arising from the NbS
	C-3.4 Opportunities to enhance ecosystem integrity and connectivity are identified and incorporated into the NbS strategy

	Indicatori
Criterion 4 NbS are economically viable	C-4.1 The direct and indirect benefits and costs associated with the NbS, who pays and who benefits, are identified and documented
	C-4.2 A cost-effectiveness study is provided to support the choice of NbS including the likely impact of any relevant regulations and subsidies
	C-4.3 The effectiveness of the NbS design is justified against available alternative solutions, taking into account any associated externalities
	C-4.4 The NbS design considers a portfolio of resourcing options such as market-based, public sector, voluntary commitments and actions to support regulatory compliance
Criterion 5 NbS are based on inclusive, transparent and empowering governance processes	C-5.1 A defined and fully agreed upon feedback and grievance resolution mechanism is available to all stakeholders before an NbS intervention is initiated
	C-5.2 Participation is based on mutual respect and equality, regardless of gender, age or social status, and upholds the right of Indigenous Peoples to Free Prior and Informed Consent (FPIC)
	C-5.3 Stakeholders who are directly and indirectly affected by the NbS have been identified and involved in all processes of the NbS intervention
	C-5.4 Decision-making processes document and respond to the rights and interests of all participating and affected stakeholders
	C-5.5 Where the scale of the NbS extends beyond jurisdictional boundaries, mechanisms are established to enable joint decision-making of the stakeholders in the affected jurisdictions
Criterion 6 NbS equitably balance trade-offs between achievement of their primary goal(s) and the continued provision of multiple benefits	C-6.1 The potential costs and benefits of associated trade-offs of the NbS intervention are explicitly acknowledged and inform safeguards and any appropriate corrective actions
	C-6.2 The rights, usage of and access to land and resources, along with the responsibilities of different stakeholders, are acknowledged and respected
	C-6.3 The established safeguards are periodically reviewed to ensure that mutually agreed trade-off limits are respected and do not destabilise the entire NbS
Criterion 7 NbS are managed adaptively, based on evidence	C-7.1 An NbS strategy is established and used as a basis for regular monitoring and evaluation of the intervention
	C-7.2 A monitoring and evaluation plan is developed and implemented throughout the intervention lifecycle
	C-7.3 A framework for iterative learning that enables adaptive management is applied throughout the intervention lifecycle
Criterion 8 NbS are sustainable and mainstreamed within an appropriate jurisdictional context	C-8.1 The NbS design, implementation and lessons learnt are shared to trigger transformative change
	C-8.2 The NbS informs and enhances facilitating policy and regulation frameworks to support its uptake and mainstreaming
	C-8.3 Where relevant, the NbS contributes to national and global targets for human well-being, climate change, biodiversity and human rights, including the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP)

From an operational point of view, the IUCN Global Standard for NbS has two functions: to support the design of an NbS and to provide a tool for verifying that the design meets the requirements of the NbS Standard. It therefore establishes a self-assessment methodology based on a process sequence that includes the following phases: *Design*, in which the design and subsequent implementation of an intervention must correspond to the eight criteria in order for the intervention to qualify as an NbS; *Scaling up*, in which the NbS acquires consistency in relation to the specific context and territorial dimension; and *Verification*, in which the Standard can be used to ascertain whether a designed solution is actually an NbS.

Finally, the resolution of the United Nations Environment Assembly (UNEA), recognising the important role that NbS can play in the global response to climate change and its social, economic and environmental effects, defines NbS more extensively as «actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits» (UNEA 5.2 Resolutions 2022).

The NbS CataTool/NBFC adopts this definition, with particular attention to terrestrial ecosystems and, more specifically, the urban environment.

3. The role of nature in the urban context

The need to integrate natural elements into urban systems emerged with particular urgency in the nineteenth century, when the city began to reveal the most harmful consequences of the massive urbanisation of the population and of the transformations produced by human activities, to the point of causing an imbalance in ecosystems.

Ebenezer Howard's Garden City project, launched at the end of the nineteenth century, represents a concrete experience that led to the creation of two garden cities, Letchworth and Welwyn in Great Britain, and inspired many other developments. The proposal to include public parks and private gardens in order to protect health and purify the air aimed to combine the benefits of the countryside and the city, while avoiding the disadvantages present in both.

The sociologist Lewis Mumford points out that Howard's great innovation was to have developed the organic concepts underpinning the physical form of the city, introducing a new idea of development and a new model of urban planning and construction (Mumford 1977, 639; 643).

The application of biological criteria of dynamic and organic balance to control urban development and ensure the functionality and containment of movement, the presence of continuous green belts designed to safeguard the health and well-being of inhabitants, and the external delimitation of the settlement by a permanent agricultural area are principles that inspired Howard's proposal and that can still be considered valid, even in a completely different context. Yet the planning model proposed by Howard, apart from its initial achievements, has been largely ignored in practice.

Today, the urban environment is the place where construction activity is most concentrated and constitutes a complex system in which artefacts—buildings, roads and infrastructure—are present to a predominant extent. In urban areas, natural spaces remain limited in comparison with artificial surfaces (EEA 2021). The scarcity of green areas and new urbanisation increase vulnerability to the disruptive impacts of climate change, such as flooding, extreme heat and droughts (IPCC 2023), and place pressure on biodiversity by altering ecosystems and causing the extinction of many animal and plant species (IPBES 2019). Furthermore, these transformations have serious impacts on the population and worsen the quality of life, well-being and health of inhabitants (Pereira Barboza et al. 2021). Abandoned or underused urban green areas, even in small towns, still represent a critical issue, and their recovery can have a positive impact on community life.

Natural spaces in cities play a key role in counteracting climate change and restoring biodiversity (Maudsley and Wallsten 2024). NbS provide essential habitats for many species of flora and fauna, contribute to urban biological diversity by fostering ecological balance, and increase ecosystem services. Furthermore, NbS support the rebalancing of outdoor comfort in terms of surface and ambient temperature control, relative humidity and air quality, and also improve the hydrogeological performance of soil and water basins, with positive effects on human health (UNEP 2022).

In recent years, ongoing research has shown how climate change and biodiversity loss can be countered by proposing new urban models that adopt NbS capable of increasing the adaptation and resilience of the built environment while improving ecosystem biodiversity (EC 2024a).

The application and diffusion of NbS in the urban domain must be considered an absolute priority, since the greatest risks and the most devastating consequences for inhabitants are concentrated in cities.

The role of NbS is strengthened by the recent promulgation of the European Nature Restoration Law, related to the European Green Deal, which aims to restore ecosystems, habitats and species across all terrestrial and marine areas of the EU in order to enable the long-term and sustained recovery of biodiversity and nature's resilience, while contributing to the achievement of the EU's climate change mitigation and adaptation objectives. EU countries are required to submit their national restoration plans within two years of the entry into force of the regulation, namely by mid-2026, indicating how they will achieve the targets. In particular, the regulation introduced by the Nature Restoration Law sets, for urban ecosystems, the goal of no net loss of urban green space and tree cover by 2030, followed by a constant increase in their total area from 2030 onwards. This is to be achieved through the restoration and expansion of green spaces—including forests, parks and urban gardens, urban farms, tree-lined streets, lawns and hedgerows—and by integrating green infrastructure and nature-based solutions, such as green roofs and walls, into building design (EC 2024b).

Despite growing political interest at higher levels, a comprehensive understanding of these alternative urban models and their adaptation to different urban settings, as well as their actual implementation at the local level, remain limited. In order to fill the gap related to the need to stimulate the widespread implementation of natural solutions, adopt the principle of natural infrastructure and respect planetary limits, it is crucial to provide municipalities with appropriate tools—including methodologies, guidelines, best-practice reports and pilot case studies—to properly integrate NbS into current urban planning processes and drive urban transition.

4. The integration between nature and artifice

In the typological classification described above, and also implemented in subsequent studies and reports on NbS, it can be seen that higher degrees of engineering and artificial ecosystems are exemplified particularly in urban areas. In the field of NbS, technical innovations are increasingly being developed; these appear in all types of NbS, but are mainly concentrated in the design and management of new ecosystems. In urban areas, innovative solutions mostly consist of smart engineering solutions (Somarakis, Stagakis, Chrysoulakis 2019).

As a decision support system, the NbS CataTool/NBFC organises NbS according to the same typological classification, correlating it even more explicitly with the type of intervention that a user intends to apply through an NbS: type 1) Protect; type 2) Manage/Restore; type 3) Create. This classification of NbS indicates the need to main-

Fig. 3 – The *Polinature* pavilion (Source: Ecosistema Urbano Creative Common CC by 4.0).

tain a broad interpretation of the term, an issue that presents certain difficulties but also favours a wider reading, one that takes into account not only the creative contribution of design but also the uncertain boundary that establishes what is nature and what is artifice.

The relationship between nature and artifice is a theme that touches on various fields, such as philosophy, art, science, technology and literature. It may refer to contrast, but also to the interaction between what is natural and what is created by human beings. If, in 2015, the European Commission established that NbS exclude methods that artificially alter nature, such as genetically modified organisms (EC 2015), today, following the rapid transformations induced by the use of artificial intelligence and by the simulation of natural processes, to what extent can this statement still be considered valid? According to the philosopher of science Pievani, the boundary between natural and artificial is no longer so clear: both terms represent the result of evolution, considering that even what is natural is now, in fact, also the result of human intervention (Pievani 2024). In an era in which we are able to manipulate the genetic bases of evolution and simulate natural behaviours through processes that are not spontaneous but induced by human beings, the dualistic vision between nature and artifice has now been superseded by the fusion between civilisation and environment (Buttafuoco 2025).

Only recently has the need for a holistic approach emerged, especially in architectural and urban regeneration interventions. This approach views nature and artifice as complex systems in continuous interaction, where the whole is capable of representing greater complexity and diversity than the mere sum of its individual elements. A concrete example of this approach is represented by the Polinature pavilion, an urban ecosystem that integrates nature, technology and AI as a trigger for a broader process of urban transformation (Tato, Vallejo, Rizzetto, Liebes 2025) (see Fig. 3).

This primarily cultural instance is well represented by the 2025 Venice Architecture Biennale, entitled *Intelligens. Natural. Artificial. Collective*, which addresses the collaborative relationship between forms of natural, artificial and collective intelligence. These forms of intelligence can guide the coexistence of living beings in the built environment and lead to adaptation and mitigation scenarios capable of counteracting the drastic changes that are putting the survival of our planet at risk.

The curator of the exhibition, Carlo Ratti, states that the theme of dwelling and urban life cannot be addressed solely through the contribution of natural elements, however fundamental they may be, but must also act on the artificial and technological components, including AI, and on the ideational capacity expressed by communities in response to complex problems. This is especially true at a time when the boundaries between nature and artifice are increasingly undefined, and creativity and innovation are now the result of shared, collaborative and multidisciplinary processes (Ratti 2025). This therefore implies a collaboration between living species that expands to include the robotic and cyborg worlds, integrating the intelligence of the natural world as well as the most advanced technologies.

Through the works on display, the exhibition proposes a wide range of links between living environments and biology: from biotopia, biomimicry and neurobotany to epidermitecture—the coexistence between urban surfaces and microbial biopatinas—baubotanik, understood as the fusion of architecture and biology, and bioacoustics, namely beneficial frequencies for the well-being of plants and people.

The architectural and urban dimension is explored through hybrid natural-artificial interweavings by Kengo Kuma, suspended multi-material structures by Ensamble Studio, cockpits shielded by living networks by SO-IL, translucent diaphragms by EMBT Architects, multi-species habitats by Studio Gang, and nomadic shelters designed to “metabolise toxic artefacts” by Emanuele Coccia. These works manifest their innovative characteristics while also expressing the potential of the interconnections between science and nature, biology and technology. More generally, all the proposals on display recall the need not to consume and waste materials, but to reuse, recycle and even combine techniques and materials in innovative ways, in search of a new aesthetic capable of implementing the principles of circularity.

With a concluding message that is as clear as it is unsettling, Ratti states that the purpose of the research brought to the fore in this edition of the Venice Biennale is to make everyone understand that we no longer have to build (Banti 2025). In echoing transformative processes of natural origin, the urban context can only evolve through its own metamorphosis.

5. Scenarios of architectural and urban regeneration

Considering the urban scope of application of NbS and the role of architectural and urban designers, including landscape architects, nature becomes a resource, like any other material, to which we can turn in order to find a sustainable response to development. This response is based on an approach that integrates nature into habitats and reconnects it with people, with the aim of increasing biodiversity and regenerating urban spaces as natural ecosystems. This means adopting the principles of biophilic design, which is based on the search for a new relationship between living species—animals or plants—in which human beings are part of the natural ecosystem, just like other living beings.

The search for new NbS will have to become a frontier that further advances the creative project integrating environmental and technological devices, while exploring new links and interdependencies between the natural and artificial worlds, which are increasingly challenged by technological evolution and the growing use of artificial intelligence. NbS will have to develop according to the logic of an evolutionary process that takes into account the dynamic character of the structures generated and transformed over time. The capacity of the natural world to implement mechanisms of renewal should inspire design towards the principles of resource circularity and economy. These approaches demonstrate how NbS and circular design can work in synergy to create multifunctional, low-impact and community-driven urban solutions.

Urban regeneration will increasingly have to be carried out by taking into account governance principles, on the basis of which NbS must not only be applied, but must also be compatible with the objectives of ordinary planning and design, which are necessary to ensure the transition of a complex organism—the city—towards a sustainable future.

In rethinking the built environment, the role of architectural and urban designers changes, as do the skills required to address new scenarios that outline a new approach to the use of available resources. It will not only be necessary to acquire the knowledge and skills needed to use natural matter, in its broadest sense, as a resource for design; it will also be necessary to develop multidisciplinary attitudes and collaboration mechanisms capable of addressing the close relationship between architecture, urban planning, landscape and all the other fields of expertise within the natural and physical sciences. Similarly, it has now become necessary to conceive design no longer as a strongly authorial act resulting from a monocentric process, but rather as a global approach based on the participation and sharing of multiple stakeholders representing different social, cultural and economic needs.

This multidisciplinary character will also need to be matched by mechanisms of consultation, co-design and cooperation, such as living labs, which can guarantee the highest possible level of acceptance and effectiveness of the proposed solutions. Such effectiveness is something we are not yet fully able to achieve, except through evidence derived from the monitoring of solutions already applied—which require a long time to achieve the expected objectives—or through very complex predictive design simulations, for which we are not yet fully equipped. Nevertheless, these simulations represent an important evolution of the design process, grafted onto the digitalisation of architectural and urban design through specific applications.

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Landscape-based Solutions for enhancing urban biodiversity

Anna Lambertini

Abstract: Landscape Architecture deals with the conscious transformation of open spaces and works with the living processes. It bases its planning and design approach on the themes of growth, movement, narrative, and the construction of relationships between diverse entities, between humans and nonhumans agencies, in space and time, in extension and depth. Observing the urban settlements through the lenses of Landscape Architecture means recognizing open spaces as their primary components, essential to support the web of life and biodiversity. Constantly exposed to the risk of being filled, eroded, and consumed, open spaces constitute the negative of built volumes: this concerns public and private areas, encompassing permeable and impermeable surfaces, planned places and vacant lands, small residual fragments of free land or vast and composite territorial areas, bodies of water, agricultural areas, and forested spaces. Open spaces should be interpreted dialectically, as entities in dialogue with the solids of the built environment and with other spaces not built, with particular attention to those with active organic soil. This applies to all possible scales of reading and interpretation (geographical, topographical, historical, temporal, etc.), considering open spaces in their different and multiple characterizations (ecological, environmental, socio-symbolic, historical, expressive, aesthetic). Every open space has a promising role (potential or actual) and it does not necessarily have to fulfil a human function. Starting from these premises, the article introduces the concept of Landscape-based Solutions as a device for improving Urban Biodiversity, also proposing to move from the paradigm of greenery to that of an open space system.

Keywords: Landscape Architecture, Urban Nature, Open Space System, Landscape-based Solutions, Biodiversity

1. Interpreting Urban Biodiversity

The concept of «urban biodiversity», which emerged in the 1990s[1] from the broader field of urban ecology as a specific area of research (Sukopp 2002; Nilon and Aronson 2024), is currently at the center of numerous scientific discussions, environmental policies, and social awareness campaigns. It has now become part of everyday vocabulary[2].

[1] Among the first authoritative scientific contributions to the study of urban biodiversity is *The Ecological City: Preserving and Restoring Urban Biodiversity*, published in 1994 as a collection of proceedings from the multidisciplinary symposium organized four years earlier by the Chicago Academy of Science. The symposium aimed to explore the city as a biodiverse habitat and fertile ground for interactions between human populations and nonhuman biological entities. In Italy, a first useful and innovative contribution to the topic in the form of a textbook was by Marco Dinetti, with the 2009 publication of the book *Urban Biodiversity: Understanding and Managing Habitats, Plants, and Animals in Cities*.

[2] Having become part of the sustainable planning lexicon around the turn of the 21st century, this phrase has enjoyed prodigious media coverage over the past two decades or so: for example, anyone searching the web via Google would find at least 3,100,000 results in 0.21 seconds for the Italian version and a staggering 104,000,000 results in 0.26 seconds for the English version. What emerges is a miscellany of informational materials and documents from beyond the technical and scientific literature.

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Fig. 1 – Proposing Landscape-based Solutions for reinventing a public open spaces system in the Municipality of Granarolo, Metropolitan Area of Bologna, Italy. Scheme designed within the framework of the NATU.RE.R applied research, coordinated by Anna Lambertini and developed thanks to a collaboration agreement between the UNIFI Department of Architecture and Regione Emilia Romagna., 2024-2025). Graphic design: Benedetta Pavone.

As a relatively new multidisciplinary key concept, the expression 'urban biodiversity' lends itself to exploration from various critical perspectives, at the intersection of different disciplinary approaches.

In this paper, I propose to explore its meaning from the perspective of Landscape architecture, a discipline concerned with the conscious transformation of open spaces and which, by tradition, is dedicated to working with living processes. Landscape architecture bases its planning, design and management approach on the themes of growth, movement, narrative, and the construction of relationships between diverse entities, between humans and nonhumans agencies, in space and time, in extension and depth. Observing the cities through the lens of Landscape architecture means recognizing open spaces as integral components of the built environment. It also means acknowledging them as essential common goods for sustaining the web of life, ensuring the proper functioning of the urban ecosystem, and achieving the visual and perceptual quality of human settlements. Constantly exposed to the risk of being filled in, fragmented, eroded, or consumed, open spaces constitute the negative of built volumes: they include public and private areas, permeable and impermeable surfaces, designed places and residual fragments, "green" and "gray" spaces, cultivated and uncultivated areas, pieces of *Third Landscape* (Clèment 2005), bodies of water, and forested areas. Every open space has a multifunctional role (whether potential or actual); it does not always have to serve a human-centered function directly.

When viewed as part of a system, open spaces take on the role of connective tissue, a fabric, or a framework, and provide an inverted image of the city.

A widespread, capillary network of interconnected open spaces, with particular attention to those with biologically active organic soils, constitutes the fundamental prerequisite for maintaining and enhancing urban biodiversity - a dimension that, in addition to biological diversity and the variety and multiplicity of species and habitats, implies the recognition of the cultural, figurative, aesthetic, socio-symbolic diversities and historical-testimonial value of places. Building on this disciplinary and critical-interpretive framework, I propose a paradigm shift that replaces the notion of urban green space with that of open space systems, thereby introducing the multidimensional concept of *Landscape-based Solutions* as a useful tool for developing planning and design instruments that promote urban biodiversity.

2. Urban Green and Nature-based Solutions

Although the various expressions of nature within built environments have been observed and studied for centuries, the interpretation of cities as significant reservoirs of biodiversity has only been embraced by the broader scientific community in recent decades. Since the beginning of the third millennium, renewed emphasis has been placed on the role of "urban green spaces", which have taken on increasing importance in environmental policies formulated at the global, European, and national levels.

A product of functionalist urban planning that emerged in the early decades of the 20th century, the term *urban greenery* refers to the collection of public open spaces characterized by the presence of vegetation. Parks, gardens, and tree-lined avenues are its archetypal expressions. From its earliest uses, this term has carried different shades of meaning, though initially these were always tied to hygienic, aesthetic, social, and educative considerations. Despite the conceptual weaknesses and interpretive ambiguities of a term based on a chromatic and largely quantitative approach—one that refers simultaneously and indiscriminately both to the totality of plant formations distributed throughout the public city and to the open spaces that host them—the expression *urban green* maintains a dominant position in common parlance, as well as in technical, scientific, and regulatory lexicon. Furthermore, over the past two decades, it has taken on additional nuances, precisely in relation to the spread of the notion of biodiversity. The various definitions of urban green space tend to emphasize its connecting role and its infrastructural connotations. At the same time, they emphasize the need to adopt a multi-scale approach. However, they frequently adopt a perspective that is heavily skewed toward the ecological-environmental-quantitative dimension. Moreover, this dimension is interpreted in a markedly performance-oriented manner, based on dimensional parameters and biophysical indicators (such as the number of trees planted or the CO_2 absorption capacity of various tree and shrub species).

As the climate emergency has intensified and urban populations have grown, the traditional restorative, therapeutic, and healing role attributed to green spaces in cities has been increasingly emphasized in recent years. The introduction in 2004 of the new *One Health* model (which considers human, animal, and environmental health as a single entity) and the dramatic and unsettling experience of the recent SARS-CoV-2 pandemic have contributed to fueling the debate on its benefits. Recognition of the close correlation between biodiversity, ecosystem health, and human well-being underpins policies and measures guided by the ecological-economic paradigm of *Nature for People*, to which the well-established concept of ecosystem services belongs: human populations are considered part of ecosystems, and Nature provides services indispensable to their sustenance and health, which can also be quantified economically. This paradigm also encompasses the widely adopted concept of Nature-based Solutions, introduced in 2009. The potential strategic and multifunctional role that NbS can play has been extensively explored and documented. It is worth highlighting, however, the problematic aspect: NbS thrive on the ambiguity of a paradigm that remains skewed toward a predominantly anthropocentric vision.

3. Ideas of Nature, Urban Landscape and Paradigm Shifts

Georgina Mace, a British ecologist considered one of the most brilliant and rigorous scientists of our time, writes that the concept of *Nature for People*, intertwined with the idea of biodiversity conservation, began to emerge in the late 1980s: until then, international nature conservation policies (and related practices) had been predominantly shaped by the notions of *Nature for itself* [3] and *Nature despite People*[4].

The three paradigms of nature just mentioned reflect different attitudes, developed over time by urban societies in response to the effects of the progressive expansion of human settlements across the planet's surface. They evoke different ethical and aesthetic ideas of *Nature* and the *City*, filtered over the course of the last three centuries or so (Brevini 2013), through the dominant cultural frameworks that have established a sharp opposition between urban and natural, between human and nonhumans, and between cultivated and spontaneous.

It seems appropriate to recall that from the evolution of the *Nature for People* paradigm in an ecological-economic key have derived the concepts of Natural Capital, Ecosystem Service, and Nature-based Solutions. For this reason, various scholars have not missed the ambiguous flavor of an idea of Nature that is compliant, serviceable, and salvific, working primarily to satisfy the needs of the human species.

As a substantial body of postcolonial scholarship suggests, it is time, instead, to adopt a different ecological paradigm and to chart, once again, new paths for conservation biology and for planning and design practices in the human world. After all, there is a need to develop descriptive and interpretive tools that bridge disciplines and can then be translated into practical tools.

Mace, for example, has used the expression *People and Nature* (Mace 2014), which effectively emphasizes the coexistence of people and nature but still leaves open the possibility of an ontological separation. By reversing the order of the terms - a move that suggests a significant semantic shift - Randrup, Buijs, Konijnendijk, and Wild instead propose the phrase *Nature with People* (Randrup, Buijs, Konijnendijk, Wild 2020), placing the emphasis on the idea of humans as part of nature. Warning against the risk of exploiting natural resources due to the persistent reliance on the concepts of ecosystem services and Nature-based Solutions, these authors propose developing a

[3] Cfr. Mace 2014. « Conservation thinking before the 1960s was broadly of the *nature for itself* type which prioritizes wilderness and intact natural habitats, generally without people, and has scientific underpinnings from wildlife ecology, natural history, and theoretical ecology. This thinking continued throughout the 1960s (…) and remains a dominant ideology for many people today ».

[4] Cfr. Mace 2014. «In the 1970s and 1980s, rapid increases in the impacts of human activity and awareness of the consequences of habitat destruction, overharvesting, and invasive species led to the emergence of *nature despite people* conservation. Here, the focus is on threats to species and habitats from humans, and on strategies to reverse or reduce them. Ideas concerning minimum viable population sizes and sustainable harvesting levels, as well as intense debates about community-based management and the sustainable use of wildlife, stem from this period and persist to the present».

more open and inclusive *Nature-based Thinking* (NBT), to be used primarily in urban transformation processes. "We define NBT as an approach to urban inclusive planning, drawing inspiration from nature to act socially, environmentally, and economically in the transition toward sustainable cities. (..) NBT does not only view nature as providing solutions to urban challenges; it also recognizes that more space needs to be allocated to wild nature. NBT takes a cyclical approach to creating space for wildscapes and less manicured urban green spaces, but also aims to be truly transdisciplinary" (Randrup, Buijs, Konijnendijk, Wild 2020: 921-22). Nature-based Thinking aims to promote the diversity of urban nature and takes a firm stand in favor of spaces of wild nature. This is certainly not a new principle, but it deserves our support. We must not forget to include the dimension of beauty in this approach, so as to avoid falling into the insidious trap of the stubborn and sterile dichotomy between ecology and aesthetics.

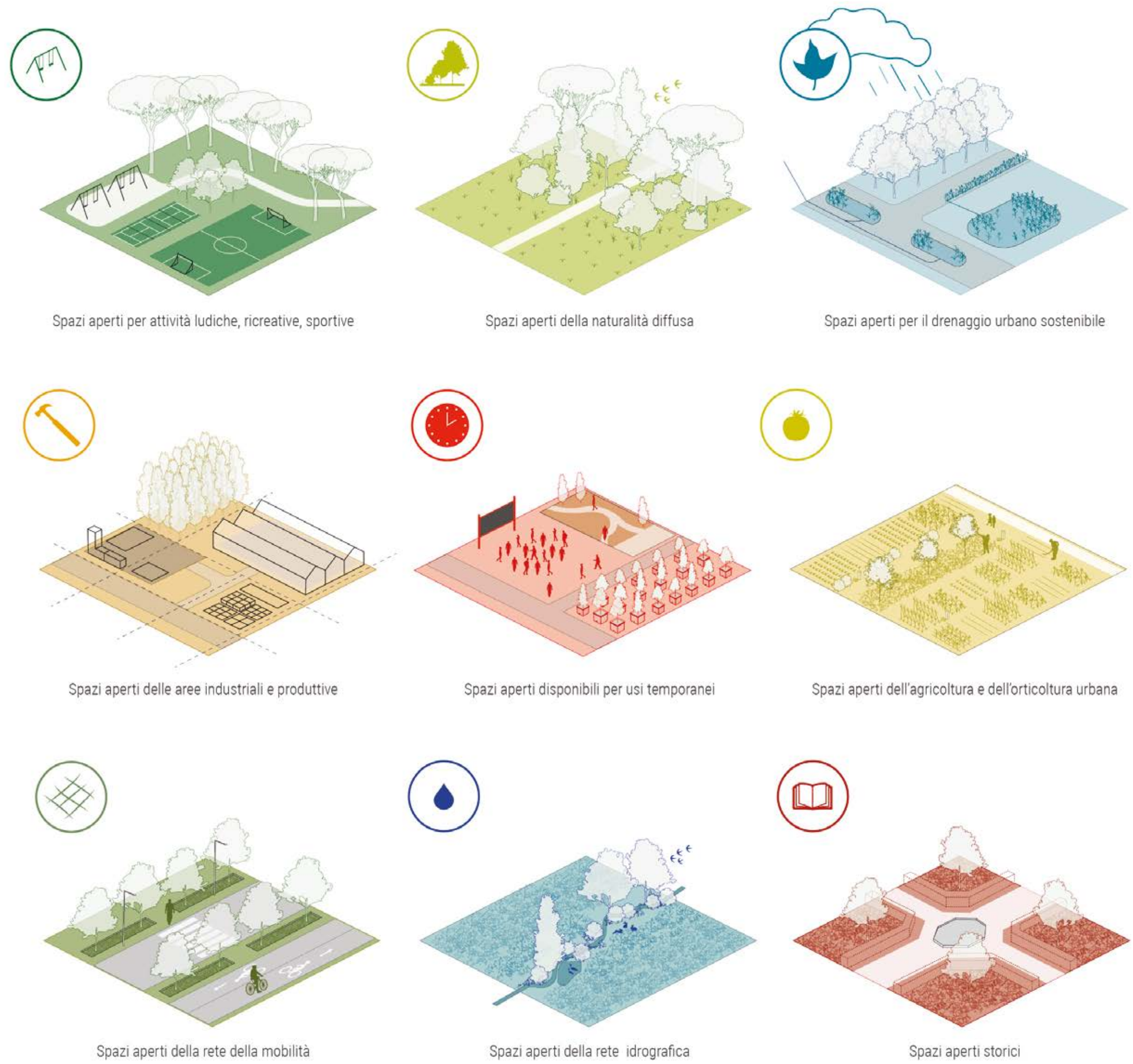

Fig. 2 – Possible open space classes to set up a Landscape Approach-based mapping. Classification proposed within the framework of the NATU.RE.R applied research (coordinated by Anna Lambertini and developed thanks to a collaboration agreement between the UNIFI Department of Architecture and Regione Emilia Romagna., 2024-2025). Graphic design: Cristian Farina.

To describe and nurture the urban natural environments of the 21st century, we need new ethical and aesthetic categories, as well as to experiment with updated, transdisciplinary operational tools for managing urban biodiversity.

In this context, among the emerging concepts pointing to promising research horizons is that of *Urban Wild* (Lambertini 2022), as a planning and design category that refers to different forms, expressions, and processes of spontaneous nature within urbanized territories.

In addition to representing one of the most prolific fields for experimenting with practices and poetics of critical landscape regeneration, the theme of the presence of spontaneous vegetation and wild animals in cities poses an important scientific and cultural challenge. A challenge specifically regarding the conservation of urban biodiversity through the management of networks of abandoned open spaces with free evolutionary dynamics capable of hosting secondary ecological successions.

To bring about the bold paradigm shift required by the ecological transition, it is not enough to ask ourselves what and how much natural capital to invest, or how many thousands of trees need to be planted in cities to secure the future of a species - the human species - that has become increasingly less generalist and increasingly specialized in living in urban contexts. Rather, we must understand what forms of urban governance can be experimented with to enable *Multispecies Urbanism*[5], embrace super-diversity (Lambertini and Trovato 2025), and foster the complexity of interspecific relationships. The challenge of the biodiverse city is to make it desirable not only to cohabit with the welcome and docile companion species evoked by Donna Haraway (Haraway 2003), but also to coexist and co-evolve alongside a strange, surprising, even unsettling, cosmopolitan multitude of living entities (Schilthuizen 2021). All of this requires bold exercises of imagination.

4. A Cognitive and Imaginative Challenge

The loss of global biodiversity, documented over the years by numerous authoritative scientific studies and reports, is not merely a problem to be assessed quantitatively; it also involves a "perceptual, cultural, and epistemological crisis that challenges us as a Western society and, more broadly, as the human species, directly affecting the meaning that life—and its value—holds in and for us" (Di Stefano, Elisabetta, Valeria Maggiore, e Salvatore Tedesco. 2025). Since the 21st century, thanks to the powerful narrative of the Anthropocene, research trajectories have emerged that invite us to break free from the binary structure upon which the Western mind has been shaped for centuries. Thinking in terms of pairs of opposing categories such as nature/culture, organic/inorganic, wild/domestic, has led us dangerously off course. The well-established dualism of Man/Nature is not symmetrical; on the contrary, it is based on the dominance of one species over others. To overcome these antagonisms, we need "to construct the apparatus for new perceptions, infrastructures of speculative sensibility, open to the unknown" (Manghi 2021, 35). The *post-humanist approach*, *queer theory* and *queer ecology* (Gandy 2011), the *more-than-human city*, and Donna Haraway's the concept of *Humusity* are theories and perspectives that invite us to explore the hybridity, mixtures, and the mystery of "the inclusion of all in the same world" (Coccia E. 2022). They also

[5] For a more in-depth look at this topic, see "Debra Solomon: Multispecies Urbanism" in Landezine, https://landezine.com/debra-solomon-multispecies-urbanism/. Last viewed 12/11/2025.

pose uncomfortable questions, such as: "despite all the talk of sustainability, what chance do we have of leaving a habitable environment for our descendants of different species?" (Lowenthaupt Tsing A. 2021).

A focus on urban biodiversity involves exploring which ethical and aesthetic ideas about nature human populations are actually willing to embrace, and with which nonhuman communities and entities they can learn to coexist in urban areas undergoing transformation. It is not so much a matter of asking what place to reserve for nature in the city: as the American landscape architect Anne Whiston Spirn argued very well as early as the 1980s (Whiston Spirn 1984), cities are in some ways already part of nature. This seemingly provocative statement rests on a clear interpretation: the biochemical and biophysical processes that govern energy exchanges, air movement, the hydrological cycle, and soil erosion can manifest and act, with varying intensity and outcomes, both in cities and in vast natural open spaces. *The Granite Garden* aims to dismantle one of the most common oppositional dichotomies—that of urban versus natural—and to shed light on the workings of an ecological mindset that has very little to do with today's reassuring *green* rhetoric. Landscapes, gardens, and open spaces are shaped and molded by human action and imagination as well as by the elements, plants, animals, erosion processes, and geological movements; they can change slowly and imperceptibly or suddenly and violently. This is why "landscape architects have been exploring and discussing what it means to design with nature for over a century", Whiston Spirn further explains, urging designers and planners to use terms like "natural" or "ecological" consciously when referring to the nature of their work. She suggests that it is necessary to adopt an informed critical stance on the concept of Nature - or rather, on the "Nature of Nature" in question - if we wish to facilitate an appropriate updating of the tools of landscape architecture and urban planning and design (Whiston Spirn A 1995, 29).

5. Expanding the Scope: towards Landscape-based Solutions

With the aim of contributing to the ongoing debate, I propose shifting from the concept of NbS to that of *Landscape-based Solutions*, a design framework that I have placed at the center of some recent applied research projects. In essence, it is a question of always considering the *Landscape approach* (Koh 2013) to NbS: this means outlining solutions informed by a trans-scalar vision, through iterative planning and design processes that take into account the ecological and cultural characteristics of the sites and/or areas of intervention, whether it be a portion of a city, a system of local open spaces, or specific urban greening projects.

Referring to *Landscape-based Solutions* means explicitly adopting distinctly trans-scalar visions that bridge territorial networks and the micro-scale, and addressing the issue of urban regeneration "through design forms that reframe the focus on ecology and the environment" (Russo 2013, 218). Landscape is, in fact, a cross-sectoral, multidimensional, and communicative field: "it points to innovative paths for planning and design, helping to regenerate the concept of sustainability, which - due to its centrality but also to the pervasive use of the term - requires constant redefinition and new focuses" (Russo 2013, 218).

Landscape-based Solutions combine themes and approaches specific to ecological planning and design with the 'desperate' need for beauty, pleasantness, and meaning in the places where we live, within a perspective of territorial governance that leverages issues such as, among others, multispecies coexistence, coevolution, and multiculturalism.

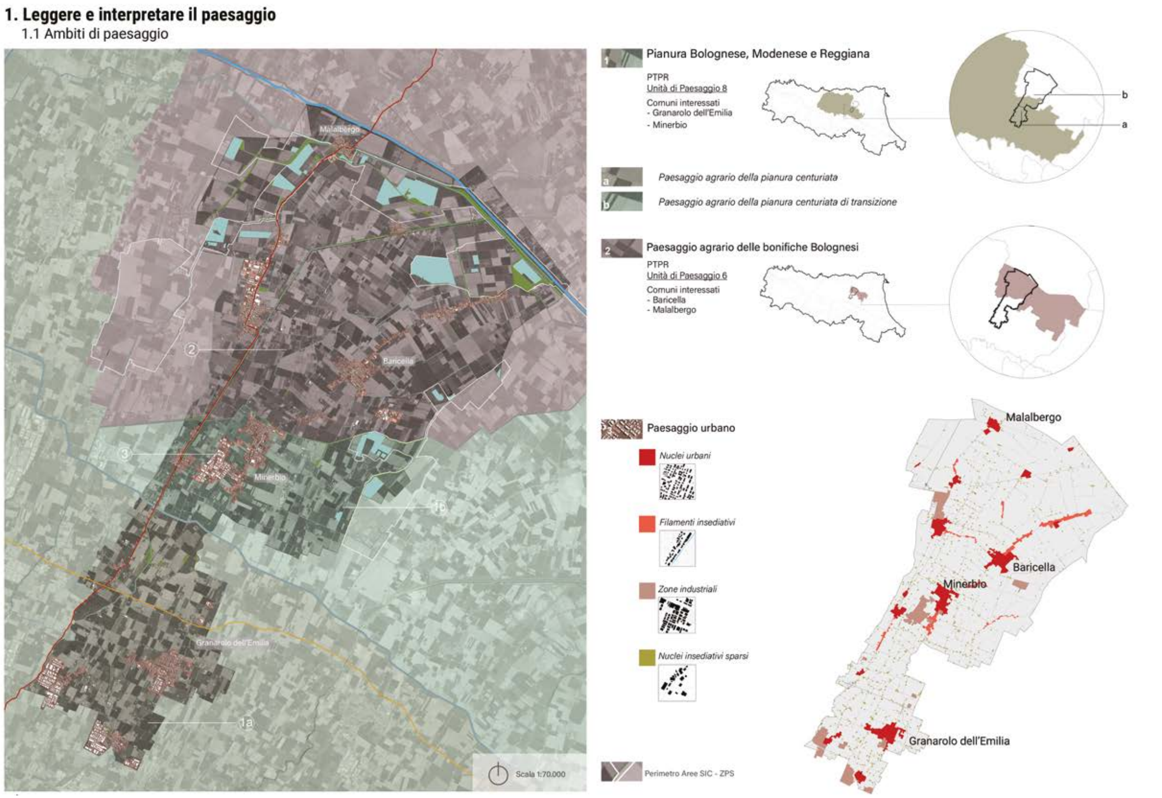

Fig. 3 – Landscape Units: a Landscape interpretation of the Municipal territories. Union of Municipalities of Terre di Pianura, Metropolitan Area of Bologna, Italy. Map developed within the framework of the NATU.RE.R applied research coordinated by Anna Lambertini and, conducted thanks to a collaboration agreement between the UNIFI Department of Architecture and Regione Emilia Romagna. Graphic design: Simone Cortonicchi.

For this reason, *Landscape-based Solutions* are figurative: they transform the territory of plans into systems of places and spaces experienced through the gaze, explored hand-to-hand.

To define these, it is necessary to incorporate certain key themes into the knowledge-based and diagnostic framework of biodiversity and green planning tools (such as the Green Plans developed in accordance with the initial guidelines of Italian Law 10/2013 or the Urban Nature Plans outlined in the *European Biodiversity Strategy*), including:

- the definition of landscape unit delineated at the local level, which implies a significant change in the scale of interpretation, representation, and assessment, consistent with what has been outlined at the regional level;
- a survey of open spaces, conducted on the basis of classes and subclasses that are not tied to the functionalist and sectoral approach still underlying the definition of various categories of urban green space in land-use planning;
- a survey of plant structures and the various vegetation patterns (tree, shrub and herbaceous layers) present in the territory that characterize the quality, configuration, and functioning of landscapes;
- a map of urban soil characteristics;
- a map of different habitat.

Landscape-based Solutions indicate that, at all scales of intervention (spatial and temporal), every planning decision and every transformation project should be landscape-sensitive, dealing with the system of open spaces. And thus engag-

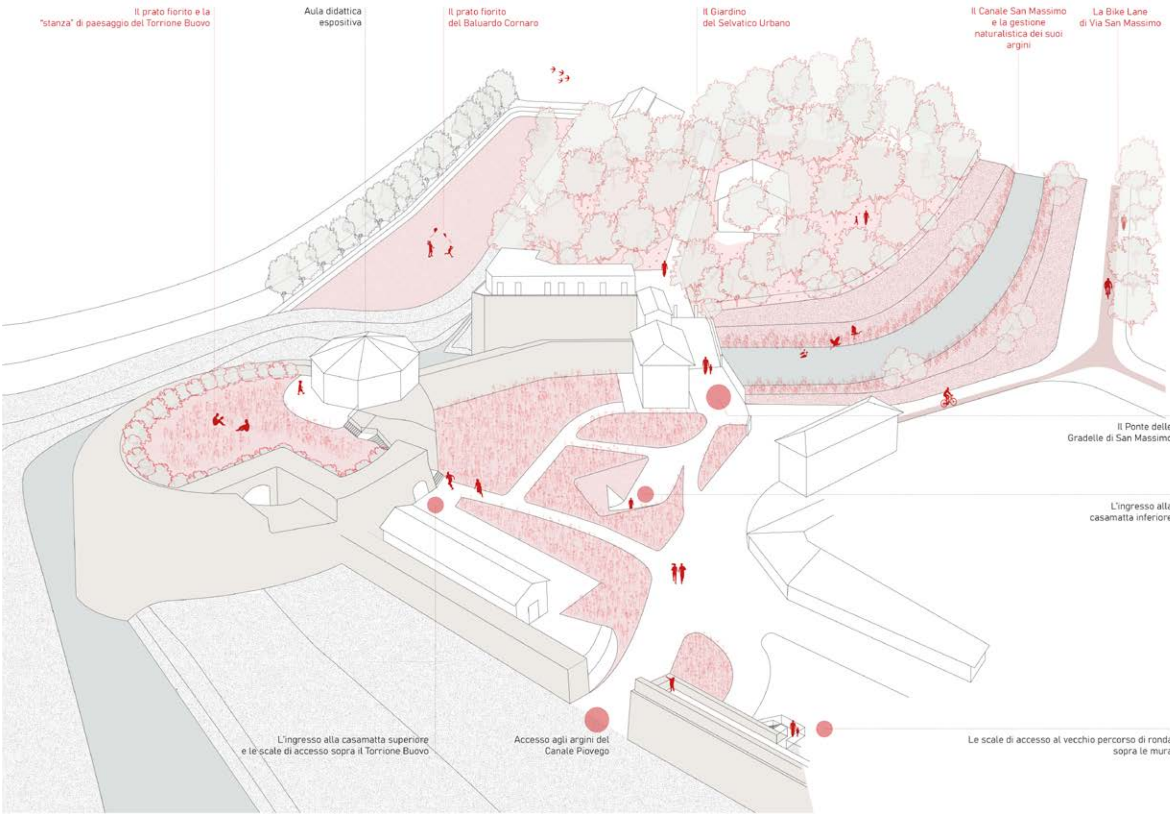

Fig. 4 – *Landscape-based Solutions* for the active conservation and enhancement of urban biodiversity along the Padua Walls Park System. Designing interpretation developed within the framework of an applied research conducted thanks to a collaboration agreement between the UNIFI Department of Architecture and the Municipality of Padua. (Anna Lambertini and Tessa Matteini scientific coordination, 2025-2026). Graphic design: Cristian Farina.

ing with the various contexts (in the broadest sense of the term) and the diverse evolutionary dynamics, paying attention to issues of an ecological-environmental, historical-cultural, socio-symbolic, aesthetic, and visual-figurative nature.

Because if biomass, carbon, the number of plants to be planted, and the amount of new urban green space were to be the only reference indicators, then one place would be just as good as another, all parts of the territory would be equal from the perspective of quantifying ecosystem services, and all open spaces (regardless of their specific historical, socio-symbolic, or relational value, irrespective of their suitability for use, their geographical location, or their unique characteristics) would be equivalent. If, on the other hand, we speak of landscape quality - in the broad sense that the term *landscape* can express far beyond the clichés and lazy interpretations of reductive cognitive and interpretive models - then a different approach is needed.

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Preserving and improving biodiversity in Historic Urban Landscape

Tessa Matteini

Abstract: In the theoretical framework of the research, focused on urban biodiversity, it seems crucial to include those landscape fabrics and ecological networks composed by a wide range of heritage open space systems, strongly featuring urban and periurban areas and building a specific *Historic urban Landscape* (according with UNESCO definition, 2011). Often interpreted as single and isolated heritage sites, each historic open space, if appropriately planned, designed and managed with a relational landscape approach and a proactive attitude, can offer a crucial contribution in supporting and fostering urban biodiversity. Moreover, exploring the concept of biological diversity and trying to reinterpret it according to a specific research dimension, the paper proposes the introduction of the term *temporal diversity*, to be understood as a variety of historical phases, evolutionary sequences, chronological documentation, visible or invisible, present or even just perceptible in a given open space or landscape context. This specific kind of diversity, particularly evident in historic gardens, archaeological places and heritage sites, is immediately recognizable in continuously inhabited urban landscapes, strongly diachronic and dyschronic contexts, where the density and variability of the times pertaining to the different settlement phases are higher, alternating with the progressive stratifications of open spaces; where finally, further layers, more mobile and ephemeral, but no less important, attest the temporality and seasonality in the use of places and their continuous daily variation.

Keywords: Historic Urban Landscape; historic gardens; temporal diversity; landscape approach; urban biodiversity

> "Gardens as cultural assets must become scientific model laboratories to understand cultivation and conservation as essential cultural tasks of our societies. These challenges must lead to a new understanding of nature that initiates and perpetuates a responsible, humane sense of life through the gardens."
>
> (M. Rohde 2022)

1. Focusing on biodiversity in Historic Urban Landscape

In the theoretical framework of the research, focused on urban biodiversity, it seems crucial to include those landscape fabrics and ecological networks composed by a wide range of heritage open space systems, strongly featuring urban and periurban areas and building a specific *Historic urban Landscape*. This peculiar kind of urban landscape is often a suitable ambit to explore and interpret biodiversity issues in historic cities. Beyond that, HUL is an important field of planning/design experimentation in landscape architecture, when considering goals as preserving and improving biodiversity.

As stated by UNESCO Recommendation drafted on November 10th, 2011, *Historic urban landscape* (HUL) can be defined as the "urban area understood as the result of a historic layering of cultural and natural values and attributes, extending beyond the notion of "historic centre" or "ensemble" to include the broader urban context and its geographical setting". This wider milieu embraces "the site's topography, geomor-

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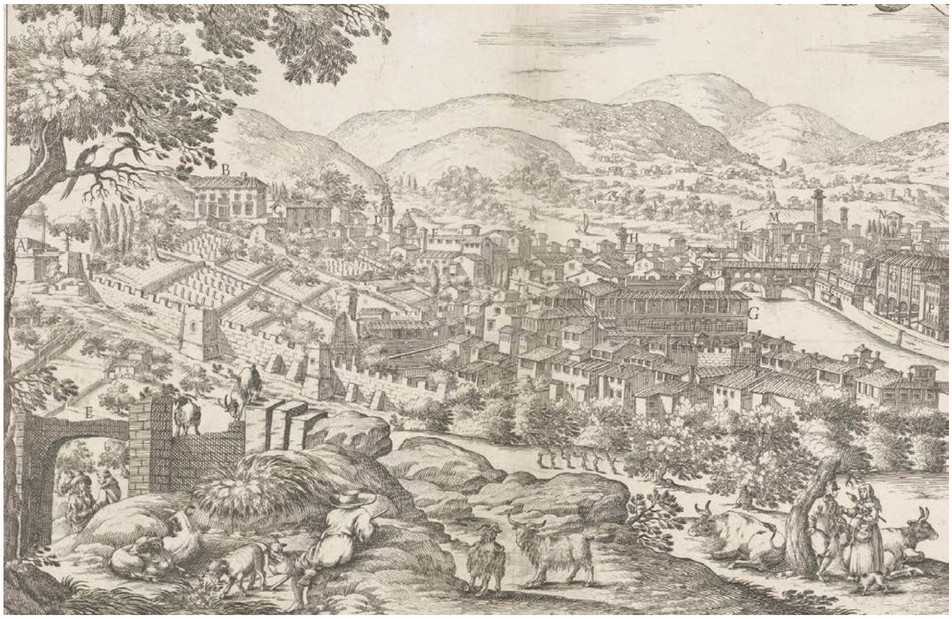

Fig. 1 – Historic Urban Landscape in Florence, Oltrarno: the network of minute and various open spaces in the first half of the XVII century. Valerio Spada, *Veduta della città di Firenze dal muricciolo dei Padri di S. Francesco al Monte*, metà XVII secolo. (Source: Wikimedia Commons).

phology, hydrology and natural features, its built environment, both historic and contemporary, its infrastructures above and below ground, its open spaces and gardens, its land use patterns and spatial organization, perceptions and visual relationships, as well as all other elements of the urban structure. It also includes social and cultural practices and values, economic processes and the intangible dimensions of heritage as related to *diversity a*nd identity."[1]

This exhaustive, detailed and multidimensional definition was intended to provide the basis for a comprehensive and integrated approach for the identification, assessment, conservation and management of historic urban landscapes within an overall sustainable development framework.

In this sense, the UNESCO *Recommendation* explicitly suggest a "*landscape approach* for identifying, conserving and managing historic areas within their broader urban contexts, by considering the interrelationships of their physical forms, their spatial organization and connection, their natural features and settings and their social, cultural and economic values"[2].

We may add that the *landscape dimension,* as proposed by the European Landscape Convention (Council of Europe, Florence, 2000)[3] is a specific and integrated way of gazing places and territories, supporting their protection/planning/design and management approach, and always considering the landscape as a whole to be an inscindible *unicum*[4].

Adopting this attitude (already consolidated in Landscape Architecture discipline) it does not seem appropriate to consider separately heritage sites on one side and their natural features/patterns and biodiversity on the other. Instead it's crucial to face the complexity generated by the coexisting and coevolving historical and natural resources integrately.

1 Available on World Heritage Centre - Recommendation on the Historic Urban Landscape (last access on August, 12th, 2025).

2 Ibidem.

3 Reference texts - Council of Europe Landscape Convention (last access on August, 12 th, 2025)

4 1981 ICOMOS IFLA Italian Committee proposal for *Historic Garden Charter.*

Fig. 2 – An aerial view of Boboli garden in Florence. Realized since 1549 and constantly evolving, today is an interface landscape between the walled city and the rural territory of the surrounding hills (Source: google).

2. Historic gardens and heritage sites as laboratories for urban biodiversity

In this framework and considering specifically heritage places, such as historic gardens and archaeological parks and sites located in urban and periurban areas, a reflection on biodiversity issues following a landscape-oriented approach, can be proposed.

Often interpreted as a single and isolated heritage spot, each historic open space, if appropriately preserved, designed and managed with a relational landscape approach and a proactive attitude, can offer a crucial contribution in supporting and fostering urban biodiversity.

First of all, as widely demonstrated by scientific literature in the last decades (Caneva et al. 2007; Signorini 2017), it's important to remind that heritage places often host a rich e peculiar variety of botanical and fauna species.

Also exploring the idea of *diversity* in historic urban landscape can be interesting and promising in order to widen its semantic relevancy and investigate other landscape related issues.

In fact, surveying the concept of biological diversity and trying to reinterpret it according to a specific research dimension, the introduction of the term *temporal diversity* is proposed, to be understood as a variety of historical phases, evolutionary sequences, chronological documentation, visible or invisible, present or even just perceptible in a given open space or landscape context (Matteini 2024).

This specific kind of diversity, particularly evident in historic gardens, archaeological places and more generally in heritage sites, is immediately recognizable in continuously inhabited urban landscapes.

These can often be considered as strongly diachronic and dyschronic contexts, where the density and variability of the times pertaining to the different settlement phases are higher, alternating with the progressive stratifications of open spaces. Moreover, further layers, more mobile and ephemeral, but no less important, attest the temporality and seasonality in the use of places and their continuous daily variation[5].

[5] Ibidem.

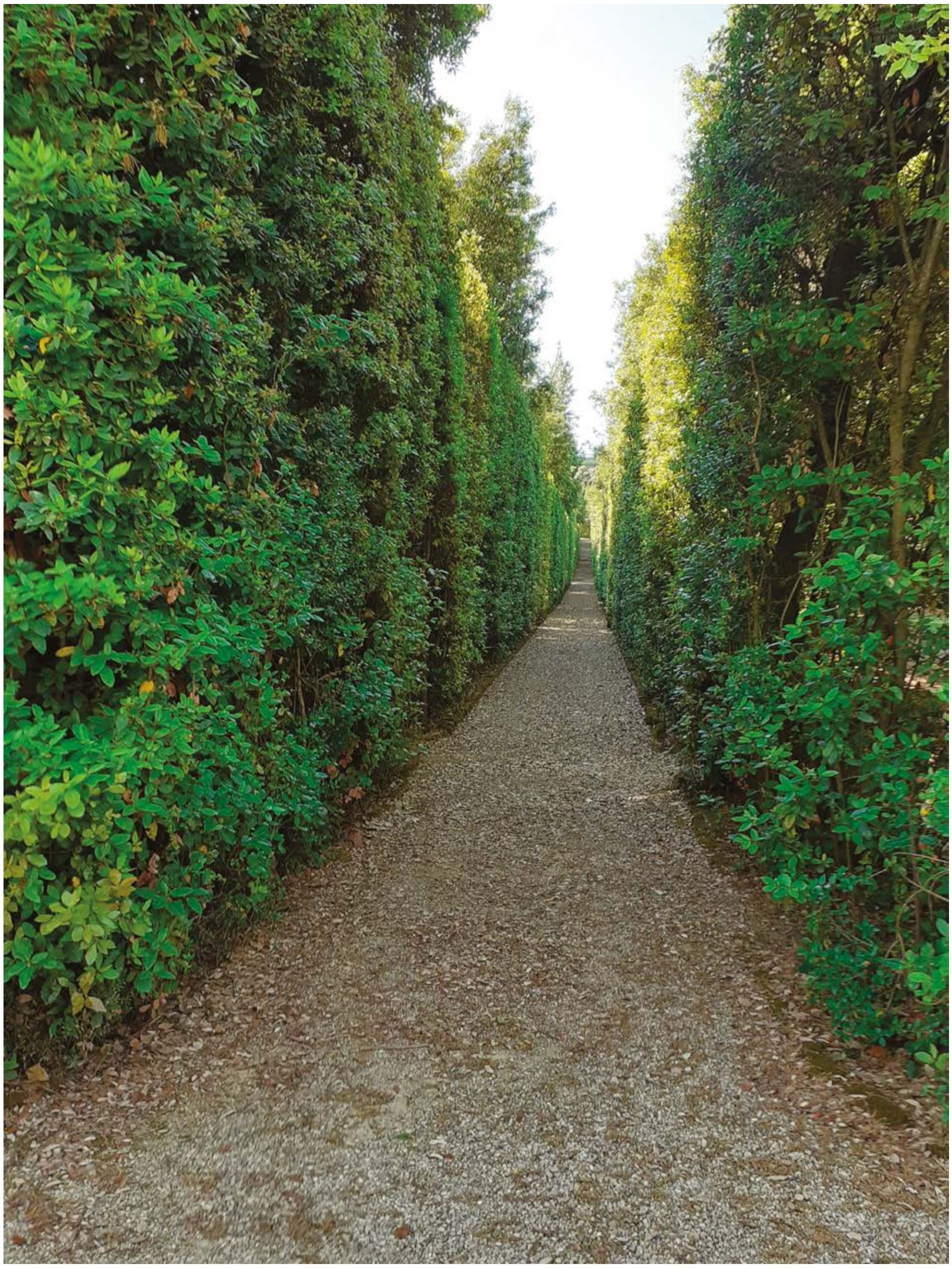

Fig. 3 – Historic gardens are often important hotspots of biodiversity in the urban fabric. The Ragnaia della Stella (a green architecture for hunting in Boboli) hosts many sclerophyll species of the Mediterranean area, such as *Rhamnus alaternus L., Phillyrea latifolia L., Phillyrea angustifolia L., Myrtus communis L.,* but also a broad range of spontaneous species. (Photo T. Matteini 2020).

In particular, focusing specifically on historic gardens, conceived as continually evolving living systems[6], often essential ecological stepping stones in urban fabric, it's important to remark that they often include botanical collections, resulting from their birth or conception, integrated with subsequent transformations, but also spontaneous natural ecosystems, generated over time due to management (or lack thereof).

[6] 1981 ICOMOS IFLA Historic Gardens Florence Charter and 1981 ICOMOS IFLA Italian Committee proposal for Historic Garden Charter.

In this sense, we can affirm with Michael Rohde (2022) that historic gardens can create significant social identities of culture and education, but they also "have enormous potential biodiversity (Agenda 2030, SDG 15 Life on Land)".

To propose their dynamic conservation and integrated, compatible management for the purpose of fostering and improving biodiversit (Prigioniero et al. 2021), it is necessary to understand their historical, evolutionary, climatic, and vegetation dynamics. Archival research can be crucial to understand how the garden has evolved, whether through maps, iconography, or documents and registers that provide specific information on the species present at different times and their management.

Another key issue is the climatic history of the site, that can often be recomposed through a deep and diachronic investigation on archival and bibliographic sources [7].

As stated by Rohde, proposing to adopt a *Garden Thinking*[8], to raise the challenge of historic gardens protection and management with awareness, grounding on an effective and appropriate toolbox, creating an interdisciplinary and multiprofessional research team is absolutely necessary, in order to interpret and understand relationship, interaction and conflicts between living components and architectural ones[9].

3. An applied case study: the Oltrarno open space system in Florence

Specifically focusing on Urban biodiversity, a case study of potential great interest is the Oltrarno open space system in Florence, recently included in the new UNESCO core zone[10].

Featured by a minute network of several historic public and private gardens and parks (such as Boboli, Bardini, Torrigiani and Annalena gardens, Villa Strozzi al Boschetto park) and heritage sites (San Miniato and San Salvatore al Monte, Porte Sante Cemetery, Monte Oliveto Monastery etc.) and strictly related with the various and layered structures of the city walls (both existing or demolished) the whole system has been recomposed and, we could say, infrastructured in the 1870s by the historic greenway of the Viale dei Colli (Pozzana 2003), planned and designed by Giuseppe Poggi, supported by the gardener Attilio Pucci for the botanic choices.

This unique landscape boulevard, realised with huge earthworks and planting sequences and intended to offer a belvedere promenade over Florence, consolidated an organic system of open spaces, became today an essential ecological network for preserving and enhancing urban biodiversity.

Within this remarkable ecological complexity and botanical variety, we can currently recognize several different landscape layers and vegetation codex. Just proposing hereby a tentative and not exhaustive list: some layers can be referred from one side to

[7] For Florence gardens, a crucial source is the Library/Archival repository of the Osservatorio Ximeniano conserving data since the second half of XVII century (*Osservazioni Metereologiche fatte a Firenze dagli Accademici del Cimento tra il Dicembre 1654 e il Marzo del 1670* in Ferdinando Meucci, *Le prime osservazioni meteorologiche: Studi sul clima di Firenze nella seconda metà del secolo XVII*, R. Istituto di studi superiori di Firenze, Archivio meteorologico, 1873.

[8] In original "Garten-Denken" proposed by Michael Rohde, quoting Hubert Markl (Rohde 2019, 32).

[9] In this sense, a case study investigated since 2022 is the historic Medici garden of Villa La Quiete in Florence which has been analysed through an interdisciplinary research cluster, composed by various scholars from different disciplinary fields (B. Foggi, G. Galletti, L.Ghelardini, G. Ghinassi, T. Matteini) and early researchers (C. Bartolucci, V. Castellucci, E. Della Giovampaola, C. Goodrich, E. Paglia) and focused on active and dynamic conservation of the garden.(Galletti, Matteini 2026).

[10] The boundaries of the property - Firenze Patrimonio Mondiale, last access on August, 28th, 2025.

Fig. 4 – The Viale dei Colli boulevard, realized in the second half of the XIX century is today a crucial ecological network connecting many of historic open spaces of the Oltrarno area. (Photo T. Matteini 2019).

Medici gardens vegetation features and botanical collections (Ghinassi et al. 2014); from the other to historic landscape agricultural patterns; some are linked to the Giuseppe Poggi and Attilio Pucci great Masterplan and botanical palette for Viale dei Colli; then we have the huge repertory of spontaneous species growing in these various habitats. In fact, in the Oltrarno area it is possible to survey pioneer species in abandoned areas; new species in historic gardens due to climatic change; ruderal species growing in the city wall, hygrophilous species along the river fringes, and many more.

This *Historic Urban Landscape* has been studied and explored over five years (2018-2023) within the Laboratory dedicated to Preservation of Historic Gardens and Parks[11], in the framework of the Landscape Architecture Master at the University of Florence[12].

Teachers and students worked specifically on Boboli garden, intended as an integrated tile of a broader and more complex landscape mosaic. In this case, the historic garden has been considered, not only a heritage site, but also a living part of an ecological and landscape network, which has a great potential to be a biodiversity and temporal diversity hot-spot within the urban context.

Actually, Boboli can be interpreted as an ecotonal open space connecting the historic Walled City with the periurban landscape systems: for this crucial role, the garden has a remarkable ecological value and is considered a biodiversity hotspot (Gellini et a. 1991)[13].

[11] Teachers L. Ghelardini and P.Capretti for *Plant management and pest control* Course, T. Matteini, *Active conservation of Historic Gardens and Park* Course, with the supporting expertise of G. Galletti and P. Grossoni. Tutors: F. Torelli, V. Castellucci, C. Bartolucci.

[12] Corso di Laurea Magistrale in Architettura del Paesaggio - UniFI Last access on 30.08.25.

[13] See also B. M. Landi, G. Simonti, D. Angelotti, *Il giardino di Boboli come scrigno di biodiversità: dal collezionismo mediceo all'attualità*, contribution presented at the Conference/Giornata di Studi, *Orti botanici e biodiversità delle piante*, organized by Accademia dei Georgofili and Società Botanica Italiana, on June, 29th 2023. Available on www.georgofili.net; Last access on 30.08.25.

Fig. 5 – The Oltrarno heritage landscape system interpreted within the Laboratory (A.Barcellesi, S. Gaspari, R.Zeen 2023).

The challenging issues in its active conservation (such as climate change, reduction of biodiversity, plants pathogens and pests) (Carrari et. al. 2022) have been faced yearly within semester laboratories, following an interdisciplinary landscape approach.

Teaching methodology sequence for the Laboratory embraces a first phase of interpretative reading, including landscape frameworking, historical investigations, climatic analysis and a deepened survey on architectural and vegetation features in the garden; a second phase in which a landscape Masterplan is drafted and a third phase dedicated to garden's ambits specific planning/design/management.

Grounding on the outputs, a specific interdisciplinary research project on Oltrarno Historic Urban Landscape could be planned and proposed in order to survey, interpret and face biodiversity issues, with planning, design and managing strategies, defined adopting the *Landscape Approach* recommended by UNESCO[14].

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14 "The landscape approach is a framework for making landscape-level conservation decisions. The landscape approach helps to reach decisions about the advisability of particular interventions (such as a new road or plantation), and to facilitate the planning, negotiation and implementation of activities across a whole landscape". *UNESCO HUL Recommendation* cit., p. 6 World Heritage Centre - Recommendation on the Historic Urban Landscape (last access on August, 12 th, 2025).

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Urban plants biodiversity

Francesco Ferrini, Ermes Lo Piccolo

Abstract: Biodiversity in the urban setting plays an important role in preserving ecological processes and social well-being. Urban green spaces such as parks, gardens, hedgerows and road verges also in densely urbanized environments,, can provide refuge for pollinators, birds, small mammals, and native plants. These 'mini-biodiversity hotspots' not only provide ecosystem services like water management, air filtration, microclimate regulation, and health benefits for dwellers, but can be essential hubs for the urban ecological network. However, the biodiversity richness of these spaces can be limited by their fragmentation and simplification (i.e., low plant species adopted), and in some cases, by intensive management (i.e., excessive mowing). Therefore, this section analyses the current state of urban biodiversity to highlight the importance of a strategic planning and management of urban green spaces. We propose strategies, like habitat diversification, native planting, and lower maintenance schedules, that can greatly increase biodiversity in alignment with sustainability and public health goals. Moreover, we show the most widely used indicators for assessing biodiversity, useful tools for integrating biodiversity into urban development policies. In an era in which environmental sustainability and ecosystem conservation are global priorities, landscape architects have a crucial responsibility in embedding biodiversity-focused practices into urban projects.

Keywords: Green Infrastructure, Nature conservation, Plant species diversity, Urban ecosystems, Urban green spaces.

1. Understanding urban biodiversity

The term «urban biodiversity» has been described in different ways by previous authors, based on its complexity and ecological significance. For instance, Werner and Zahner (2010) defined it as the whole aggregation of animals and plants within cities. While the MAMROT (2013) expanded this concept, highlighting the inclusion of genetic variation among species and habitat heterogeneity in and around urban settings. Moreover, Puppim de Oliveira et al. (2014) highlighted both the diversity of living organisms and the ecological systems they inhabit. It must be noted that, contrary to common assumptions, cities are not just a mix of concrete, asphalt, and steel. Empirical studies confirmed that urban areas can support many biodiversity hotspots that can have ecological conservation functions. Consequently, the capability for urban areas to host a huge amount of biodiversity needs to be acknowledged by city planners so that management practices that maintain and support such diversity can be pursued (Gentili et al. 2024). In Switzerland, urban tree species richness was found to be up to 17 times greater than that of near forests (Augustinus et al. 2024), illustrating the potential of urban areas not only to maintain but also to enhance biodiversity so that cities often exhibit higher species richness than surrounding rural areas (Wania et al. 2006). Such complexity places cities as potentially emergent hubs of biodiversity. Nevertheless, urbanization may also drive biotic homogenization and the spread of invasive species (McKinney 2006; Gentili et al. 2024; Xie et al. 2024), threatening local biodiversity, highlighting the need for expert planning and management of urban green spaces.

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Plants in urban environments can adapt to a broad range of microhabitats. Urban vegetation is shaped by silvicultural expertise, nursery availability, and administrative regulations, and in certain cases, also by the lack of these factors. Different land uses and habitat types (e.g., street edges, riverbeds, public parks, gardens, private green areas, abandoned areas, and remnant natural patches) create distinct urban floristic compositions. A proper alignment between plant characteristics, site conditions, and management goals is fundamental to ensuring the delivery of ecosystem services. Preserving biodiversity, incorporating biodiversity into urban design, and promoting sustainable building practices are fundamental to a greener, healthier, and more resilient urban environment.

2. Components and scales of urban biodiversity

Urban biodiversity can be categorized into different levels, each interacting with the built environment and city dwellers. Understanding the different biodiversity levels and the scale-related factors that influence them is important to creating sustainable and resilient cities.

2.1. Levels of urban biodiversity

Urban biodiversity comprises several levels:

Genetic diversity is important for species survival and adaptability in urban environments marked by extreme and very variable microclimatic conditions. The genetic variability within populations allows individuals to respond differently to the urban environmental constraints such as pollution, heat, and resource scarcity, thus improving the survival rates. Therefore, the consequent natural selection of urban plants can result in specific genetic adaptations enhancing tolerance to urban stressors and improving the whole ecosystem resilience (Williams et al. 2009).

Species diversity in the urban environment, although often underestimated, can be, as previously said, considerable. Urban green spaces host both native and newly introduced species. Some non-native species become invasive, replacing native flora and fauna. Parks and gardens serve as habitats and ecological corridors that facilitate species movement between urban and rural areas, enhancing ecological connectivity and urban ecosystem resilience (Aronson et al. 2014).

Ecosystem diversity refers to the variety of ecosystems within urban areas, including green roofs, parks, artificial wetlands, tree-lined streets, and spontaneous vegetation. These ecosystems provide critical services, including climate regulation, water retention, and air purification (Pickett et al. 2013). Their conservation and especially management are increasingly essential in rapidly urbanizing contexts.

2.2. Spatial scales influencing urban biodiversity

Urban biodiversity is shaped by factors acting at multiple spatial scales:

At the local scale, biodiversity is influenced by habitat heterogeneity, resource availability, and management practices and planning (Niemelä 1999). For instance, different plant formations in parks can support a wide range of species. Conversely, monocultures reduce ecological complexity and resilience.

At the neighborhood scale, the connectivity between green spaces and the presence of ecological corridors are important to species dispersion and new habitat colonization. Corridors such as rivers, hedgerows, road verges, or green roofs facilitate movement and genetic flow, enhancing biodiversity (Hostetler et al. 2011).

At the metropolitan scale, factors like land use planning, habitat fragmentation, and urban sprawl are dominant. Sustainable cities should mitigate fragmentation and biodiversity loss through integrated green networks and land-use strategies (McKinney 2008).

Urban planning must recognize that biodiversity is driven by processes across scales and must involve urban planners, scientists, landscape architects, and local communities, as an integrated, multi-scale approach is essential for urban biodiversity conservation.

2.3. Beyond a simple tree species selection

Urban forest planning and management must consider age, size, and genetic diversity:

Species diversity buffers against pest and disease outbreaks and ensures the provision of different ecosystem services such as carbon sequestration, microclimate regulation, and wildlife habitat.

Age diversity enhances habitat heterogeneity. Older trees often support symbiotic communities (e.g., fungi, lichens, insects, birds), increasing ecosystem richness and resilience.

Size diversity reflects structural differences among species. Larger trees offer more ecological benefits due to greater biomass.

Genetic diversity within tree populations is often ignored. Many urban trees are clonally propagated, reducing the variability and increasing the vulnerability to potential stressors (i.e., heat and drought). The adoption of different genetic backgrounds within species by expanding the range of used varieties and provenances can mitigate this risk.

A resilient urban forest should avoid overrepresentation of any single species, genus, or family. Guidelines from Santamour (1990) and others suggest no single species should exceed 10% of the total population, no genus more than 20%, and no family more than 30%. This taxonomic diversification enhances resistance to biotic and abiotic threats and ensures continuity of ecological functions across urban landscapes.

3. Urban habitats and ecological dynamics

Cities are increasingly recognized as complex and dynamic ecosystems. An ecological interpretation of the urban environment moves to understand the interactions between built and natural components, highlighting how urban habitats cannot only support but also promote a rich and evolving biodiversity, as previously mentioned. This ecological approach perceives the city not merely as an assembly of infrastructures but as a mosaic of interconnected habitats, including parks, gardens, green roofs, courtyards, abandoned industrial areas, hedgerows and road verges, each providing unique characteristics to support different wildlife. Indeed, when adequately managed, these spaces can serve as refuges for a wide range of plant and animal species, thereby contributing to both local and global biodiversity conservation.

An important aspect of urban ecological analysis lies in the understanding of the different types of habitats and their specific roles in maintaining biodiversity:

Public green spaces, such as parks and gardens, represent key habitats by providing refuges and food resources. Vegetation diversity within these areas is critical for attracting a wide range of fauna, including pollinating insects, birds, and small mammals (Gill et al. 2007; Kaiser and Resasco 2024). For instance, Kaiser and Resasco (2024) demonstrated that pollinator abundance is significantly reduced in gardens surrounded by large impervious surfaces, suggesting that decreasing such surfaces in the urban matrix may enhance bee abundance and then pollination.

Semi-natural areas, including urban woodlands, artificial wetlands, and riparian margins, are crucial for species that require more natural conditions. The presence of native vegetation and an ecologically oriented management significantly increases the biodiversity of these areas.

Green roofs and *Living walls* represent innovative solutions to increase the availability of habitats in densely built environments. When designed with different plant species, these architectural elements create microhabitats suitable for insects, birds, and even rare plant species. Beyond supporting urban wildlife, they also contribute to urban ecosystem resilience (Oberndorfer et al. 2007; Francis and Lorimer 2011).

Vacant and unmanaged spaces such as abandoned fields and spontaneously vegetated areas, though often ignored in urban planning, can serve as biodiversity refuges (Gandy 2013). These unmanaged areas allow pioneer species to establish and thrive, offering significant ecological benefits, including native species conservation, urban climate mitigation, and ecological enrichment of highly anthropized environments. However, the uncontrolled nature of these green areas can pose some risks. Indeed, without proper management, they may degrade, increasing the spread of potential invasive alien species such as *Ailanthus altissima*, *Robinia pseudoacacia*, *Paulownia tomentosa*, and *Broussonetia papyrifera*. These opportunistic plants are characterized by rapid growth and high adaptability; they may dominate native habitats, transforming them into poor and homogeneous landscapes.

4. Ecosystem services and the integration of biodiversity into urban planning

4.1. The impact of biodiversity on the ecosystem services provided by urban forests

Urban forests provide a range of ecosystem services, including regulatory, habitat, and provisioning functions (Dobbs et al. 2011; Nowak et al. 2016). Regulatory services sustain ecological processes and support life through biogeochemical cycles, contributing to ecosystem stability and human well-being via air, water, and soil purification and biological control. Urban forests also serve as essential habitats, promoting the conservation of genetic and biological diversity and enhancing resilience against potential biotic and abiotic stressors.

The role of tree species diversity in ecosystem services delivery is particularly relevant in urban contexts. However, not all species contribute equally, as services depend on species-specific morphological traits and temporal dynamics (Clapp et al. 2014). The presence of different tree species can affect rainfall interception (Xiao et al. 2000), temperature regulation (Bowler et al. 2010; Rendon et al. 2024), pollution removal (Vigevani et al. 2022), and the biological richness (Nielsen et al. 2014; Scherber et al. 2014). For example, Rendon et al. (2024) linked species diversity to lower peak summer temperatures, suggesting that the enhanced diurnal cooling effect was favoured by tree structural diversity. While single species can be effective in providing unique specific services, studies show that multifunctionality is best achieved through the use of a mix of species (Zavaleta et al. 2010; Lundholm et al. 2010). Thus, diversity is critical to create a resilient urban green infrastructure. However, as already stated in previous paragraphs, increasing species diversity does not always improve ecosystem performance. Some species may be undesirable due to invasiveness, allergenic pollen, volatile emissions, or damage to infrastructure (Potgieter et al. 2017). Therefore, a strategic selection is required to balance service optimization with minimization of ecological disservices.

Biodiversity can also be linked to human health. Indeed, exposure to nature can enhance mental and physical well-being. Healthy, diverse ecosystems can help regulate the spread of pathogens, reducing the prevalence of some infectious diseases (the so-called "dilution effect")(Civitello et al. 2015; Robinson et al. 2024). When ecosystems are disrupted, animals and humans may come into closer contact, increasing the risk of diseases jumping from animals to humans (zoonotic diseases). Also, access to natural environments rich in biodiversity supports mental health through calming effects and provides spaces for physical activity. A healthy human microbiome, which influences our immune systems, also benefits from exposure to diverse natural environments. However, while many studies support this, results are not always consistent, highlighting the need for interdisciplinary research. Integrating ecological, psychological, and public health perspectives may yield a more complete understanding of biodiversity role in promoting human well-being.

4.2. Biodiversity is about the planning, design, and management of cities and open spaces

The relationship between biodiversity and urban planning has been recently explored in depth by Lazzarini et al. (2024). Authors highlighted a critical role that biodiversity can play in promoting human well-being, planetary health, and economic prosperity.

Urban areas have the potential to conserve and promote biodiversity through actions such as habitat preservation, improving landscape connectivity, incorporating green infrastructure into planning processes, and promoting management strategies that draw attention to biodiversity. Despite this potential, the practical implementation of biodiversity in urban contexts still encounters significant challenges, including political inertia, limited competencies, and insufficient stakeholder engagement. Conventional urban planning often fails to address the complexity required to sustain biodiversity, and thus, radical transformations are necessary. Indeed, Lazzarini et al. (2024) suggest key issues that should be addressed, including i) the consistent implementation of biodiversity-enhancing measures across spatial scales; ii) the development of effective monitoring and evaluation systems; iii) the establishment of governance frameworks and political will to promote the biodiversity benefits; iv) the long-term engagement of citizens in urban regeneration processes.

Landscape ecology offers key tools to understand and preserve urban biodiversity (Norton et al. 2016). This field of study has significantly contributed to the scientific knowledge about urban landscapes and ecological communities. Factors such as city size, total green space area, settlement age, and regional context are fundamental for planning urban plant communities. Nevertheless, these variables have often been neglected in urban research. Traditional principles of landscape ecology, such as patch size, shape, and composition, continue to influence biodiversity in urban environments. However, the spatial fragmentation and altered temporal dynamics of urban areas necessitate the use of hierarchical, multiscale models specifically adapted to these settings. A major challenge lies in translating these scientific insights into concrete planning practices.

Historically, the spatial distribution and accessibility of green spaces have been evaluated primarily in terms of their proximity to human activity, often ignoring the mobility ranges of other biological species. Nowadays, green infrastructure and sustainable construction approaches are redefining urban development, generating spaces that not only offer aesthetic and recreational value but also protect habitats and contribute to the survival of urban wildlife. To enhance biodiversity outcomes in the urban environment, green spaces should be spatially arranged to remain within the dispersal range of various species, thus reducing barriers to movement and enabling genetic exchange. This can be achieved by creating stepping-stones at multiple scales, linking large green spaces with medium and small patches such as roadside vegetation. These ecological corridors serve as temporary stations that facilitate species migration and reproduction. For example, design solutions such as green roofs, vertical gardens, and elevated migration pathways that connect rooftops to ground-level vegetation can create a three-dimensional ecological network that can be essential for different species. The integration of strategies that prioritise biodiversity into urban projects is a critical duty of landscape architects.

5. Indicators for urban biodiversity

The most widely used indicator for assessing biodiversity is the Shannon-Wiener Index, also known simply as the Shannon Index (Fedor and Zvaríková 2019). This is an ecological measure that allows the quantification of the diversity of species within a community, considering both the richness and the evenness of the species present. A higher value of the Shannon Index indicates greater biodiversity, as it reflects not only a greater number of species but also a more balanced distribution of individuals among the species. Conversely, a lower value of the Shannon Index suggests lower biodiversity, characterized by a dominance of one or a few species. This makes the index particularly useful for comparing biodiversity between different ecosystems or for monitoring changes over time within the same ecosystem. Despite its widespread use, the Shannon Index has received various criticisms over time. One of the most frequently mentioned limitations is the difficulty of interpretation: the index uses logarithmic calculations that may not be intuitive for users unfamiliar with this type of mathematical function. Unlike more straightforward measures such as species richness, the Shannon Index requires more complex interpretation. Another limitation relates to the influence of sample size. In some cases, if the sample is too small or not representative, the index may overestimate or underestimate biodiversity. This is particularly problematic when not all species present in the ecosystem are adequately sampled. Some researchers also argue that the index lacks a strong biological or ecological foundation, as it is essentially a mathematical abstraction. This makes it difficult to use the index to infer the ecological functioning of a system. Moreover, comparing Shannon Index values among very different ecosystems may have limited usefulness due to their differing ecological characteristics and structural complexity. A further point of criticism concerns the index limited sensitivity to dominance. In ecological systems, the dominance of one or a few species can significantly affect ecological functioning, but the Shannon Index does not fully capture this aspect. Nevertheless, despite its limitations, the Shannon-Wiener Index remains one of the most widely used tools in ecological and biodiversity studies due to its ability to combine richness and evenness into a single value. For this reason, it is often used alongside other indices to provide a more comprehensive and detailed picture of biodiversity.

Other biodiversity indices (Fedor and Zvaríková 2019), commonly used include:

Simpson's Index (Simpson 1949), measures the probability that two individuals randomly selected from a community belong to the same species. There are two main variants: the original Simpson's Index (D) and its complement (1-D), known as Simpson's Diversity Index. While the Shannon-Wiener Index is sensitive to the presence of rare species, Simpson's Index is more influenced by dominant species, making it particularly useful in contexts where species dominance is a key feature.

Pielou's Evenness Index (Pielou 1966), quantifies the evenness of species distribution, showing how evenly individuals are spread across species in a community. It is calculated as the ratio between the Shannon-Wiener Index and the natural logarithm of the number of species (S), providing a measure of uniformity in species abundances.

Fisher's Alpha Index (Fisher et al. 1943), is a statistical model that assumes a logarithmic species distribution and estimates diversity based on species richness and relative abundance. It is especially useful when comparing ecological communities of different sizes.

The Top Diversity Index (TD-50) (Love et al. 2022), describes the cumulative number of species accounting for 50% of tree abundance in an urban forest. It is a robust diversity metric and a reliable predictor of more comprehensive measures such as the Shannon Index.

Each of these indices offers a peculiar perspective on biodiversity and is often used together to obtain a multidimensional analysis of species diversity.

In addition to quantitative indices, it is also essential to identify specific biodiversity indicators for urban ecosystems, especially given the rapid growth of cities and the increasing pressure on biodiversity caused by urbanization. Such indicators help monitor the state of biodiversity, allowing timely interventions and guiding urban planning and management toward sustainable solutions.

Examples of useful urban biodiversity indicators include:

i) The proportion of natural or semi-natural areas within the city.
ii) The ratio of native to non-native species.
iii) The degree of permeability of surfaces.
iv) The abundance and diversity of fauna species, particularly birds, are often used as bioindicators.

One of the most structured and widely adopted tools in the international context is the City Biodiversity Index (CBI), also known as the Singapore Index, developed within the framework of the 2010 Conference of the Parties (COP) of the Convention on Biological Diversity (Kohsaka et al. 2013). The index includes 23 indicators grouped into three main areas: native biodiversity, ecosystem services, and governance and management. This tool allows municipalities to self-assess the state of urban biodiversity and monitor changes over time. The CBI promotes awareness of biodiversity among policymakers and urban planners, encouraging the development of local strategies to conserve and enhance biodiversity. It also facilitates comparison between different cities and the sharing of best practices. Thanks to its flexibility, the index can be adapted to different local contexts and levels of data availability, making it a highly useful instrument for integrating biodiversity into urban development policies. Cities that adopt the CBI are better equipped to respond to the challenges of urbanization and contribute to the global goals of biodiversity conservation.

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Nature-based Solutions for water risks resilience

Costanza Carbonari, Luca Solari

Abstract: Urban environments face increasing threats from a range of physical water risks, including flooding, water scarcity, and poor water quality, all exacerbated by climate change, rapid urbanization, and ecological degradation. Traditional water management has historically prioritized hydraulic risk, especially flooding, due to its immediate and visible impacts on lives, infrastructures, and economies. However, this narrow focus overlooks equally critical but less apparent threats such as drought and pollution, which pose long-term risks to human and ecological health. The concept of water security offers a broader framework, encompassing the availability, quality, and sustainability of water for people, ecosystems, and economies while addressing all water-related hazards. In this context, Nature-based Solutions (NbS) present a holistic and resilient approach, integrating ecological processes with engineered systems to manage water risks more sustainably. A shift from solely grey infrastructure to hybrid "blue-green" systems demonstrates how certain infrastructures, like multipurpose retention basins, can evolve into NbS, while others, such as centralized treatment facilities, may remain conventional. This blended paradigm enhances resilience by aligning risk reduction with environmental restoration. Emphasizing NbS within urban water management represents a necessary evolution toward comprehensive, adaptive, and sustainable responses to the growing complexity of global water challenges.

Keywords: Water-related risks, Risks mitigation, Integrating ecological approach in risk management.

1. Key concepts and different approaches in water management

Surface water bodies and ground water have been a key resource for human development since ancient times, but the relationship between man and this natural capital has changed over time passing from a use of resources without degrading the environmental integrity to an overexploitation together with depletion and ecological decline of natural capital because of anthropic stressors and anthropogenic climate change. The drive of progress and rapid population growth leading to unprecedented exploitation and ecological degradation of water resources applies to almost all types of water bodies, but it is particularly systematic and severe in rivers (Dudgeon et al. 2006, Dudgeon 2019, Harrison et al. 2018). Major anthropic pressures are present in urban and densely built as well as agricultural river basins where soil sealing, dams construction, dense infrastructure network and polluting land use practices have altered the river environment at the hydrological, morphological and ecological level, increasing flood risk and worsening physico-chemical water quality.

The traditional water management poorly addresses water scarcity and water quality issues and almost disregards the ecological status of riverine environments, being mainly focused on the mitigation of flood risk. Moreover, in this framework traditional hard engineering works and techniques have been widely adopted: grey detention basins for temporary storage of flood water; in-channel modifications to increase channel capacity and speed up water flow, such as channelization, dredging, diversion spillways; bank reinforcement such as levees to increase streams water-holding capacity.

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More recently, a comprehensive approach relying on multiple water risks reduction joined by the definition of targets to halt ecological degradation and biodiversity loss has been spreading. Indeed, at the European level the Water Framework Directive (European Parliament and Council of the European Union 2000) is an overarching regulatory tool with the goal of protecting and improving freshwater and wetland ecosystems (achievement of good ecological status), supporting a sustainable water use based on long-term protection of resources, mitigating floods and droughts effects. Also the Floods Directive (European Parliament and Council of the European Union 2007) couples flood mitigation and environmental goals by recommending Natural Water Retention Measures, NWRM, (Burek et al. 2012 European Commission 2014, European Commission et al. 2015). Both the Water Framework Directive and the Floods Directive enforce a river basin district approach in order to better address catchment-scale environmental issues and make the cooperation of neighbouring authorities more effective in facing transboundary river management. The set-up and goals of these directives definitely meet the efforts of the Nature Restoration Law (European Commission 2022) in recovering river connectivity and ecological functioning. Overall, this new green approach to water management can be implemented by adopting Nature-based Solutions, NbS, which both aim at mitigating water risks and halting, and possibly reversing, environmental degradation and biodiversity loss (International Union for the Conservation of Nature 2016 2020).

In the present contribution we illustrate water risks, their causes and their impacts (section 2); in particular, we analyse flood risk and the reasons why traditional water management mainly focuses on it overlooking other risks water-related (subsection 2.1); in the following we argue on the importance of moving beyond hydraulic risk in the perspective of adopting a water security approach (subsection 2.2). We then illustrate how NbS can represent an effective integration of conventional engineering works with ecological solutions (section 3), and within this framework we focus on some emblematic examples (subsection 3.1). We finally draw up conclusions and perspective remarks (section 4).

2. What are water risks and why they are exacerbated in urban settings

"Water risk" refers to the possibility of an entity, such as a community, a business, an ecosystem, experiencing a water-related challenge, this being for instance drought, water scarcity, water stress, flooding, infrastructure failure. The risk consists in the impact of an event, and, following the terminology by the United Nations (United Nations Office for Disaster Risk Reduction 2017), this impact is given by the combination of hazard, exposure and vulnerability: hazard is a process, phenomenon or human activity that may cause loss of life or health impacts, property damage, social and economic disruption or environmental degradation; exposure is the situation of people, housing, infrastructure, businesses and other tangible human assets located in hazard-prone areas; and vulnerability is the conditions determined by physical, social, economic and environmental factors that increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards (United Nations Office for Disaster Risk Reduction 2017).

Water risks are many and are grouped in two main categories: physical water risks and regulatory water risks. The second class consists in changes in public policy or ineffective regulations that can impact water accessibility, availability, quality and management; regulatory water risks also include transboundary water management conflicts; in the present contribution we just provide the definition of regulatory water risks, but the in-depth discussion of this subject is outside of our scope. We rather aim at analysing physical water risks.

Physical water risks relate both to water quantity and quality and are strongly interconnected with one another (United Nations 2018): excess water quantity may lead to flooding, that depending on the source is generally distinguished in pluvial, fluvial and coastal flooding; insufficient water quantity to meet demand consists in water scarcity risk; poor quality is the risk of unfit water for use or habitats due to pollution (Figure 1). It is worth stressing that the concept of risk is defined and quantitatively assessed if all the three elements of hazard, exposure and vulnerability are present, clearly identified and quantified (this condition is graphically represented in Figure 1 through the intersection of the hazard, exposure and vulnerability elements). For instance, in case of a flood event (presence of hazard) if there is no human assets located in the flooded area (absence of exposure), there is no overall flood risk. Another illustrative example is the case of a drought taking place in a certain populated area (presence of both hazard and exposure), but if a successful water management strategy provides water supply and solutions in general that completely remove people's susceptibility to drought (absence of vulnerability), there is no overall water scarcity risk. It is therefore clear that water risks are exacerbated in urban areas because in cities the exposure is maximum, being densely populated and built, and in general characterized by the highest values of economic assets. Moreover, urbanization and dense population represent a factor that worsen the hazardousness of phenomena (both natural and anthropogenic) that may cause water risks: prevalence of impervious surfaces increases runoff and flooding, dense population raises water demand, industrial and domestic waste raise pollution. Finally, climate change has intensified extreme weather events, while in general, and in cities in particular, infrastructures for risk reduction and water management are designed for conditions prior to climate change, thus face difficulties in reducing impacts of unprecedented events with magnitude not previously experienced (Kreibich et al. 2022). Collectively, these factors increase the likelihood of both water scarcity and pollution-related health issues and ecological decline, as well as the risk of flooding and infrastructure damage.

2.1. Why traditional water management mainly focuses on the mitigation of hydraulic risk

Hydraulic risk refers to the potential for harm from excess quantity of water in various forms, including floods, landslides, and the consequences of malfunctioning water systems and infrastructures. Floods and flooding represent a primary aspect of hydraulic risk, where intense rainfall or sea-level rise causes rivers and channels to overflow, leading to inundation of land and structures. Hydraulic risk is the dominant focus in water risks because it directly relates to the destructive forces of water, leading to significant immediate and catastrophic damage, including widespread flooding, landslides, and the failure of critical infrastructure like dams, bridges and other hydraulic structures. Unlike other water-related risks, hydraulic risk emphasizes the physical impact and danger posed by excessive or uncontrolled water, which can cause high numbers of casualties and widespread socioeconomic disruption, as seen in major flood events. Indeed, hydraulic risk, and in particular flood risk, is treated as predominant with respect to other water risks mainly because resulting impacts are especially evident and clearly identifiable above all when subject exposed to flood hazard are people and human assets in densely populated areas. In other words, what makes flood risk the most considered among water risks is the high socioeconomic impact with widespread and direct threat to life and property and the catastrophic potential (e.g. dam and levee

Fig. 1 – Physical water risks (central box), their causes (left box) and their impacts (right box). Risk assessment is given by the combination of hazard, exposure and vulnerability; risk assessment allows for the quantification of impacts.

failure leading to sudden, uncontrolled release of large amounts of water, creating immediate and devastating consequences) that configure it as a disaster risk. Finally, flood risk assessment is generally "easier" with respect to the assessment of other water risks, in particular those related to poor water quality, since frequency and magnitude of floods can be unambiguously determined as well as exposure and vulnerability (Grey and Sadoff 2007).

Secondly, also droughts are disasters that can be assessed through the "hazard times exposure times vulnerability" procedure almost as easily as flood risk, and also frequency and intensity of droughts can be determined through time series, even though there is the same difficulty found for floods dealing with unprecedented extreme events due to climate change (Kreibich et al. 2022). Conversely, the assessment of ecological risk due to poor water quality is scarcely integrated in water management and ecological disasters are overlooked. This insufficient consideration is probably driven by several reasons among which greater difficulty in identifying frequency and intensity of hazardous processes, and indirect impacts on people. The underestimation of ecological risks in water management is further analysed in the following section within the wider framework of water security.

2.1. Moving beyond hydraulic risk towards water security

An integrated water management needs a more comprehensive evaluation of water risks beyond hydraulic risk, and in particular ecological risk requires more consideration. A first reason contributing to an insufficient integration of ecological risks in water management is that ecological degradation has apparently less direct effects on people, even if it severely impacts people through decline and disruption of ecosystem services. Moreover, the exposure assessment traditionally focuses almost exclusively on people and human assets directly exposed to hazard, and usually ecosystems are not sufficiently included in the exposure evaluation. In addition, also hazard assessment is generally complex, and frequency and magnitude of hazardous processes are not always possible to determine, for instance in case of continuous water quality decline due to diffuse and continuous pollution, and in case of resulting continuous impoverishment of local diversity in terms of taxa richness and functionality. Overall, therefore, the traditional risk assessment by means of the "hazard times exposure times vulnerability" evaluation suits well for floods and droughts, but may not suit other water risks for which is reductive or may be more difficult to apply (Grey and Sadoff 2007, Hall and Borgomeo 2013).

A second issue that contributes to an underestimation of ecological risk is that it seemingly appears less catastrophic with respect to other disasters such as intense floods and droughts. However, also ecological disasters exist, and among them the current mass extinction of species caused exclusively by human activities is particularly severe. Indeed, it represents an unprecedented loss with extinction rates currently over one thousand times the natural "background" rate, and even accelerating (Pievani 2014). Pievani (2014), among others, argues that mass extinction happening in the Anthropocene is not just an environmental problem for nature; it is an existential threat to humanity because it dismantles the natural systems that make human life possible. Actually, it is a major threat to humans because it destroys the ecosystem services we depend on, such as clean air and water, pollination for crops, and soil fertility. The loss of biodiversity makes ecosystems less efficient and stable, leading to more extreme weather, a decline in food and water security (e.g. from pollinator loss, from soil and water impoverishment of purifying microorganism communities), and increased risk of zoonotic diseases, ultimately undermining human survival and well-being.

An integrated water resources management needs therefore the widespread adoption of the water security concept, which is a complex and broader framework encompassing acceptable quantity and quality of water for health, livelihoods, ecosystems and production, and acceptable levels of water-related risks to people, environments and economies (Grey and Sadoff 2007). In particular, with respect to traditional water risks management the water security approach adopts a wider formalization of risks definition (Hall and Borgomeo 2013) also better considering the ecological status of aquatic ecosystems, for instance valuing attributes such as the frequency of violating water quality standards and the counts of aquatic species (Hall and Borgomeo 2013). Conceptions of water security integrate the protection of natural water resources with societal efforts to meet human needs, recognize trade-offs and synergies across interconnected systems, and support transitions from negative to positive tipping points (Scheffran 2025). Water security implies a holistic approach, namely a comprehensive strategy addressing the interconnectedness of different water-related hazards and vulnerabilities, as well as ecosystem services. This approach can be successfully implemented in practice through Nature-based Solution, an analysis of which is provided in the following section.

3. Grey + Blue-green infrastructures, a new paradigm for water risks resilience

Nature-based Solutions for water management are described as actions within the blue-green infrastructure - organized networks of natural and modified green areas and water bodies across a variety of landscapes - (Krauze and Wagner 2019) or even synonym of blue-green infrastructures (Santiago Fink 2016); this discrepancy notwithstanding, there is general consensus in the scientific community that blue-green infrastructures should be formally classified as "critical infrastructure" and overseen by the same national and international laws and operational regulations (Wagner 2022). Wagner (2022) argues that most authorities consider "critical infrastructures" a top priority. By contrast, national and local governments are frustratingly slow to adopt blue-green infrastructure, even though it may largely contribute to climate adaptation by buffering hydrometeorological extremes such as floods, droughts and heat waves.

In urban settings where water risks are exacerbated and ecological degradation is particularly severe, blue-green infrastructure represents the backbone of ecosystem restoration interventions and Nature-based Solutions (Frantzeskaki et al 2019, Krauze and Wagner 2019, Wagner and Breil 2013). However, the implementation of NbS alone to reverse severely altered hydrological cycle and extreme ecological decline typical of urban areas is unrealistic. For instance, a channelized stream enclosed by a concrete shell with very low water quality because directly receiving contaminated waters from domestic waste and urban runoff can not sufficiently improve through restoration interventions and riverscape NbS such as depaving, connectivity and riparian vegetation restoration (Carbonari and Solari 2025). A traditional treatment of waste waters is also needed. In this case, as in many others such as piped drainage systems interspersed with bio-swales and SuDS ponds, residential developments with sunken rain gardens, buildings with green and blue roofs, the "blue-green + grey infrastructure" turns out to be the most effective, and due to its efficacy for water risks resilience it is becoming increasingly common (Li et al. 2023); within this framework, NbS represent the pathway to integrating conventional engineering structures with ecological solutions.

3.1. Some water management infrastructures can effectively integrate or be transformed into NbS and some other can not

The acknowledgement of the effectiveness of integrating blue-green infrastructures with grey ones for water risks management (Li et al. 2023) is the first step, then very careful consideration is needed in order to determine if an integrated design of new works or the design of retrofitting projects can achieve water management infrastructures that affectively include NbS. Actually, both the following issues are quite diffused: a certain resistance among local authorities and "traditional practitioners" in including more green, ecological and multipurpose solutions in conventional water management projects even if such innovation is feasible; on the other hand, above all subjects which are not in charge of practical applications tend to emphasize the use of NbS, in some cases overextending the range of applicability of such solutions with no sufficient attention to technical limitations. In the present section, we provide two emblematic examples: the first case illustrate multipurpose basins, which represent an example of infrastructure that actually can be implemented as NbS rather than traditional, grey solutions; the second example addresses constructed wetlands illustrating the limitations and ultimately the inapplicability in certain circumstances of the NbS for the treatment of waste water.

As an effective example of integrated green + grey solution we select the case of multipurpose basins: often artificial reservoirs are planned with the primary aim of fluvial flood mitigation but also designed in order to meet the community's needs for potable water, irrigation, energy as well as the ecosystems' requirement of improving ecological conditions. A first important ecological choice consists in preferring flood-mitigation basins as permanent waterbodies with increased, temporary water storage during flood attenuation, instead of dry detention basins flooded only during major floods. This choice provides a twofold ecological advantage: a valuable permanent wetland and the possibility of discharging water volumes from the reservoir to the river during lean periods. Moreover, vegetation can be included in the basin according to an integrated design; ecological flooding (i.e. flooding during events with minor return periods) can be easily supplied. It is obvious that an ecological implementation like ecological flooding requires the double of engineering works equipping the reservoir, for instance the spillway and the bottom outlet, but no technical impossibility prevents this choice. Overall, multipurpose basins can be designed and implemented (and retrofitted in case of grey structure conversion) as NbS since they answer several societal challenges, they can be designed according to ecological principles, but they also include indispensable engineering works such as mechanical devices and hydraulic structures.

The second example we select is that of Constructed Wetlands (CWs), a common Nature-based Solution for sustainable urban drainage consisting in engineered systems that mimic the function of natural wetlands to treat various type of contaminated waters through physical and biological processes. In all types of Constructed Wetlands, plants providing phytoremediation are always present and largely provide pollutants reduction before discharging water into natural water bodies or before aquifer recharge. Two main limitations are inherent to Constructed Wetlands compared to wastewater treatment plants (WWTPs), preventing CWs from achieving equivalent performance levels: i) CWs cannot provide the same consistent, high-quality treatment as WWTPs when subjected to a constant, high pollutant load (i.e. very large population equivalents), as they are less efficient in primary and secondary treatment; ii) for an equivalent pollutant load, CWs require a significantly larger land area than conventional plants, resulting in a lower overall "land use efficiency".

We finally want to point out that considerations similar to those illustrated for the two examples of this section must be carried out for each traditional engineering work for water management as well as for each SuDS and riverscape NbS; in any case when designing site-specific projects further insights about the above considerations are necessary taking into account local constraints.

4. Concluding remarks

NbS can represent a powerful tool to address water security challenges (such as water availability, flood risk, water quality aspects) also considering climate change which is typically increasing extreme events in both floods and droughts worldwide. NbS can, in some cases such as reservoirs and storage areas, be implemented in traditional engineering work for water management thus potentially providing relevant societal benefits.

While NbS can improve water risks resilience in urban settings, their functions in case of both extreme water events (floods and droughts), due to the lack of field evidence, can be uncertain; therefore, some caution needs to be paid in their design to avoid trade-offs or bad practices (Penning et al. 2025). Additionally, monitoring the effects of NbS on proper environmental indicators (related to both water quantity and quality) at various temporal scales is crucial to derive quantitative evaluations of their benefits and impacts.

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Policies and regulatory frameworks for urban and riverine nature restoration

Giulio Hasanaj, Costanza Carbonari, Lorenzo Nofroni

Abstract: The paper examines the evolution of policies concerning urban and riverine biodiversity at the global, European and national scales, with particular attention to the Italian context. At the international level, the Rio Conference (1992) marked the beginning of a process which, through the Convention on Biological Diversity (CBD), progressively integrated urban and riverine dimensions into conservation and restoration strategies. Subsequently, the Strategic Plan for Biodiversity 2011–2020 and the Kunming–Montreal Global Biodiversity Framework (2022) reinforced the role of cities and river areas as priority spaces within multilevel governance. In parallel, the European Union developed an increasingly binding body of legislation: from the Habitats and Birds Directives to the EU Biodiversity Strategy for 2030 and the *Nature Restoration Regulation* (2024), which introduces quantitative targets and reporting obligations also for urban ecosystems. In Italy, the regulatory trajectory reveals a gradual shift from sectoral approaches, centred on protected areas (Law 394/1991), towards integrated instruments for urban planning and management, such as Law 10/2013 on urban green spaces, the Minimum Environmental Criteria for public green areas, the National Biodiversity Strategy 2030, and, most recently, the National Climate Change Adaptation Plan. Nonetheless, significant challenges remain, including institutional fragmentation, weak integration between environmental, urban and climate policies, and the lack of effective monitoring tools. The study highlights how cities and surface watercourses are not merely sites of environmental impacts, but also spaces of opportunity for the implementation of Nature-based Solutions (NbS), capable of enhancing climate resilience, quality of life and social cohesion. The paper underscores the need to strengthen multilevel governance and participatory processes, promoting place-based approaches capable of adapting global and European objectives to local specificities. Urban and riverine nature constitutes a fundamental infrastructure for the ecological transition, yet the shift from ambitious goals to concrete action requires greater regulatory, institutional and design integration.

Keywords: Urban biodiversity policies, Biodiversity Strategy, Nature restoration regulation, Global Biodiversity Framework, Multilevel governance

1. Urban and riverine biodiversity: from the origin of the term to the global policy frameworks

The term *biodiversity* emerged as a contraction of *biological diversity* and was first introduced by Walter G. Rosen in 1985, in the context of preparations for the National Forum on BioDiversity. The worldwide dissemination of the concept is, however, attributed to Edward O. Wilson, who in 1988 published the volume *Biodiversity*, thereby establishing the term as standard usage within the scientific community. Formal recognition was achieved in 1992 with the Convention on Biological Diversity (CBD), adopted at the Rio de Janeiro Conference, which, in Article 2, defines biodiversity as «the variability among living organisms from all sources, including, inter alia, terrestrial, marine and freshwater ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems (UN 1992, p. 4)». Since that time, biodiversity conservation and restoration policies have evolved progressively, moving towards regulatory frameworks of increasing binding

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force and characterised by a growing recognition of the strategic role of cities and riverine ecosystems within multilevel governance structures (MASE 2023b).

Cities constitute central actors in biodiversity conservation and climate adaptation: in addition to hosting a large share of the global population, they exert significant pressures on ecosystems through land consumption, habitat fragmentation, pollution and the intensification of climate-related hazards (Seto, Güneralp, and Hutyra 2012). At the same time, they represent spaces of opportunity, capable of sustaining high levels of biological diversity through parks, gardens and surface water bodies, which provide vital habitats for numerous species (Aronson et al. 2014). These natural spaces within cities also delivers essential ecosystem services, including microclimatic regulation, air purification, cultural benefits such as recreation and place identity, and, in some cases, provisioning services linked to food and plant resources. (Elmqvist et al. 2015).

Within this framework, connections with the hydrographic network, or *blue infrastructure*, also acquire significance, implying an integrated approach in which the city is conceived as an inseparable component of the broader landscape (Wagner and Breil 2013; Krauze and Wagner 2019). Rivers, in particular, are regarded as the backbone of ecological restoration, yet they remain highly vulnerable to anthropogenic and climatic pressures: increasing water demand, rising temperatures, flow discontinuities and invasive species have accelerated the decline of freshwater biodiversity, at a rate faster than that observed in marine and terrestrial ecosystems (Dudgeon et al. 2006; Dudgeon 2019; Harrison et al. 2018). This is particularly evident in European rivers, which have lost connectivity and natural processes, especially in urban contexts.

Nevertheless, rivers, smaller watercourses and canals possess high ecological potential due to riparian zones and their function as ecological corridors connecting urban and peri-urban areas (Chester and Robson 2013; Carbonari and Solari 2025). They provide important regulatory and provisioning services, which restoration can further enhance. Managed across both rural and urban areas, watercourses enable the sustainable transfer of critical ecosystem services (Krauze and Wagner 2019; Basak et al. 2021).

At the policy level, the Kunming–Montreal Global Biodiversity Framework explicitly recognises cities as a priority domain, introducing through Target 12 the objective of increasing both the quality and the extent of urban green and blue spaces (CBD 2022). The European Union has likewise emphasised the urban and riverine dimension through the Water Framework Directive, the Biodiversity Strategy for 2030 (EC 2021c) and, more recently, the Nature Restoration Regulation (EC 2025a). In Italy, instruments such as the Environmental Code (Legislative Decree 152/2006), the Minimum Environmental Criteria (MATTM 2020), the National Biodiversity Strategy 2030 (MASE 2023b) and the National Climate Change Adaptation Plan (MASE 2023a) identify cities and surface water bodies as hotspots for promoting Nature-based Solutions (NbS) and initiating an effective ecological transition.

The paper analyses the evolution of policies and regulatory instruments for the protection of urban and riverine nature, situating the Italian case within the broader global and European frameworks. It demonstrates how the governance of urban and river biodiversity is shifting from sectoral approaches to an integrated model that recognises nature as strategic infrastructure for climate resilience, public health and social cohesion. The article adopts a chronological approach, tracing the temporal evolution of biodiversity policies from the global to the national scale, thereby constructing a multi-level framework and applying a spatially consistent perspective. Section 2 reconstructs the evolution of global environmental policies, from the Brundtland Report to the Convention on Biological Diversity and up to the Kunming–Montreal Global Biodiversity Framework, illustrating how cities and river areas have gradually been acknowledged as strategic actors and spaces for conservation and restoration. Section 3 examines the European framework, highlighting how the European Union has translated these principles into binding legal instruments, from the founding directives (Habitats and Birds) to the most recent strategies and regulations, culminating in the Nature Restoration Regulation, which introduces quantitative targets also for urban and river ecosystems. Section 4 focuses on the Italian case, emphasising the shift from sectoral legislation centred on protected areas to an integrated approach that frames urban nature and river networks as ecological infrastructures, through laws, environmental criteria and national strategies aligned with European directives.

The research draws mainly on scientific literature and secondary data sources (including articles from accredited journals, government reports, and legislative documents). The materials were gathered from carefully chosen academic databases and trustworthy sources, in order to ensure that the data are both reliable and relevant to the research themes.

2. Evolution of the global environmental policies from the Brundtland Report to the Kunming–Montreal Global Biodiversity Framework

The Brundtland Report, *Our Common Future* (1987), represents a milestone in global environmental policy. The document systematically introduced the concept of sustainable development, asserting the integration of economic, social and environmental dimensions within a unified perspective (Meadowcroft 2000). The Report played a dual role: on the one hand, it provided a shared theoretical framework and a common language; on the other, it served as the starting point for the Rio de Janeiro Conference of 1992, where its principles were translated into legal and programmatic instruments (Sachs 2015).

The Rio Conference marked the beginning of global environmental policies and led to the adoption of three fundamental conventions: the Convention on Biological Diversity (CBD), the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Convention to Combat Desertification (UNCCD) (UN 1992). However, the primary addressees of these policies were nation states; cities were not mentioned, and riverine areas appeared only in Agenda 21, Chapter 18, in relation to the protection of the quality and availability of freshwater resources, promoting integrated approaches to the development, management and use of water resources. The Brundtland Report thus constituted the epistemological and normative foundation that enabled multilateral consensus on binding treaties, paving the way for subsequent global frameworks, from *Agenda 2030* to the Kunming–Montreal Global Biodiversity Framework (Dodds et al. 2012; UN 2015).

A crucial milestone in nature policies was the Strategic Plan for Biodiversity 2011–2020 (SPB), adopted at COP 10 in Nagoya. Developed in response to the failure to achieve the 2010 targets (Butchart et al. 2010), the SPB introduced a measurable framework for action (CBD 2010a; Perrings et al. 2011). The vision *Living in harmony with nature* outlined the long-term goal, while the short-term mission called for urgent measures to halt biodiversity loss. At the core of the plan were the twenty Aichi Biodiversity Targets, grouped into five strategic areas ranging from the reduction of anthropogenic pressures to the integration of biodiversity into sectoral policies.

It was in this context that, for the first time, the CBD introduced an explicit reference to urban areas. Decision X/22 (CBD 2010b) initiated a phase of institutional inclusiveness, recognising cities, subnational governments and local communities as strategic actors (Puppim de Oliveira et al. 2011). It invited cities to develop Local

Biodiversity Strategies and Action Plans (LBSAPs) (CBD 2012), urged Parties to include local authorities within their National Biodiversity Strategies and Action Plans (NBSAPs), acknowledged the value of transnational networks (ICLEI 2011), and promoted local community engagement, emphasising the importance of educational programmes (CBD 2010b). Although many of the Aichi Targets were not achieved by 2020 (CBD 2020), the SPB laid the foundations for the subsequent Kunming–Montreal Global Biodiversity Framework (GBF), which expanded upon its structure by adapting it to the new post-2020 global agenda (UN 2015). Adopted in 2022, the GBF set as its central objective the protection of 30% of terrestrial and marine areas by 2030 (Target 3), extending the Aichi goals (17% terrestrial and 10% marine) and rendering the framework more ambitious and aligned with scientific recommendations (Lo and Jang 2022).

The new framework incorporates the *One Health* approach, which seeks to optimise sustainably the health of people, animals and ecosystems by recognising their interdependence (WHO 2021). It reaffirms the importance of local communities and, for the first time, designates urban areas as a strategic priority, in line with UN projections estimating that 68% of the global population will reside in cities by 2050 (UN DESA 2019). Target 12 establishes that conservation cannot be confined to protected areas but must integrate nature within the urban fabric through NbS that enhance ecological connectivity, climate mitigation, adaptation and social well-being (Kabisch et al. 2017; CBD 2022). Target 12 addresses a long-standing gap in the CBD, strengthening the role of cities as central actors in multilevel governance, translating the *One Health* paradigm into integrated urban policies, and providing the operational basis for the development of LBSAPs.

3. The European biodiversity policies: from the founding directives to the Nature Restoration Regulation

3.1. The foundational European legal framework for biodiversity protection: the Habitats Directive and the Birds Directive

Over the past three decades, European biodiversity policy has evolved along a regulatory trajectory that, beginning with the protection of habitats and species, has progressively incorporated more complex objectives of urban planning, ecological resilience and environmental restoration. The European Union's legal framework rests upon two historical pillars: the Habitats Directive (92/43/EEC) and the Birds Directive (2009/147/EC), which regulate conservation across the entire territory of the Union, including peri-urban and urban areas (CEU, 1992). The Habitats Directive introduced the protection of natural habitats and species of Community interest and established the Natura 2000 network, the largest coordinated network of protected areas in the world (CEU, 1992, Evans 2012). From an urban perspective, this network connects natural environments and anthropised contexts, encompassing peri-urban or transitional zones when relevant for habitats or species. In parallel, the Birds Directive regulates the protection of wild bird populations, safeguarding both migratory and resident species that breed or overwinter in urban contexts, while acknowledging the adaptation of many species to artificial landscapes (Donald et al. 2007). The deliberately broad wording of both directives makes it possible to include city parks, historic gardens, urbanized riverbanks and peri-urban woodlands within conservation policies, thereby reinforcing a concept of multilevel governance that integrates cities into the European ecological network.

3.2. The EU Biodiversity Strategy for 2030

The main reference framework for the current decade is the EU Biodiversity Strategy for 2030 (EUBS 2030), adopted in 2020 and integrated into the European Green Deal in 2021. It responds to global alarms concerning the state of nature: IPBES (2019) estimates that up to one million species are at risk and identifies habitat loss, pollution and climate change among the main drivers; the final evaluation of the Aichi Targets demonstrated that none of the twenty goals had been fully achieved (CBD 2020). At the European level, the review of the 2011–2020 Biodiversity Strategy showed that, despite the expansion of the Natura 2000 network, biodiversity loss had not been halted, in almost all environments, ranging from urban and agricultural ecosystems to aquatic ones (EC 2019a).

On this basis, the EUBS 2030 commits Member States to protect at least 30% of EU terrestrial and marine territory, aligning with the "30 by 30" target of the Kunming–Montreal GBF (CBD 2022); of this share, at least one third must be strictly protected. A second innovative commitment concerns the urban dimension: all cities with more than 20,000 inhabitants are required to adopt Urban Greening Plans (UGPs), with measures to expand green and blue spaces, improve ecological connectivity and contribute to well-being (EC 2021c), in line with the *One Health* approach and SDG 11 (Kabisch et al. 2017). UGPs are conceived as an overarching framework for "biodiversity-positive" and "climate-resilient" planning and design, integrating NbS across multiple sectors (Wilk et al. 2021). They aim to expand green and blue areas through parks, ecological corridors, green roofs and façades; reduce soil sealing; restore degraded urban ecosystems (canalised rivers, brownfields); and generate co-benefits for health, mitigation and climate adaptation (Kabisch et al. 2017).

UGPs are structured around three main design approaches: (i) conceiving buildings as part of the urban ecological network through green roofs, vegetated façades and sustainable urban drainage systems (SUDS); (ii) bioclimatic design and the integration of natural elements to reduce energy consumption, mitigate heat islands and improve comfort (Beatley 2016); (iii) resilient and ecological construction materials and solutions that foster permeability and renaturalization. This results in spatial planning oriented towards the development of green and blue infrastructures, recognizing corridors and natural areas as genuine structural infrastructures (EC 2013), promoting ecological regeneration of artificial spaces, adopting adaptive planning approaches to address climatic, hydraulic and health risks (EEA 2019), and at the same time ensuring environmental justice by guaranteeing equitable access to high-quality green spaces for all communities (Wolch, Byrne, and Newell 2014). UGPs, therefore, are not merely environmental instruments but an integrated planning framework, which nonetheless requires alignment with existing plans, measurable objectives and monitoring through SMART indicators harmonised with EU and international frameworks.

A third commitment of the EUBS 2030 concerns the restoration of freshwater ecosystems and in particular rivers, recognising their role in ecological regulation, water supply and the reduction of flood and drought risks (EEA 2019). Priority actions include river renaturalization and the removal of artificial barriers. Moreover, the strategy foresees a 50% reduction in the use and risk of pesticides by 2030, linked to the protection of pollinators and the quality of soil and water, in synergy with the Farm to Fork Strategy (EC 2021c). The 2030 Strategy thus transcends conservation in the strict sense, integrating biodiversity into urban, agricultural, energy and health policies and contributing to the European implementation of the GBF and the 2030 Agenda.

3.3. The Nature Restoration Regulation

With the approval of the Nature Restoration Regulation (NRR) in 2024, the EU introduced the first binding instrument for the large-scale restoration of urban, terrestrial and marine ecosystems. As a regulation, the NRR is directly applicable in all Member States and makes the long-term objectives of the EUBS 2030 legally binding (EC 2025a). Its purpose is the lasting recovery of biodiversity and ecosystem resilience, while contributing to climate change mitigation and adaptation, land degradation neutrality, food security and the fulfilment of international commitments. Quantitatively, it requires the implementation of restoration measures on at least 20% of urban, terrestrial and marine areas by 2030, extending to all degraded ecosystems by 2050 (EC 2025a).

The NRR sets binding objectives accompanied by precise temporal milestones: the improvement of 30% of degraded habitats by 2030, 60% by 2040 and 90% by 2050. It further requires Member States to prepare a National Restoration Plan by 2026, to be formally adopted by 2027, and introduces a particularly rigorous monitoring and reporting system, based both on standardised indicators—such as urban tree cover, pollinator status and wildlife indices—and on satellite data from the Copernicus programme (EC 2025a).

The NRR identifies seven priority areas: (1) terrestrial, coastal and freshwater ecosystems; (2) marine ecosystems, with a focus on high-carbon storage habitats and breeding grounds; (3) river connectivity and floodplains; (4) pollinator populations; (5) agricultural ecosystems, including drained peatlands and landscape diversity; (6) forest ecosystems, with the objective of three billion trees by 2030; and (7) urban ecosystems. For the latter, the NRR requires no net loss of green space and tree cover by 2030 (relative to 2024 levels) and a subsequent progressive increase, to be defined through national benchmarks (by 2030) and an EU methodological framework (by 2028). Member States must map urban ecosystems by 2026, identify priority areas, and integrate NbS into urban planning and architectural design (EC 2025a).

As early as 2021, the European Commission had published guidelines and a toolkit for Urban Nature Plans (UNPs) to support the integration of nature into urban planning in line with the EUBS 2030 (EC 2021a; EC 2021a). The UNP guidelines propose a ten-step process—from political commitment to governance, from co-creation to vision, from state analysis to indicators, from the selection of actions to financing, and finally communication, monitoring, adoption and implementation—promoting an integrated and interdisciplinary approach (Federal Agency for Nature Conservation 2024; NetworkNature 2021). The operational toolkit translates the strategy into concrete interventions (green roofs and façades, ecological corridors, urban forests, community gardens) with clear climatic, environmental and social co-benefits (EC 2021a).

For rivers and freshwater ecosystems, the NRR establishes the restoration of connectivity and ecological functioning, with the objective of achieving at least 25,000 km of free-flowing rivers by 2030 compared to 2020. Article 9 provides for an inventory of barriers (9.1), the removal of obsolete or unnecessary ones (9.2), and the restoration of lateral connectivity and floodplain functions (9.3–9.4). Among the innovative elements introduced by the NRR with regard to river and freshwater ecosystems are the establishment of specific quantitative targets for rivers and floodplains, the adoption of a broad-scale perspective for assessment and restoration interventions, the extension of restoration goals beyond the boundaries of Natura 2000 sites (EC 2008), and, finally, the emphasis not only on conservation but also on the recovery of the most degraded habitats (Stoffers et al. 2024).

However, the NRR also presents intrinsic weaknesses for these ecosystems. The main issue concerns the absence of clear criteria for determining which rivers should be prioritised for restoration (Stoffers et al. 2024). Article 9.2 suggests the removal of obsolete barriers, such as those no longer required for hydropower, water supply or flood protection. Yet this approach does not ensure that interventions focus on areas where the benefits for ecosystems, water resources and ecosystem services would be greatest. It also leaves unresolved whether priority should be given to restoring highly degraded urban reaches or safeguarding rural watercourses with better ecological conditions and greater potential.

Another limitation relates to harmonisation with other European policies. While synergies exist, conflicts also emerge due to competing uses of water resources (Stoffers et al. 2024). The most significant include those with the Common Agricultural Policy (EC 2012), which, through subsidies for intensive practices and water-demanding crops, damages habitats and water resources, and with the Renewable Energy Directive (EPCEU 2018), which recognises hydropower as an activity of public interest, even though it entails the construction of dams contrary to river connectivity restoration.

Interactions with the Water Framework Directive (EPCEU 2000) are particularly significant. This directive, based on a river basin approach, aims to achieve good ecological status and ecological flows (EC 2016), objectives consistent with the NRR. However, measures to address drought and water scarcity, such as new dams and reservoirs, risk undermining connectivity itself (EC 2015). Similarly, the Floods Directive (EPCEU 2007), while aiming to reduce risks, often promotes rigid engineering works that hinder ecological restoration, particularly in urbanized contexts.

A way forward in overcoming such conflicts could lie in the adoption of Natural Water Retention Measures (Burek et al. 2012; EC 2014; EC et al. 2015), which offer more nature-based alternatives compared to grey infrastructures. Nonetheless, their application remains marginal, as Member States continue to prioritise traditional approaches that are poorly integrated with NbS (EC 2025b).

Overall, from the Habitats Directive to the NRR, the EU has constructed a progressive framework which, moving from the protection of habitats and species, now extends to urban strategies, water management and binding restoration measures. This represents a paradigm shift: biodiversity is no longer regarded as a heritage confined to natural areas, but as a structural component of cities and anthropised ecosystems, intrinsically linked to health, well-being and climate resilience. Alongside quantitative targets (e.g. urban green cover), ensuring the ecological quality of spaces (Klaus et al. 2025) remains central, as an essential condition for the actual effectiveness of the new regulatory framework.

4. Italian biodiversity policies: from the proliferation of sectoral laws to harmonisation with European directives

4.1. The Italian regulatory pathway towards the Environmental Code

Biodiversity protection in Italy has undergone a progressive regulatory and strategic consolidation which, from the 1990s to the present, has increasingly incorporated the urban dimension and the role of NbS in spatial planning and architectural design.

Law No. 394/1991 constitutes the first comprehensive reference on protected natural areas: it established national and regional parks and nature reserves, while also envisaging urban parks and local protection areas with the dual purpose of safeguarding ecosystems and enhancing green spaces for quality of life in cities (MATTM 2016; Legambiente 2021; NBFC 2023). Nevertheless, the law was shaped by a predominantly territorial conception of conservation, without fully embedding an integrated framework for environmental management.

Towards the end of the 1990s, EU alignment reshaped the architecture of national environmental policies. On the one hand, the Habitats and Birds Directives were transposed, leading to the establishment of the Natura 2000 network; on the other, a range of sectoral regulations on waste, remediation and water were introduced, although this generated a fragmented framework (ISPRA 2023).

The first comprehensive codification of environmental matters in Italy, harmonising VAS and VIA, water protection, waste and remediation, air and soil, is the Environmental Code (Legislative Decree 152/2006). Although not directly aimed at urban biodiversity, the Code introduced cross-cutting instruments with implications for green space planning and for reducing ecological fragmentation in urbanised contexts, and has evolved over time to align with EU legislation (Sassone 2014). It is within this Code that the Water Framework Directive is transposed, which introduced a management system based on district basin authorities responsible for the preparation of integrated management plans (MASE n.d.). The Floods Directive was transposed through Legislative Decree 49/2010 (MASE n.d.). Nevertheless, at the national level conflicts persist between restoration measures, land uses and existing infrastructures, linked to competing demands on water resources and ongoing land consumption.

A peculiarity of the Italian context is the excessive fragmentation of competences, distributed among a multiplicity of bodies with differing mandates and authorities. This fragmentation, further compounded by a stratification of instruments, generates uncertainty regarding responsibilities and the scope of intervention, and fails to ensure adequate coordination between planning, programming and implementation. The result is a marked disconnection between those who formulate strategies and those tasked with implementing and monitoring them, with negative repercussions for the effectiveness of interventions.

4.2. The contributions of Law 10/2013, the Minimum Environmental Criteria and the National Integrated Energy and Climate Plan

Since 2010, alongside "hard law", a new phase of strategies and policies for urban ecosystems has emerged. Between 2011 and 2020, Urban Green Plans (UGPs) and local strategies became widespread, also through networks such as Local Agenda 21, while many municipalities experimented with regulations and integrated ecological plans that recognise the city as a complex ecosystem in which green and blue infrastructures support regeneration (CSVP 2019). Within this context lies Law 10/2013, "Provisions for the development of urban green spaces", a key reference for the management and enhancement of urban nature. The law recognises the multifunctional role of urban green spaces (climate regulation, pollution reduction, biodiversity conservation, well-being) and promotes the notion of green as ecological infrastructure, rather than mere ornament (Salbitano et al. 2016).

Among its measures, the law introduced the obligation for municipalities with more than 15,000 inhabitants to undertake tree censuses and encouraged the promotion of UGPs, although without formal obligation (MTE 2017), as well as educational initiatives (e.g. "National Tree Day") and citizen engagement. Nevertheless, limitations persist: the absence of shared operational standards, uneven implementation, weaknesses in monitoring and indicators, as well as poor integration with urban planning, resulting in territorially heterogeneous outcomes (Hasanaj et al. 2025). Although it did not introduce a generalized obligation for UGPs, the law anticipated orientations later reinforced at European level by the EUBS 2030 and the NRR, marking a cultural shift towards conceiving nature as ecological infrastructure for adaptation and social cohesion.

Another significant milestone is the Ministerial Decree of 10 March 2020, which introduced the Minimum Environmental Criteria (CAM) for the design, implementation and maintenance of public green areas and for the supply of products for green care. Mandatory for all contracting authorities, the CAM reduce the environmental impact of urban green spaces by orienting them towards biodiversity conservation, water and energy efficiency, and low-impact management (MATTM 2020). The objectives include the use of native species and the limitation of invasive ones, the ecological and climatic functions of green infrastructures, sustainable maintenance, reduction of pesticides and efficient use of water.

The CAM specify requirements for the different phases of design (use of local species, climate resilience, reduction of soil sealing, connectivity), implementation (protection of soil fertility, sustainable materials, SUDS), and management (reduced pesticide use, organic practices, efficient irrigation). As a result, sustainability in urban green procurement becomes a binding requirement, influencing both administrations and designers, while also aligning with the EUBS 2030 and the National Biodiversity Strategy 2030.

Within the CAM, references to blue infrastructure are very limited. Water is considered primarily in relation to plant irrigation and the water requirements of different species; it is further mentioned in connection with NbS such as sustainable drainage systems (e.g. rain gardens, bioretention channels), the use of which is recommended. The only NbS relating to riverine landscapes that is briefly mentioned in the CAM is riverbank bioengineering. There is no recommendation regarding the use of the wide variety of NbS for riverine landscapes (such as riparian vegetation restoration, natural wetlands restoration, artificial wetlands; see Carbonari and Solari 2025), nor is the issue of water bodies, their ecological functioning and the restoration of connectivity with the surrounding landscape addressed.

Nevertheless, the CAM standardize practices and consolidate the vision of green and blue as ecological infrastructures delivering environmental, social and climatic benefits (Alatri 2023).

Urban biodiversity also intersects with energy and climate policies: the National Integrated Energy and Climate Plan (PNIEC), although not explicitly focused on urban biodiversity, links ecological transition with nature conservation. Decarbonisation measures and the reduction of greenhouse gas emissions contribute to mitigating the effects of climate change, one of the principal threats to urban ecosystems (EC 2019b). Furthermore, interventions in energy efficiency and urban regeneration can support the integration of green and blue infrastructures and the widespread use of NbS, thereby enhancing ecological resilience and environmental quality (Frantzeskaki et al. 2019). Embedded within the framework of the Green Deal and the EU Biodiversity Strategy for 2030, the PNIEC thus contributes to strengthening the coherence and interdependence among climate, energy and environmental policies (MASE 2024).

4.3. The National Biodiversity Strategy 2030 in Italy

The National Biodiversity Strategy 2030 (SNB 2030) constitutes the instrument through which Italy transposes the commitments undertaken at the international level under the CBD and at the European level through the EUBS 2030 and the Green Deal (MASE 2023b). Approved in 2022, the strategy is considering for the first time cities as complex ecosystems, and acknowledges the need to safeguard and enhance biodiversity even in highly anthropised contexts. From this perspective, it integrates urban green and blue areas into the national ecological network and reinforces the contribution of the Natura 2000 network.

Action B10 constitutes the cornerstone of the strategy for urban and peri-urban ecosystems, structured along three main axes.

The first (B10.1) foresees the expansion of urban and peri-urban greenery through the creation and management of woodlands, parks and ecological corridors, the implementation of greening plans in cities with more than 20,000 inhabitants, and the diffusion of NbS such as green infrastructures, green roofs and façades, SUDS and urban gardens. These actions are coordinated with the National Urban Green Strategy, with European initiatives such as the Green City Accord, and with the application of the CAM in procurement (MASE 2023b).

The second axis (B10.2) focuses on halting urban biodiversity loss, promoting tree censuses, biodiversity atlases and sustainable management practices. Priority measures include de-sealing interventions, the reduction of pesticides and biocides, the limitation of intensive mowing, and the strengthening of municipal resources for green space management. Citizen involvement is also significant, through citizen science initiatives and the promotion of pollinator-friendly plant species (MASE 2023b).

The third axis (B10.3) concerns the integration of NbS into urban planning, through innovative administrative and financial instruments, including support from private investment. The strategy also encourages the adoption of standardised monitoring systems to assess the benefits of NbS in terms of climate adaptation, pollution reduction, urban well-being and new governance models (MASE 2023b).

In the hydraulic–fluvial domain, Action B.11 of the SNB 2030 addresses the restoration of freshwater ecosystems and the natural functions of water bodies, setting the objective of achieving "good status" by 2027 in line with the Water Framework Directive. This is complemented by other actions, including A.3, B.2, B.8 and B.10, related to aquatic biodiversity, pollutant reduction and the mitigation of natural risks, particularly hydraulic risks. Significantly, the Strategy devotes considerable attention to the physico-chemical and abiotic dimensions of ecosystems, since ecological restoration can only be considered complete if the anthropogenic pressures responsible for degradation are addressed (Carbonari and Solari 2025).

4.4. Biodiversity and climate change in urban processes for ecological regeneration and vulnerability reduction

With the approval of the National Climate Change Adaptation Plan (PNACC) in 2023, Italy introduced a framework for climate adaptation that integrates biodiversity into urban and territorial planning processes, promoting ecological regeneration, NbS and measures to reduce the vulnerability of cities to extreme events. The plan identifies urban settlements as climate risk hotspots due to the concentration of population, infrastructures and services: heatwaves, floods, droughts and air pollution affect urbanized areas with particular intensity (MASE 2023a).

To address these challenges, the PNACC proposes integrated actions combining environmental, social and planning dimensions. A priority is the reduction of urban heat islands through the increase of tree cover, the expansion of green infrastructures (parks, green roofs and façades, tree-lined avenues) and the use of reflective materials to reduce thermal accumulation. A second area concerns the sustainable management of rainwater, with the adoption of SUDS and the renaturalisation of urban and peri-urban watercourses, aimed at mitigating hydraulic risk and restoring ecological dynamics (EC 2021b). A third strand is the ecological regeneration of degraded and abandoned areas, through renaturalisation interventions and the expansion of accessible green spaces centred on NbS. Finally, the plan emphasises the integration of adaptation criteria into urban planning, promoting coherence with existing instruments and strengthening synergies with the CAM (MATTM 2020).

However, despite the relevance of urban spaces, the PNACC exhibits significant limitations: of the 361 actions envisaged, only 46 are related to green infrastructure, highlighting the limited valorisation of NbS, which are also presented in generic terms and without technical or design detail. The planning process appears weakly integrated, with postponements and poorly defined priorities, while multilevel governance remains fragmented and responsibilities insufficiently specified. Finally, there is an urgent need to improve monitoring and objectives by introducing measurable targets, defined financial resources and greater alignment with European instruments such as the NRR and the EUBS 2030 (ASviS 2023).

Overall, the evolution of Italian regulation illustrates the shift from a protection model centred on traditional protected areas to a systemic vision in which urban biodiversity is a structural component of environmental, urban and climate policies. UGPs, CAM for public green areas, the SNB 2030 and the PNACC mark a paradigm shift: the city is no longer conceived in opposition to nature, but as a space to be regenerated through ecological infrastructures and integrated solutions oriented towards well-being and resilience.

5. Challenges and needs for the policy integration of biodiversity in the urban and riverine environment

The regulatory and strategic evolution at the global, European and national levels reflects a paradigm shift: biodiversity is no longer understood solely as a heritage to be preserved within protected areas, but as a fundamental infrastructure also within urban spaces, capable of delivering multiple benefits in terms of climate resilience, health, quality of life and social cohesion (NBFC 2023). Nonetheless, critical issues persist, linked to the fragmentation of competences and the difficulty of translating ambitious objectives into integrated, measurable and effective actions (Hasanaj et al. 2025).

The governance of urban biodiversity, as with climate governance, suffers from structural limitations: fragmentation, weak multilevel mechanisms and limited continuity in participatory processes. Since each city presents specific economic, social and environmental conditions, there are no universal rules for nature restoration; rather, place-based approaches are required, capable of integrating local economies and ecologies and of actively engaging stakeholders (Alberti et al. 2025).

Against the backdrop of an increasingly articulated European and national regulatory framework—which includes binding instruments such as the EU Biodiversity Strategy 2030 and the Nature Restoration Regulation (EC 2021c; EC 2025a)—Italian local policies and plans often remain fragmented and sectoral. In urban planning, ecological objectives are predominantly declarative, lacking operational tools and monitoring indicators; in urban projects, biodiversity is treated as an accessory element rather than as a central ecological infrastructure, confirming a "dis-integrated" approach. This highlights the need for greater alignment between global, European and local policies, alongside the strengthening of planning, monitoring and civic engagement instruments, in order to make urban biodiversity an integral part of the ecological transition (Lapenna et al. 2024).

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SECTION 2

Topics and Applied Methodologies

Nature and Culture-based Solutions for urban and territorial regeneration: governance models and tools

Giuseppe De Luca

Abstract: The paper advances an evolutionary reading of Nature-Based Solutions (NbS) towards Nature and Culture-based Solutions NCbS, conceived as bio-technological and cultural devices that trigger systemic processes of urban regeneration. The challenge, it argues, is not to reproduce nature but to govern hybrid systems in which humans are active and co-responsible components. This entails moving beyond the paradigm of ecological transition towards that of ecological conversion, grounded in reciprocity between society and the environment. NCbS requires collaborative, adaptive, and multi-level governance capable of integrating institutions, communities, and plural knowledge. The paper introduces the figure of the reflective ecotechnician, a professional who combines technical competence with ethical responsibility. NCbS thus emerge as ecological and cultural commons, instruments of territorial and ecological justice, and cornerstones of a transformative urbanism linking planning, care, and political imagination. Only through reflective and inclusive governance can planning transform transition into conversion, regenerating both the city and the very forms of human coexistence.

Keywords: Collaborative governance, Nature and Culture-based Solutions, Socio-ecological regeneration, Transformative urbanism, Ecological justice.

1. From Ecological Design to Systemic Governance

In recent years, NbS has emerged as one of the most promising strategies for addressing, in an integrated way, the environmental, social, and climatic challenges of contemporary cities.

The definitions provided by UNEA and the European Commission – describing NbS as *solutions inspired and supported by nature, cost-effective and capable of generating multiple benefits* – highlight their function as integrated actions aimed at protecting, conserving, and regenerating ecosystems. Yet, their true strength does not lie in the *naturalness* of their materials, but in their ability to generate ecological relationships among space, society, and technology. This reveals their transformative potential compared to merely engineering approaches: no longer punctual devices, but systemic and regenerative levers.

For this very reason, NbS face a structural paradox: while they have matured in technical and design terms, they often struggle to produce lasting effects where appropriate institutional conditions are lacking.

The challenge, therefore, is not to reproduce nature but to govern hybrid systems of which humans are active and co-responsible components. NbS thus become both ecological and social infrastructures – bio-technological and cultural devices that sustain territorial regeneration through adaptive and cooperative processes.

Their effectiveness depends, consequently, on governance and instruments capable of ensuring maintenance, cross-sectoral coordination, informed participation, and long-term co-production. No longer an *accessory green*, but structural infrastructures of urban transformation, endowed with their own spatial, functional, and symbolic logic.

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They do not operate in a vacuum: they require coordinated policies, coherent planning tools, stable financial models, and an administrative culture capable of mediating among disciplines, actors, and scales.

The shift from a *design* approach to one of *governance* implies recognising that ecological and social challenges cannot be solved through individual interventions but through institutional ecosystems that enable continuous processes of regeneration.

From this stems the dual proposal advanced in this text: both a conceptual and substantial evolution towards *Nature and Culture-based Solutions* (NCbS) and, at the same time, a move beyond the paradigm of *transition* to embrace that of *conversion*.

Including the cultural dimension does not mean adding a rhetorical embellishment, but rather acknowledging that nature – especially urban nature – also embodies intangible values, identities, practices, and narratives constructed over time and *naturally* embedded in the physical heritage.

Moving towards the paradigm of conversion, beyond transition, means essentially passing from a society centred on human dominance to one centred on a balanced relationship between humans and nature. This perspective has been particularly developed in theological contexts (Francesco 2015; Cassibba and Quadrelli 2021; Ormerod and Vanin 2016).

Here, however, it is interpreted in a secular sense (De Luca 2019), as an *act of humility and responsibility* (Latour 2017) and, above all, as an *active form of resistance to the collapse of modern civilisation* (Stengers 2015) – in the end, a conversion of thought and perception, and the construction of a new and desirable narrative of the world (Wieland et al. 2023), partly in the wake of a territorial principle (Magnaghi 2020), which calls for a co-evolutionary relationship between humans and nature.

In contemporary debates on the relationship between society and environment, the terms *ecological transition* and *ecological conversion* are sometimes used as synonyms belonging to the same logical-argumentative continuum. In reality, they express two distinct – epistemological, cultural, and operational – visions of the change required to shape a different future.

At the epistemological level, transition relies on quantitative and functional knowledge, whereas conversion invokes relational and reflexive knowledge. The former mobilises engineers, economists, and planners; the latter engages educators, theologians, philosophers, but also citizens and local communities. They are two complementary ways of responding to the ecological crisis: transition acts *upon* systems, conversion acts *within* systems and subjects.

At the cultural level, the difference is even more evident. Transition retains a modernist and technocratic framework: change is managed, measured, and optimised. Conversion, by contrast, recentres the principles of care, sobriety, and fraternity with other species, proposing a reconsecration of the world as our common home. It is a bottom-up, generative change that treats the ecological question not merely as a technical problem, but as a crisis of meaning.

From this standpoint, NCbS – within the paradigm of conversion – can assume the role of common goods, generating belonging, care, and ecological justice, thus strengthening social cohesion, attachment to place, and community spirit.

While, at the technical and operational level, transition translates into plans and strategies (decarbonisation, circular economy, green infrastructures, energy transition), conversion, on the contrary, is expressed through everyday practices, educational and communal pathways, and new ways of inhabiting and designing. In planning terms, this means shifting from a planning that *manages* sustainability to one that *builds* reciprocity between society and environment, between the built and the living.

For this shift to occur, however, a new form of governance is required – one able to guide and orient urban and territorial transformation.

2. Governance as an Enabler: Models, Actors, and Transformative Capacity

The forms of governance applicable to NbS are manifold, yet they converge on one central idea: no single actor can face the complexity of urban transitions alone. What is needed are collaborative, adaptive, and multi-level models capable of facilitating dialogue among institutions, citizens, businesses, and the research world.

Their transformative capacity depends on government devices that coordinate policies, mobilise heterogeneous actors, stabilise shared visions, and guarantee continuity over time.

Rather than *governing NbS*, it is necessary to rethink urban governance starting from NCbS.

Let us see how.

2.1. Collaborative Governance: From NbS to NCbS

Collaborative governance is founded on co-production among public, private, and civic actors, and on the construction of common goods. It is particularly effective at the neighbourhood or district scale, where the direct involvement of communities fosters belonging, stewardship, and shared maintenance.

However, it is not without challenges: it requires trust, management of power asymmetries, adequate timeframes, and above all institutionalisation – mandates, resources, rules, and accountability – to prevent it from remaining episodic.

The extension towards NCbS strengthens this framework, as they connect nature with social practices, heritage, and symbols, generating *eco-cultural commons*. In this sense, models inspired by plant biology – distributed networks, adaptability, mutualism – help to imagine cities as resilient organisms, with horizontal and cooperative governance.

Typical tools include: participatory (and digital) mapping that merges ecological and cultural data; co-design laboratories; integrated management plans for open spaces; and policies protecting urban cultural landscapes.

This reading, in dialogue with biomimetic metaphors – the city as a cooperative and adaptive organism – shifts the focus from the technical solution to the relational system that keeps it alive, incorporating the issue of proximity to individual and collective services into co-design as a key driver of this approach.

2.2. Adaptive Governance

NCbS are living elements: they require monitoring, feedback, and continuous learning. Adaptive governance institutionalises iterative cycles – experimentation in living labs, participatory evaluations, updates of plans and standards – and values the management of uncertainty.

However, this demands robust inter-institutional capacities, shared metric bases (microclimate, energy, ecosystem services), and an administrative culture that treats error as an opportunity for learning.

2.3. Hybrid and Multi-Level Governance

In practice, hybrid and multi-level arrangements prevail, combining collaboration and adaptability within broader institutional systems.

Vertically (municipality–metropolitan city–region–state–EU) and horizontally (across sectors and actors), the governance of NCbS requires coordination mechanisms that overcome compartmentalisation.

These can take the form of sustainability-oriented public–private partnerships, inter-municipal consortia, transformation agencies, multi-stakeholder platforms, or intermediate institutions capable of translating territorial complexity into coordinated action.

Experiences beyond the European context further illustrate the diversity of governance arrangements supporting nature-based urban transformations. In Latin America, community-based territorial governance inspired by the Buen Vivir paradigm has connected ecological restoration with social participation and cultural values (Escobar 2020; Gudynas 2011). In Asia, large-scale programmes such as China's Sponge City initiative demonstrate how adaptive governance can institutionalise nature-based infrastructures through coordinated planning and monitoring (Li et al. 2017). In African cities such as Durban, ecosystem-based adaptation strategies have combined biodiversity protection, climate resilience and community stewardship within municipal governance frameworks (Roberts et al. 2012). These experiences suggest that NBS governance can emerge through different institutional trajectories–community-driven, state-led or hybrid–while converging around collaborative and adaptive approaches.

3. Key Actors and Transformative Capacity

Success depends on the interaction among multiple actors: local administrations, called upon to integrate ecological, design, and relational competences; communities and citizens, as co-producers of value and stewards of shared spaces; the third sector, as a catalyst for social innovation; universities and research centres, for their knowledge bases, archives, and technical as well as theoretical expertise; and the private sector, through green finance, social responsibility, and measurable impacts.

What matters is not only *who participates*, but *how* they interact: shared visions, coordination tools (intersectoral roundtables, river contracts, integrated plans, participatory budgets), clear responsibilities, and stable resources turn isolated interventions into collective infrastructures.

Thinking in terms of NCbS means referring to everything that roots and sustains a solution over time: the ensemble of practices, local knowledge, care forms, and behavioural models that make both the built and surrounding environment part of a shared ecosystem.

NCbS may therefore represent the convergence of three inseparable planes:

a) the **ecological-technical**, concerning environmental performance and ecosystem services;
b) the **social**, based on participation, co-design, and community responsibility;
c) and finally the **cultural**, understood as the recognition of symbolic and immaterial values, identities, and relationships that motivate care for places, restoring meaning to the local proximity between homes and services as a fundamental component of living.

At this point a key question arises: which professional figure can assist this conversion? Which *institutional design* can translate ecological strategies into normative, fiscal, and managerial instruments within urban and territorial policies?

Such a figure could be termed a "Reflective ecotechnician", following Schön (1983) and his notion of professional reflexivity; or a "Sensitive ecotechnician", drawing on Escobar (2017) and Davoudi (2015) – someone who, combining the ability to measure with the ability to listen, can operate across environmental humanities, landscape governance, eco-urban design, and public participation.

In both cases, this is a form of territorial curator: a professional who combines technical expertise with ethical responsibility, connecting nature, society, and meaning.

The key ethical principles within an *ecotechnical* perspective include:

- *Social responsibility*: the duty to consider the needs and interests of all members of society, particularly marginalised and vulnerable populations, and to promote social justice and equity in policy planning decisions.
- *Environmental sustainability*: the effort to minimise the negative environmental impacts of development and to promote sustainable practices in land use, transport, and resource management.
- *Transparency and accountability*: operating transparently and involving the public in planning processes to ensure that decisions are made openly, fairly, and responsibly.
- *Integrity and professionalism*: maintaining high ethical standards in professional conduct, including honesty, fairness, and impartiality, and avoiding conflicts of interest or even their appearance.
- *Long-term vision*: considering the long-term consequences of decisions and aiming to create resilient, adaptable communities capable of thriving amid future challenges such as climate change and demographic shifts.
- *Cultural sensitivity*: respecting and incorporating diverse cultural perspectives and heritage in the planning process, recognising the importance of identity and cultural heritage in community formation.
- *Legal compliance*: adhering to laws, regulations, and professional codes of conduct that govern institutional activities, ensuring that actions are both legitimate and ethical.

4. Tools for Integrating NCbS into Policy-Making

Making NCbS effective, from an *ecotechnical* perspective, means working across strategies, rules, finance, and collaboration.

The goal is twofold: to make them structural within the language and fabric of plans, and to provide flexible, enabling tools for complex and evolving projects.

4.1. Integrated Planning and Systemic Vision

Traditional planning, often sectoral and rigid, struggles to capture the dynamic nature of NCbS.

The most advanced experiences adopt integrated frameworks: green and blue infrastructure strategies, climate adaptation plans, ecological networks, and multiple corridors in which NbS guide transition and connect cohesion with regeneration.

In Italy, the newest general plans are beginning formally to recognise the role of NbS within the plan's structure, but they still occupy a secondary position compared to land-use regulation.

4.2. Normative and Regulatory Instruments

To give NCbS binding strength, it is necessary to:

- introduce minimum standards (permeability, ecological surfaces, green endowments);
- provide obligations or incentives for green roofs and façades, SUDS, and tree-lined corridors;
- activate ecological equalisation and compensation mechanisms to engage private operators.

Building and urban green regulations can reward ecosystemic performance and environmental quality; international *green codes* demonstrate how to integrate such requirements into urban standards.

The key lies in linking rules to measurable indicators and ex-ante/ex-post evaluations.

4.3. Financial and Fiscal Instruments

Fragmented funding remains a recurrent obstacle.

A diversified *policy-mix* is needed – including green bonds, European and national funds, public–private partnerships oriented towards measurable impacts, fiscal incentives, and *Payments for Ecosystem Services* (PES).

Integration with circular economy principles – local supply chains, reuse, reduction of operational expenditures along the life cycle – reinforces the economic sustainability and managerial durability of NCbS.

4.4. Participatory and Collaborative Instruments

The collaborative dimension is a key enabler: partnership agreements, participatory budgeting, community monitoring protocols, citizen science, *ecological citizenship agreements* and *revitalisation of local services*.

These are not mere accessories but structural components of design, especially in fragile contexts.

Their institutionalisation prevents engagement from remaining episodic and ensures continuity of care.

5. Recurrent Challenges

NCbS are not an automatic remedy. Certain challenges recur frequently and demand governance antidotes:

- *Greenwashing and technocratic simplification*: the risk lies in using *green* as a narrative ornament or reducing complexity to standardised metrics, neglecting local contexts and cultures. The antidote is a set of measurable objectives linked to explicit social and cultural values, with transparent monitoring.
- *Institutional fragility*: weak or fragmented institutions, political discontinuities, and normative instability undermine coherence and longevity. Intermediate institutions, multi-year mandates, and multi-level coordination mechanisms are required.
- *Environmental injustices and green gentrification*: without redistributive design, NbS may increase rents and displace vulnerable populations. Key questions are: who decides, who benefits, and how is access ensured? Answers lie in territorial equity criteria, the *just green enough* principle, and structural participation practices.
- *Maintenance, management, monitoring*: the weak point is often not implementation but what comes after. NbS demands differentiated care, adaptation, and long-term evaluation. Ecosystem performance contracts, dedicated funds, and structured feedback systems are necessary.
- *Local vs systemic scale*: NCbS work when they are place-based, but to exert real impact they require metropolitan coordination and networked action. The tension can be resolved through multi-scalar architectures connecting micro-participatory interventions with urban ecological infrastructures.

6. Towards a Transformative Urbanism

The transformative potential of NCbS lies not only in their technical or environmental dimensions, but in their capacity to regenerate relationships among nature, society, and institutions.

They invite a different understanding of urbanism: no longer a prescriptive discipline, but a transformative, reflexive, and relational practice.

Transformative urbanism arises when planning becomes a space of collective learning and co-production among actors – where scientific knowledge intertwines with situated knowledges and the cultural fabric of places.

In this perspective, transformative urbanism represents the operational translation of the paradigm of *ecological conversion*: a passage from a system that *designs* sustainability to one that *builds* reciprocity between human and non-human environments.

It is a way of planning that embraces complexity as a generative condition, values difference and uncertainty, and recognises the plurality of knowledge and agencies inhabiting territories.

Within this framework, NCbS become *living infrastructures of conversion*, connecting care, ecological justice, and political imagination.

Such urbanism does not merely *mitigate* environmental impacts, but promotes systemic transformations – of the urban metabolism, of administrative culture, and of collective imaginaries.

Its strength lies in activating adaptive and collaborative processes that connect design, governance, and participation, reconfiguring the city as an ecosystem of relationships rather than a functional machine.

In this sense, *designing with nature* also means *designing with society* – with its conflicts, vulnerabilities, and aspirations.

A transformative urbanism is therefore:

- *Ecological*, as it regards the city as part of a living continuum and recognises biophysical limits as project resources;
- *Cultural*, as it values material and immaterial heritage, practices of care, and local identities as structural components of regeneration;
- *Collaborative*, as it grounds its effectiveness in the interaction between institutions, communities, and plural knowledges;
- *Ethical and reflexive*, as it connects technical responsibility and social sensitivity, translating design action into public responsibility.

From this viewpoint, NCbS become keystones of a new urban metabolism, mediating between physical and social infrastructures, between natural and relational capital.

Through them, urbanism regains its original political dimension: not only regulating land use but orienting the transformation of ways of living and coexisting.

NCbS thus appear as *ecological commons* and *devices of citizenship*, tools for redistributing access, opportunity, and well-being, and for promoting ecological justice as territorial justice.

Transformative urbanism cannot be measured solely by spatial outcomes, but by its ability to foster collective learning and mutual responsibility.

It is an urbanism that unites technical competence and cultural sensitivity – in line with the figure of the *reflective ecotechnician* described earlier: a professional able to listen to the territory, translate complexity, and build alliances among nature, technology, and community.

In this sense, planning becomes again a public and dialogical art, capable of generating meaning, trust, and shared care.

Only such an urbanism can transform NCbS from environmental experiments into enabling urban policies – capable of reorienting territorial transformation according to principles of conversion, justice, and ecological responsibility.

7. NCbS as frontiers of contemporary territorial governance

Today, NCbS represent one of the most advanced frontiers of contemporary territorial governance, as they enable the integration of biodiversity, resilience, the definition of proximity service areas, and collective well-being into a single systemic vision.

They transcend the logic of technical solutions to become *cultural infrastructures of ecological conversion* – instruments through which the city rethinks its relationship with nature and with itself.

However, their effectiveness depends not only on design quality but on the ability to embed them within institutional, social, and cognitive ecosystems that can sustain them over time.

NCbS fully express their transformative potential – or rather, their *transformative regeneration* (Fainstein 2010) – only when they become integral to urban and territorial policies, when they generate collective learning processes, and when governance itself evolves into a cooperative platform capable of integrating competences, cultures, and scales.

In this sense, planning is no longer an act of control but a process of *ecological negotiation* among knowledges and forms of life, among communities and institutions. The resulting city is plural – it regenerates through networks of care and social alliances, where innovation is not only technological, but also cultural and relational, in accordance with the fundamental principles of harmonic innovation (Cicione, 2023). NCbS are thus not merely environmental devices, but *political devices of conversion*: they build trust, activate shared responsibility, and nurture belonging.

For this to occur, a qualitative leap in governance is needed – from technical coordination to *reflective governance*, capable of measuring but also of listening, of evaluating but also of accompanying, of treating uncertainty as an opportunity for learning.

NCbS thus become the keystones of a new public ethics, grounded in reciprocity, care, and ecological justice. Only in this way can ecological transition become ecological conversion, and planning once again a project of civilisation.

Integrated within a transformative urbanism, NCbS remind us that urban regeneration concerns not only physical spaces but also the forms of thought, dwelling, and coexistence.

It is within this renewed alliance between nature and culture, between technique and sensitivity, that the future of the planning discipline resides: no longer regulating growth, but guiding transformation – with humility, responsibility, and imagination.

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Thermodynamics for physical processes and energy environmental sustainability assessment at urban scale

Carla Balocco

Abstract: In the extreme environmental scenario, due to Global Warming (GW) and pollution, and in the necessary condition of energy saving and energy-environmental quality protection, this research proposes a method as a useful and effective tool for environmental, urban/architectural, energy and integrated Nature Based Solutions (NbS) design, applied at small and large scale, i.e. respectively, to the complex building-plant system and its surroundings (built, unbuilt and/or green system), and building, building stock, district and urban-built-up and/or green areas. The simple method proposed, links applied thermodynamics to physics-informed modelling of urban built-up and green areas, and allows the quantification of the energy sustainability of green ecosystem services and/or NbS in any urban area and their areal distribution in different built-up zones. The method is an effective operational tool for physical processes and energy environmental sustainability assessment at urban scale, focused on the reduction of anthropogenic impacts, urban heat islands (UHIs) mitigation, and climate change adaptation. Moreover, it provides comprehensive insights into the optimization of NBS planning based on thermodynamic energy footprint accounting, facilitating the improvement of mitigation of urban areas' vulnerability to GW.

Keywords: Climate-responsive urban areas, Energy sustainability, Greenery biophysical modeling, Thermodynamics, Urban heat island mitigation.

1. Physics and Thermodynamics Framework

In 2021, the EU adopted its first European Climate Law (Regulation EU 2021/1119). It set Europe's goals of becoming climate neutral by 2050, as well as a target of 55% less emissions by 2030, compared to 1990 (Regulation EU 2021/1119). The transition to clean energy and technologies is an incentive for environmental and energy sustainability, biodiversity protection, safeguard of the health of nature and people, but also economic growth and innovation, climate change mitigation, reduction of anthropogenic effects and GW. As required by the Climate Law in February 2024, an additional interim target of 90% less emissions by 2040, is envisaged.

Accordingly, scientific studies in the literature have widely demonstrated the beneficial implications of NbS on the Enhanced Weathering (EW), human health, Urban Heat Island (UHI), and other climate change related phenomena (Santamouris 2020; Cui et al. 2024; Mahmoud 2011; Yang et al. 2016; Chàfer et al. 2022; Choi and Yeom 2017).

International and National policies have recently planned reforestation interventions in urban and sub-urban areas. The International Union for Conservation of Nature (IUCN), highlights NbS as actions that protect, sustainably manage, and restore natural or modified ecosystems while addressing social challenges and providing benefits for both human well-being and biodiversity (IUCN 2020). Consequently, a method to quantify quality and effectiveness of integrated green solutions and NbS is necessary. This entails the possibility of pursuing the objectives of the European Green Deal and the Sustainable Transition by strongly supporting the decision-making policies of local authorities and public administrations.

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The physical-real knowledge of phenomena and the characterization of the urban microclimate at hyperlocal scale (i.e. under the canopy layer where mass and energy exchanges interact in transient conditions with fluid dynamics and variable and impulsive external/internal forcing) is possible by means of applied Thermodynamics (Balocco et al. 2025; Cureau et al. 2024; Piselli et al. 2022).

This allows to physically treat the huge amount of environmental data, and to define sustainable energy planning strategies at the urban scale and/or of the single building, block or district.

The identification of the most suitable NBS typologies, their optimal locations and implementation are identified by the proposed methodological approach application. It is based on applied physical informed modelling at small and large urban scale. It is a systemic thermodynamics method based on environmental energy physics that allows the quantification of the energy sustainability and effects of green ecosystem services and/or NbS integration in any urban area.

2. Materials and Methods

2.1. Thermodynamics for the physical process and energy environmental assessment

Thermodynamics has wide applications to various fields, ranging from engineering to natural living and inanimate systems, to social organization and economics, and to environmental energy management. It is fundamental for environmental data processing and energy environmental sustainability quantification at urban scale.

There are many ad hoc statements of optimality (min, max) and goal-seeking (optimal) that have been used in physical science. They continue to be used because they are effective in predictive, quantitative and parametric analysis. Sometimes these applications themselves lead to misunderstandings. They are mutually exclusive, e.g.: entropy generation minimization and the pursuit of greater efficiency are used commonly in biology and engineering (Bejan 2000; G., Balocco and Grazzini 1997; C., Balocco and Grazzini 2000); entropy generation maximization, not minimization, is being invoked in geophysics (Paltridge 1975); maximization of 'fitness' and 'adaptability' (robustness, resilience) are used in biology (Weibel and Hoppeler 2005); minimization of flow resistance is invoked in river mechanics, physiology and engineering; maximization of flow resistance is used regularly in physiology and engineering (Bejan 2007; Bejan and Merkx 2007); minimization of travel time is used in urban traffic (Balocco and Colaianni 2018); minimization of effort and cost is the core idea of social dynamics; maximization of profit and utility is used in economics; maximization of territory is used for rationalizing the spreading of living species, deltas in the desert or empires; uniform distribution of maximal stresses (irreversibility and heat and mass transfer balances) is used as an 'axiom' in rationalizing the design of animal bones and botanical trees; maximization of growth rate of flow disturbances (deformations) is invoked in the study of hydrodynamic instability and credited as the 'origin' of turbulence (Ciacci et al. 2023; D'Amato and Korhonen 2021).

Moreover, literature studies have highlighted that the energy saving obtained by the reduced thermal loads of the HVAC systems, due to the presence of green systems, must be compared with the costs of energy saved with green systems installation and maintenance (Balocco and Leoncini 2023). Furthermore, recent studies have shown that any intervention choice based on general green-washing, fails to produce significant energy consumption (Schwaab et al. 2021).

The existing literature lacks simple tools that can support decision-makers in adopting effective programming of interventions (Schwaab et al. 2021; Gratani et al. 2018; E., Costa-Filho et al. 2021).

Heat and mass transfer, and energy and/or entropy balance of any system and/or organism have important ecological consequences that are necessary to understanding responses and possibility of adaptation to climate change.

In this framework, thermodynamics is the effective tool to identify sustainable environmental (urban and greenery) planning strategies.

Thermodynamics allows the comprehension of physical processes of complex systems, starting from the knowledge of the microclimate at hyperlocal scale, and solving data granularity. Both at large and small scales, it is not possible to neglect the interactions between fluid dynamics and heat and mass transfer. This allows to represent and quantify the real physical complexity of any system (building, city, greenery) and its connected sub-systems.

2.2. Urban built-up and green areas as thermodynamic systems

If the concept of balancing exchange of energy, mass and resources between systems/organisms and their environment is simple, their implementation, referring to all the interacting physical processes, is much less so. Our method starts from the consideration that all natural living and structured-built systems – the latter as a manifestation of the anthropogenic burden on the environment – continue to respond to climate change, which is difficultly predictable. Considering thermodynamic processes, systems can shift their distributions and energy flows in opposite directions than expected. This suggested us to apply physical metrics and implement thermodynamics with multi-physics approaches and multi-domain analyses application.

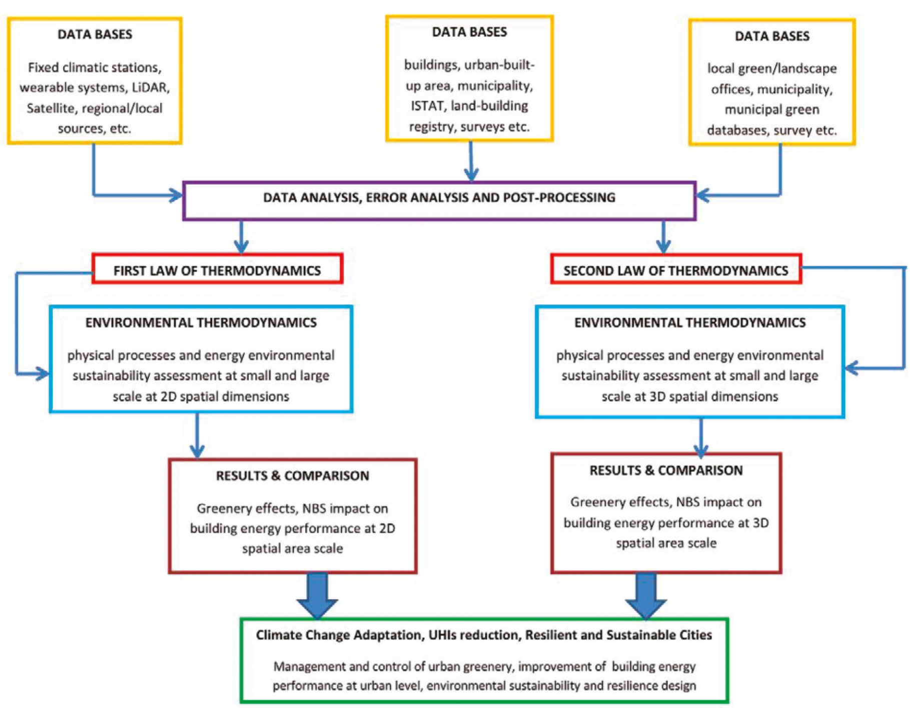

Fig. 1 – The flow chart on the method fundamental process.

The obtained differences, dynamics flows and changes constitute the fundamentals for thermal stress models, predictive models and energy-environmental sustainability quantification. The method is quick, simple and easily applicable and based on the following interconnected phases: Identification of the open thermodynamic system and its different and connected sub-systems; Definition of the physical boundary of the study; Energy balance based on the First Law (or Second Law) of Thermodynamics; Boundary conditions identification; Heat and mass transfer evaluation; Evapotranspiration and/or condensation (phase changes) calculation; Turbulence and fluid flows modelling; Soil heat transfer modelling; Governing equations and boundaries setting; Steady-state analysis to determine the initial conditions of balances for transient analyses; Iterative procedures implementation; Results post-processing; Data error analysis; Results analysis.

Figure 1 shows the flow-chart i.e. the fundamental structure of the method.

Given the complexity of natural systems connected and interacting with ur-ban-built-up ones, but in particular, the different data base interfacing, data driven and big-data available today, and all the necessary information sometimes derived from literature evidences, the method's implementation requires simplifications that however guarantee validity, meaning and physical compliance. It is easily implementable and usable by public administrations, not requiring trained and specialized personnel.

3. Some Fundamental Applications: Results And Discussion

In this section important examples of the method's application, recently published, are shown and discussed. Results, mainly indications, comparisons and discussion in the perspective of Physics and Thermodynamics analysis and implementation are provided. Specifically, the first example is the method's application at small scale (i.e. single building, groups of buildings, block, neighborhood), the second and third examples are the method's application at large scale (urban area, metropolitan area, municipality).

The first example is a small scale method's application (Balocco and Leoncini 2023) based on energy, environmental and economic impact evaluation for different regeneration proposals, combining a green system integration. The case study is the Don Milani primary school in San Lorenzo in Greve expansion zone of the metropolitan area of Florence. This study allows to extend the validity of the method to similar cases and conditions and to provide a basic tool to Municipalities and Public Administrations as basic knowledge for future projects oriented towards the energy transition, and specific tailored training. The method is composed of two interconnected phases.

The first phase concerns the energy analysis of the existing state and critical issues identification: three-dimensional modelling of the school building; boundary conditions definition (e.g. climate data, built environment and surrounding greenery data); thermo-physical features based on current legislation and the census of the National Institute of Statistics (ISTAT); model validation.

The second phase concerns the identification of green energy solutions, NbS integrations, plant systems revamping (air conditioning and lighting) and improvement of the thermo-physical and energy performance of the building; multi-scenario analysis; results analysis and comparison; energy costs and environmental impact analysis; comparisons between the existing state and the proposed energy efficiency scenarios; potential and effects of NbS solutions in relation to the green system.

Interventions with low interference on regular school activities are proposed, taking into account the environmental and social costs of the construction site, also due to the movement of students and school staff. Building refurbishment: strong insulation of all the external walls (reduced thermal transmittance from 0.75 to 0.20 W/m^{2}K); existing windows replacement with new thermal break ones (thermal transmittance reduced from 3.60 to 1.30 W/m^{2}K); attic insulation (reduced average thermal transmittance from 1.45 to 0.20 W/m^{2}K).

The result obtained is the new Energy Class D, corresponding to 120 kWh/m^2 year. The reduction in the use of primary resources is 25% equal to the reduction in equivalent CO2 emissions. At the same time the internal environment improvement, due to more homogeneous thermal field, average radiant temperature close to the set-point temperature, temperature gradients attenuation, especially near the windows, are the scope obtained. Using the PMV and PPD indices (respectively, Predicted Mean Vote and Predictable Percentage of Dissatisfied, UNI EN ISO 7730-2006), the operating temperature inside the classroom more unfavorably exposed to solar radiation is calculated. Therefore, during winter conditions, a student placed in the center of the classroom in its current state, i.e. without insulation interventions, perceives a temperature of 17.6 °C, while in the energy regeneration conditions, she/he would perceive 19.7 °C.

The cost for the solutions implementation, referring to the BAU (Building As Usual) approach and without benefiting from any form of incentive, is estimated to be higher than €1M. The unit amounts applied to the calculation basis are €170/m^2 for external insulation, €600/m^2 for window frames replacement and €120/m^2 for attic insulation.

This set of interventions cannot have recovery margins beyond the expected useful life, estimated at 20 years pursuant to EU Delegated Regulation 244/2012.

The building is more than 50 years old, during which only maintenance work has been carried out to allow its regular use. Multiple scenarios are designed with effective solutions (thermal system), combined with the integration of sustainable strategies (PV system) and greenery (NbS).

The following scenarios are then implemented and simulated. The reference scenario: maintenance of the current gas-fired mono-functional thermal power plant, with heat generator replacement (condensing boiler, 480 kW, efficiency of 95% at nominal power and 105% at reduced load). A modulating proportional regulation is implemented, with an external climate probe with a compensation curve.

The plant retrofitting strategies (named alternative scenario, AS) are: AS1(hybrid system, consisting of a 480 kW gas-fired condensing boiler and a 160 kW air-to-water aerothermal electric heat pump); AS2: "all electric" (air-water heat pump sized to cover the total thermal load (480 kW) with an average seasonal COP of 3); AS3: equal to 2), but with a PV system on the roof (monocrystalline silicon modules, 90 kWp peak power); AS4 includes all choices of 3) combined with the above PV system on the roof; AS5 green roof solution (integration of greenery as an extensive covering).

In particular, a simplified model for green coverage simulation is used, assuming the horizontal homogeneity of the slab and heat and mass flows mainly vertical, adopting one-dimensional equations to describe the thermal behavior of each layer at semi-steady state conditions.

The extensive solution is modelled taking into account a traditional structure (i.e. total thickness 16 cm, substrate thickness 12 cm, flow coefficient < 0.36, volume of water available for plants ≥ 55 l/m^2, usability ratio ≥ 0.84%, efficiency ratio ≥ 0.56, maximum water retained ≥ 65 l/m^2, system thermal resistance ≥ 0.47 (m^{2}K)/W, substrate permeability ≥ 15 mm/min, substrate cation exchange capacity ≥ 15meq/100 g.

For all the proposals the Building Automation and Control System (BACS) is implemented: it provides a centralized regulation, operating on the flow temperature of the heat transfer fluid, and a peripheral regulation for each terminal equipment.

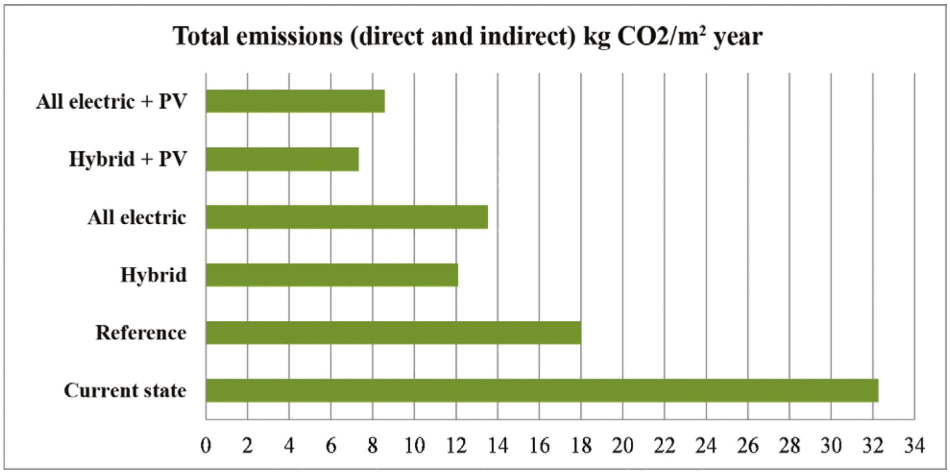

Fig. 2 – Energy efficiency of the proposed solutions.

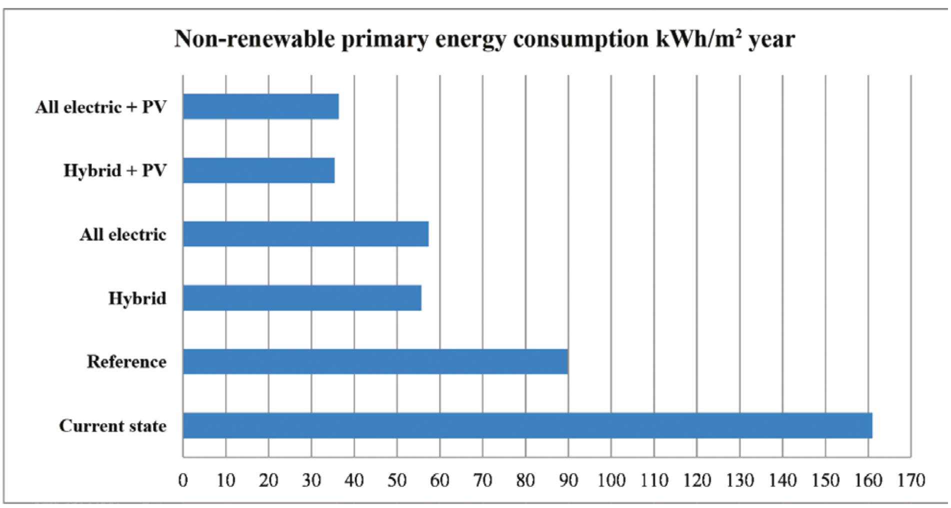

Fig. 3 – Environmental impact of the proposed solutions.

Figure 2 and Figure 3 show, respectively, results for the interventions on the energy efficiency and environmental impact.

The Life Cycle Cost (LCC) analysis allows choosing between a hybrid system and an "all-electric" system, and between drawing from the grid or self-producing the necessary electricity. The resulting Discounted Cash Flow-DCF value indicates that the hybrid system solution powered by PV is better, because it represents the best compromise between investment costs and operating costs (Figure 4). On the other hand, this solution oriented to the maximum use of renewable sources, provides a great energy autonomy to the school.

The extensive green roof is not considered for the LCC analysis and in combination with the proposed solutions, because it is not so significant compared to the advanced insulation alone. It is well-known that green roofs and cool-roof solutions allow to significantly reduce the surface temperature values but for very large surfaces.

In particular, while cool-roofs are more effective in terms of UHI mitigation, green roofs, especially the extensive type, can have an impact on the reduction of the building annual primary energy requirements when the coverage is appreciable compared to the total dispersing envelope surface. From a thermal point of view, greenery integration shows its effects on the external forces mainly for solar gains reduction therefore as an important regenerative and resilience solution.

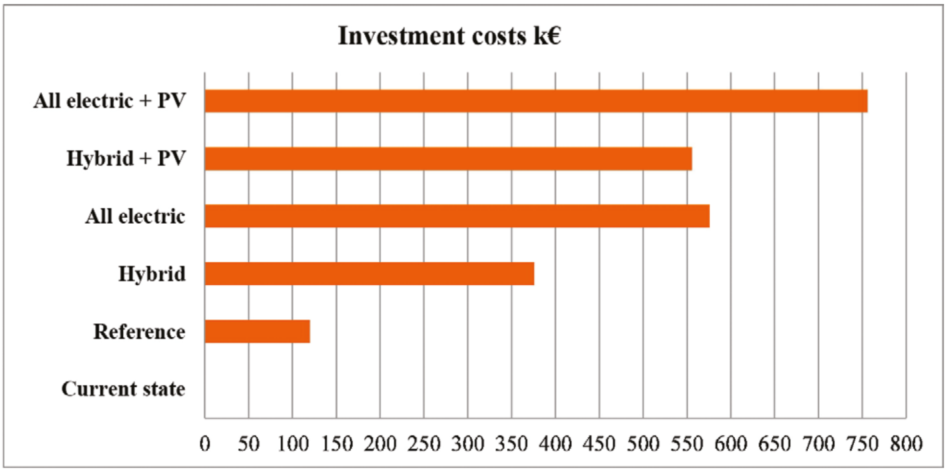

Fig. 4 – Investment costs for the proposed solutions.

A reduction in solar gains of 0.7 kWh/m^{2}year (assuming an average solar absorption factor of 0.3) capable of containing the overheating of the first floor, together with a 5% reduction in annual CO2 emissions, due to the green roof alone, compared to the current state, has been reached.

The extensive green roof has an appreciable impact on the increase in mass and thermal inertia of the floor. Therefore, the integration of the proposed efficiency solutions with a green system, in the surrounding area of the school, and NbS, has produced a UHI significant reduction with highly positive effects on biodiversity conservation, life quality and people's health.

Trees with significant leaf density (e.g. tall beech trees), in reference to literature on the subject, have produced a CO2 absorption of 10-20 kg/year, 17.50-9.5 kg/year of O3, 8.89-16.12 kg/year of NO2, within a growth cycle that reaches its maximum in a time interval between 20 and 40 years. Literature references [23-25] indicate that a developed lime tree is able to absorb 140 kg (CO2)/year, as well as an elm.

The neighbourhood of Don Milani school is located in the South-West of Florence, near agricultural areas, with a sparsely populated urban fabric and large unbuilt spaces. The school has an empty area treated as a lawn of 3500 m^2 (beyond the entrances). In this area, 70 tall trees with a dense mesh have been proposed to be planted, guaranteeing a total of 9800 kg (CO2)/year absorbed. Currently the school (building-plant system) generates direct and indirect emissions of 115000 kg (CO2)/year.

The systemic integration of vegetation with NbS has produced a buffer effect on external forcings, and damping effect on climate change. All the proposed energy regeneration scenarios involve a drastic reduction in emissions, reaching up to 25000 kg (CO2)/year for the hybrid system scenario combined with photovoltaics. Therefore, to create a school with zero impact, less than one hectare of intensive tree cultivation would be sufficient. All this, was suggested to be planned considering the different times needed for greenery and building-system.

The second example concerns large scale method's application, with a top-down and bottom-up implementing processes (Balocco et al. 2025). The implementation needs evaluation and processing of data and/or digital information on the studied urban area: e.g., standard meteorological data/files or real measurements acquired from the local meteorological stations closest to the investigated areas, the buildings characteristics as the surface area in plan, height, volume, prevalent intended use, as well as green areas for specific plant species. The next phase was the georeferencing and modelling with Geographical Information Systems (GIS).

Depending on the useful, available, and traceable information, two different but equivalent modelling processes by applying environmental thermodynamics are implemented: the "top-down" considers the urban context as a 2D footprint of greenery and buildings, or at a two-dimensional areal scale. It is of immediate application and is applied to evaluate the enthalpy variations on a large scale in the summer period, even when the information on buildings is not complete or scarce; the "bottom-up" considers the urban context and the volumetric morphology with details on the buildings, i.e., it is at a 3D volumetric areal scale. It requires a more in-depth analysis at the district level to evaluate the variation of air enthalpy connected to the air exchange volumes for the summer cooling of each building. In both approaches, the first fundamental energy balance is applied to the green cover under the hypothesis of considering leaf surfaces as continuous, uniform, and homogeneous-isotropic.

The balance involves only the 'urban forest' type as a green surface system, as it is the only configuration capable of having a real impact on the energy issue in the urban context, thus excluding low shrubs, hedges, and grass. The balance therefore allows for the determination of the surface temperature of the greenery in a simplified way, determining how a leaf surface exchanges thermal energy (i.e., latent heat and sensible heat) with the environment, disregarding the morphology, the set of physiological and water processes of the plant itself and interaction of its leaves with the soil and atmosphere. In particular, the evapotranspiration processes of the leaves surface is evaluated referring to literature evidences (Costa-Filho et al. 2021; Balocco and Petrone 2018).

The second resulting energy balance is applied to the building–plant system, to assess the HVAC–plant energy consumption due to the thermo-hygrometric treatment of the air, and the consequent environmental impact linked to the external air enthalpy variation due to the green system. To study the thermo-hygrometric effects of any green system in different built urban areas, the set of governing equations expressing the above two balances at semi-steady-state conditions at periodic regime, is implemented, applying it to the green surface and, in a subsequent phase, to the building–plant system.

All the basic governing equations are solved by a finite element code using an iterative procedure.

The studied area is a portion of the city of Florence, identified and characterized using the database of the Municipal Environmental Energy Plan (PEAC), and QGIS software (version 3.40.1-Bratislava) interfacing with data from the GEOscope Observatory (Regione Toscana n.d.) Tuscany Region. Results obtained are the following:

- the leaf surface temperature tends to be always lower than the external air temperature, except in some particular conditions, i.e., when the relative air humidity is very high (RHa > 0.8);
- without solar radiation, the whole leaf coverage reaches the equilibrium condition with the surrounding environment;
- an increase in wind speed leads to an increase in thermal exchange between the leaf surface and the air, reducing the achievable temperature difference (e.g., with Ta equal to 28 °C and all the other parameters constant, if wind speed varies from 1 to 10 m/s, Tl changes from 27.4 °C to 27.7 °C);
- if the wind speed is zero, one term of the balance becomes meaningless;
- the GHI (Global Horizontal Irradiation, expressed in W/m^2) data must be used because it is not possible to accurately determine the average solar radiation striking leaves oriented in different directions; accordingly, for greenery analysis through the GEOscope Observatory platform (Regione Toscana n.d), the leaf surface is considered as a ground area, i.e., green coverage.

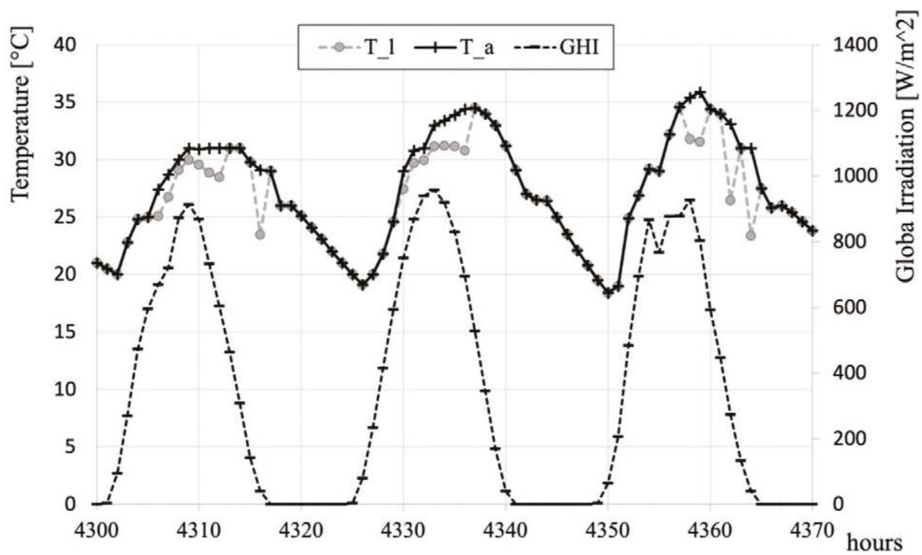

Fig. 5 – Trend plot of air temperature, global solar irradiation, and the leaf surface temperature for the three summer days (29–30 June and 1 July).

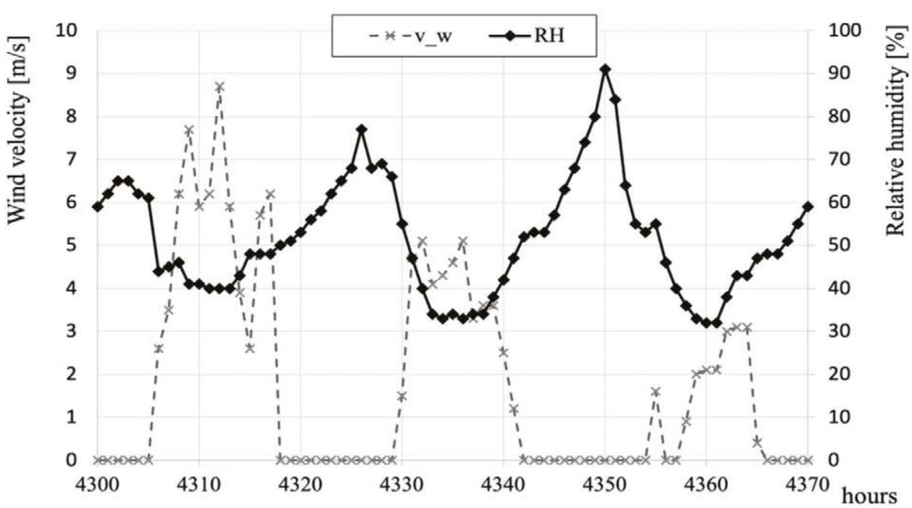

Fig. 6 – Trend plot of Plot of wind velocity and air relative humidity for the three summer days (29–30 June and 1 July).

It obtained the basic trends of temperatures of the external air and leaf surface, air relative humidity, global horizontal solar radiation, and wind velocity that are shown in Figures 5 and 6 for representative summer days (29–30 June and 1 July). The method, by means of the top-down and bottom-up processes, is applied to two important areas of the city of Florence. The first area is a neighbourhood structured around the tree-lined park of Vittoria Square (Figure 7), and the second area is the avenue, also tree-lined, extending from Libertà Square to Beccaria Square (Figure 8). In Vittoria Square, it is assumed that the treetops completely cover the space below the park (as they did originally and as they will most likely be in the years to come, when the new trees have fully taken root in the ground, developed in height and volume of root and leaf systems; in essence, they will have achieved a "mature age") and that it is config-

Fig. 7 – Map of buildings and greenery; the blocks around the park of Vittoria Square (background: city map, pink: urban built-area, violet: buildings involved by the calculation; green: trees position).

ured as a "concentrated context" in which to implement the simplified approach that starts from the buildings overlooking the square itself.

In particular, the existing buildings are identified, georeferenced and, basing on their intended use, the following mean air changes for indoor air quality and correct ventilation conditions are assigned (EN 16798-1:2019; Decree of the President of the Italian Republic 16 April 2013, n. 74): 1 volume/h for residential; 3 volumes/h for offices and accommodation facilities; 4 volumes/h for schools, considering the priority of class-rooms; 6 volumes/h for commercial activities.

Starting from the evaluation of the modified external air temperature of the green areas due to the evapotranspiration of the leaves' coverage, governing equations of all the energy balances are implemented with an hourly calculation.

The top-down approach is applied taking into account overall surface covered by the canopy trees is equal to 5628 m^2 for Vittoria Square and 34560 m^2 for the second case study. Therefore a significant reduction in thermal power is obtained, which, when hourly integrated during the summer season, provides 415 MWh and 2675 MWh, respectively. When applying the bottom-up approach, the main characteristics of the buildings, i.e., ground area, height, volume, and intended use, and effective results for greenery systems are obtained (Barradas 1991; C., Bartesaghi Koc et al. 2018; R., Baraldi et al. 2019).

With a view to the energy transition, in accordance with current regulations for air quality, hygiene and health in confined environments, as foreseen after the COVID-19 pandemic by WHO, RHEVA, ASHRAE, AICARR, and ISS, it is assumed that the buildings are equipped with air conditioning systems of the type Variable Air Volume-Controlled Mechanical Ventilation (VAV-CMV) without the air recirculation condition.

Therefore, the reduction in energy consumption of the plant for the existing different types of buildings is calculated. The air enthalpy variation, in the absence and in presence of greenery, is calculated, and the resulting energy saving obtainable for each kilogram per second of air treated by the HVAC system is quantified.

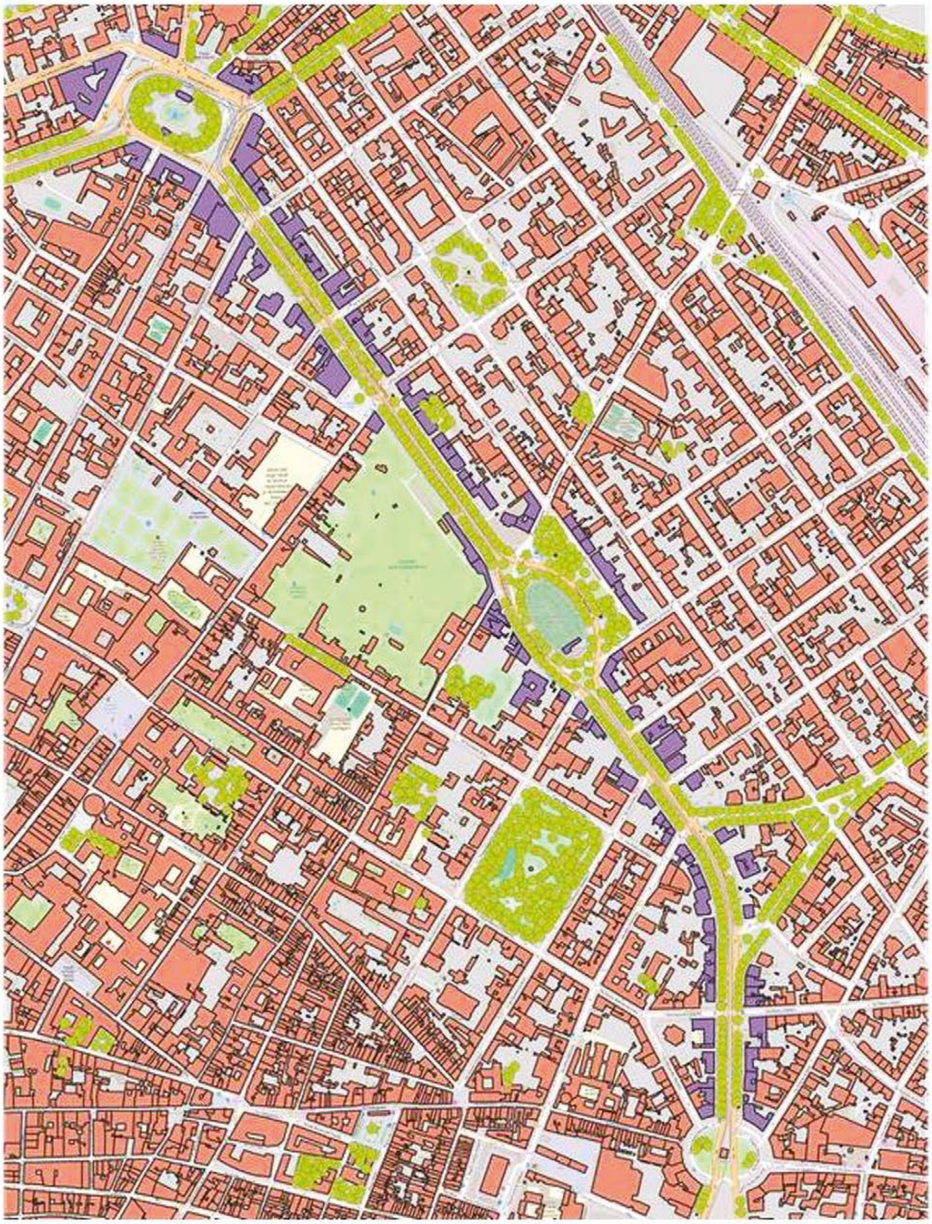

Fig. 8 – Map for avenue, greenery, and building blocks from Libertà Square to Beccaria Square (background: city map, pink: urban built-area, violet: buildings involved by the calculation; green: trees position).

Using the climatic data of Florence, the external air temperature reduction, connected to the presence of the leaves' coverage, leads to an external air enthalpy reduction of 1965 kJ/kg. This last value is obtained considering the plant system operation for all the summer daytime hours in which the external air temperature is higher than 26 °C. This temperature value is set by the Italian Decree Law (2013) as the standard average set-point. For the area of Vittoria Square, 35 building blocks with different intended uses are identified, which affect the amount of air-change volumes.

They are mainly residential (26%) and include some commercial businesses (10%), accommodation facilities and offices (17%), schools and institutes (43%), and for a single case, a small private hospital (4%). In this case, the energy consumption reduction is 504 MWh. For the avenues from Libertà Square to Beccaria Square, 114 buildings are selected.

In this area, the percentage of air-change volumes for residential is 12% and for professional offices and accommodation facilities is 41%, while commercial activities account for 17% and schools/institutes account for 30%. It is important to note that for the whole summer season, the obtained energy consumption reduction is 2350 MWh.

The two methods are equivalent and consistent: small differences are completely within the expected accuracy range for the simplified biophysical and thermodynamic modelling used. For the area of Vittoria Square, the difference between the energy saved (MWh) is 18%, and for the avenues from Libertà Square to Beccaria Square is 12%.

Findings show that urban green spaces play a crucial role in the conservation of bio-diversity, favouring ecological balance and promoting a more sustainable urban environment, in line with most of the literature on the subject (Xian et al. 2024; Zhu et al. 2023; Callaghan et al. 2021).

4. Integrating Green Spaces and NbS: Reflections, Comparisons, and Perspectives

The integrated methodological approach, of simple and easy implementation, useful for quantifying energy-environmental sustainability of urban areas was applied to different urban built-up areas with and without greenery. It is based on applied thermodynamics and physics-informed modelling, connected to high-resolution climate at urban scale, identification and characterization of plants for specific species and vegetation, and spatial georeferencing techniques, for energy exchange evaluation within the urban context. Its real applications have demonstrated the physical effectiveness of the extension of greenery, Nbs integration and any urban regeneration intervention to counteract heat islands and facilitate climate adaptation and resilience.

Energy balances of the studied system can be divided into multiple balances connected to the component sub-systems, some of which can be implemented without advanced functionalities. Therefore, small-scale and small-sized models can handle the simplest subroutines, allowing the application of large-scale and large-sized models on more complex system dynamics.

The effectiveness of the proposed method lies in the new paradigm for "collaboration", the thermodynamic interfaces between small-scale and large-sized models. This "collaborative" and dynamic adaptive paradigm allows the development of sustainable grid-connected environmental energy choices integrated with fine-tuning choices, as it proceeds and develops over time also in relation to different futures scenarios.

In general, the results (especially at small scale) show that the larger and more extensive the vegetation in densely built-up urban areas, the more effective and efficient the possibilities of reducing the load by lowering the enthalpy of the external air. As a matter of fact, it is possible: heat recovery of the exhaust air, adiabatic pre-cooling of the exhaust air; post-heating of the dehumidified air by means of external air.

The adoption of these measures reduces summer consumption for external air thermo-hygrometric treatments, while maintaining the related consumption for ventilation, absolute humidity and pumping control.

Findings (especially at large scale), demonstrate that urban green spaces play a fundamental role in regulating temperature, counteracting the UHI and contributing to citizens wellbeing as also reported in (Bartesaghi Koc et al. 2018; Baraldi et al. 2019; Xian et al. 2024; Zhu et al. 2023; Callaghan et al. 2021). Indeed, results highlight that greenery and NbS integration would address a series of engineering and energy challenges.

Refurbishment and retrofitting interventions (for existing buildings to meet the current nZEB energy requirements) with low environmental impact would be effective in achieving urban resilience and implementing environmental and energy sustainability practices. NbS integration in urban areas would be beneficial to this goal, only when wisely designed, based on thermodynamics applications and assessment evidence: this allows the quantification of external air cooling and different surfaces through shading and evapotranspiration processes.

In particular, the proposed method at the two scales of analysis and implementation (bottom-up and top-down) was also used as an effective tool for economic planning.

It provides quantitative fundamentals to find out the necessary compromise between the construction of ecological systems and benefits in terms of energy saving, environmental sustainability and associated economic feasibility. Moreover, the energy balances do not impose specific constraints on boundary conditions, making the proposed approach highly adaptable and applicable to various urban settings, by means of real physics and thermodynamics. All the real examples explained and discussed above, have shown the most significant reductions in air enthalpy with a substantial increase in green surfaces, vegetation/greenery that work as a natural thermal regulator, effectively mitigating the heat fluxes, amplified within cities due to global warming and significant mutual radiative heat exchanges.

The operability of the proposed strategy is all the more effective, when more closely connected to a truly sustainable smart city, from a systemic point of view for energy transition and the green economy. This latter can be achieved through the integration of ecosystem services, widespread and large-scale NbS, and advanced technologies. It must be noted, that it is necessary to take into account climate variations and energy environmental dynamics/changes over years, in parallel with the time necessary for the complete development/growth of plants.

Thermodynamics-informed method allows a simple implementation for the identification of the most important and suitable interventions for building-plant system energy efficiency and regeneration, climate change adaptation, and UHI mitigation. It is not a deterministic tool, but it allows the construction of an homogeneous scale, of physical significance, for the identification of the most critical and vulnerable areas on which to intervene as a priority. Moreover, it provides comprehensive insights into the optimization of NBS planning based on thermodynamic energy footprint accounting, facilitating the improvement of mitigation of urban areas' vulnerability to GW.

However, the successful implementation of such measures relies on strong institutional/municipal support. Municipalities must actively promote and support urban greening initiatives, recognizing the need for a paradigm shift in public perception of urban spaces and their role in well-being and life quality. This transition requires addressing critical issues such as mobility planning and long-term maintenance, ensuring that green ecosystem services become a fundamental element of sustainable urban development.

Findings deduced from experiences of application in the territorial reality, but also in the administrative, political-social one provide a comprehensive perspective that can provide useful support to architects in improving the urban thermal environment. The problem-solving process implemented with the proposed method, can be extended to built-up environment optimization professionals providing insights for climate-adaptive urban design.

Future developments of the proposed method, which we are currently experimenting with within a LIFE project applied to the city of Florence (LIFE23-CCA-IT-LIFE ESCAPOS "Environmental energy for Strategic CApillary urban POlicieS", https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE23-CCA-IT-LIFE-ESCAPOS-101157553/environment-energy-for-strategic-capillary-urban-policies) concerns the application of thermodynamics for the study of complexity of the physical processes linked to NbS integration, by means of machine-learning techniques.

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Circular economy and resources for architectural and urban regeneration projects

Chiara Moretti

Abstract: The circular economy is an increasingly common concept in urban studies that aims to create a more sustainable and efficient resource management system. While natural processes, characterised by continuous cycles, produce no waste or externalities, the contemporary built environment is based primarily on linear logic. The high technological and construction sophistication of cities, while ensuring efficiency, has led to the production of large quantities of waste, the progressive reduction of natural elements and increased urban vulnerability to climate change and biodiversity loss. In this context, it becomes crucial to rethink architecture as a discipline capable of following the same logic as nature, balancing the economics of construction with the ecology of production and regenerating the life cycles of resources.The integration of natural solutions and circular economy principles can support urban regeneration, improving citizens' well-being and health. This contribution explores urban transition processes according to the principles of regenerative design, enhancing the role of nature and the recycling of local resources for the transformation of critical areas into ecosystems characterised by the circularity of material and immaterial resource flows.

Keywords: Circular model, Regenerative design, Urban metabolism, Ecological balance.

1. Moving Beyond Growth for the Ecological Balance of Cities

Increasing temperatures, rising sea levels and ever-higher stakes mean we face a growing risk of disasters, while the impact of human activity on the environment is becoming increasingly evident. The planet is experiencing its sixth mass extinction, with over a million species at risk in the next decade. More than 90% of this loss is caused by the extraction and processing of natural resources, a direct consequence of a linear economy based on the "take-make-dispose" model. (EMAF 2021)

Natural and socio-economic systems are closely linked: economies depend on ecosystem services, but economic activities can profoundly affect ecological balances (Nassl and Löffler 2015).

In fact, in order to ensure high levels of functionality in residential, infrastructural, social and cultural areas, contemporary cities are configured as hypertrophic and energy-intensive metabolisms, characterised by high resource consumption and the production of large quantities of waste: they consume about 70% of the world's energy (UN-Habitat 2022), use 75% of natural resources (Mancuso 2023), emit 75% of CO_2 and generate 70% of global waste (Luqman et al. 2023). This trend increases the vulnerability of urban systems, reducing their resilience to the impacts of climate change and accelerating biodiversity loss.

Predictions regarding global population trends require ever-rising urban capacity, further increasing pressure on natural ecosystems. (Bardi e Alvarez Pereira 2022) Faced with these challenges, the transition to a sustainable approach can no longer be postponed.

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Addressing this crisis requires a transformative shift in production and consumption systems towards regenerative models, recognising that the circular economy is the only model capable of reducing pressure on ecosystems and ensuring long-term resilience. (UNEP 2024a). This change is at the heart of the United Nations Sustainable Development Goal 12 (Responsible Consumption and Production), whose intrinsic interconnection with other goals (including those related to life on land, life below water and climate change) highlights the synergistic nature of the transition to regenerative models. At the same time, IPBES (Intergovernmental Science-Policy Platform on Biodiversity) emphasises that genuine transformation requires profound changes in worldviews, values, social norms and governance structures, which are fundamental to achieving lasting sustainability (O'Brien et al. 2025).

It is possible to decouple economic growth from resource use and the environmental impacts that this causes. The concept of the circular economy, which promotes the reduction of waste production and resource consumption through symbiotic relationships between economic activities in closed material cycles, is increasingly cited in this debate as a framework for rethinking the ways in which cities can develop without exceeding the finite planetary boundaries that set limits on economic growth. (Williams 2021; Williams 2019). In this scenario, the adoption of circular economy models, capable of regenerating resources and reducing waste, becomes crucial for rethinking architecture and urban planning, promoting cities that are resilient and compatible with the planet's ecological limits.

In recent years, the concept of urban regeneration has evolved to take on an increasingly multidimensional and strategic dimension in response to the growing complexity of urban transformation phenomena. The Urban Agenda for the EU (2023) highlights its integrated dimension, while UN-Habitat (2022) emphasises its participatory, inclusive and resilient nature geared towards sustainability. These definitions converge in recognising urban regeneration not only as a set of physical interventions, but as an integrated process capable of addressing the challenges of ecological transition, spatial justice and social cohesion. Recognising this interdependence is essential for promoting development models that are sustainable in the long term and capable of regenerating natural resources rather than depleting them. In this sense, circular regeneration should not be understood solely as a technical operation of reusing materials, but as a reactivation of new life cycles (Bocchi and Marini 2015).

Based on these premises, the article examines how a circular design paradigm can support climate neutrality in cities and explores how architectural and urban design can contribute to imagining territorial models capable of enhancing biodiversity, local resources and nearby production cycles. Through the analysis of literature, case studies and international experiences, a reflection is formulated on the main circular regenerative strategies aimed at the recovery of the urban environment by integrating ecological, spatial and social dimensions.

2. Residues. From discarding to upcycling to reimagine cities as living organisms

At the 19th International Architecture Exhibition (Venice Biennale), the Circular Economy Manifesto sets bold targets for waste reduction and the promotion of material reuse. The Spanish Pavilion, curated by architects Roi Salgueiro Barrio and Manuel Bouzas Barcala, explores how architecture can contribute to the decarbonisation of the sector through an approach that goes beyond the model of environmental externalities, instead promoting "internalised" production practices that balance ecology and economics. «Nature produces no waste or externalities: every material flow

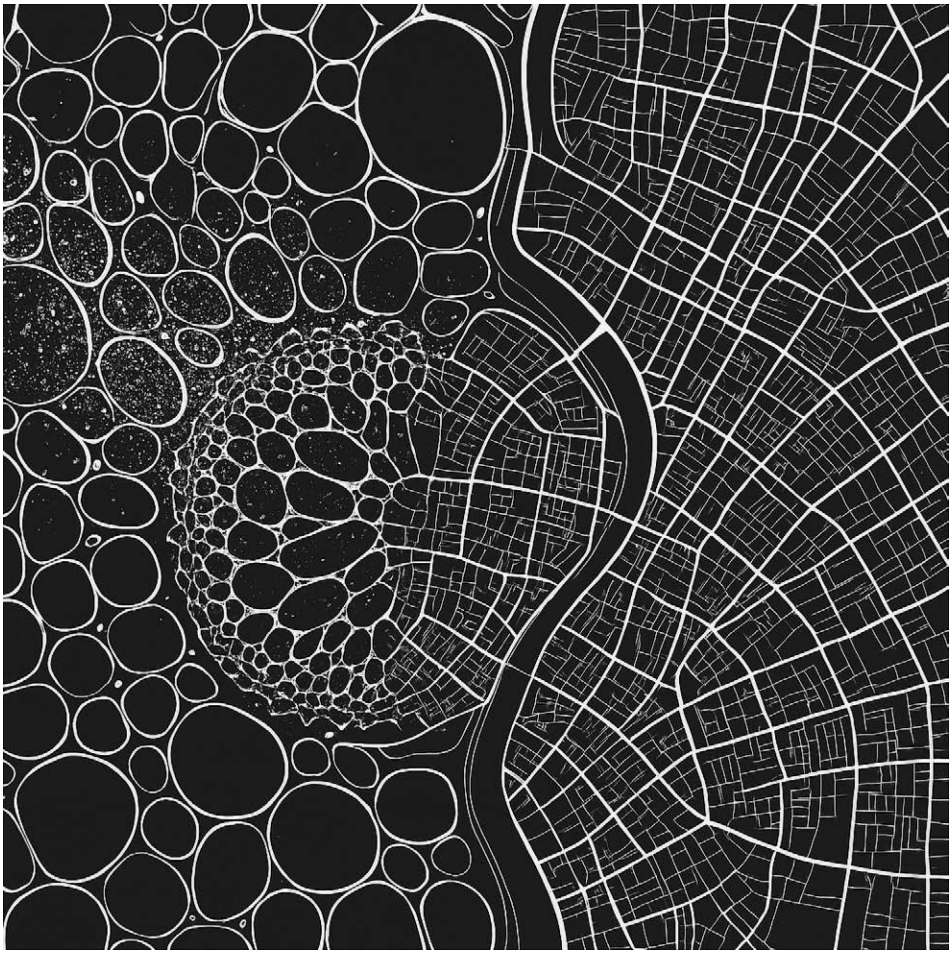

Fig. 1 – Cities as living organisms (Source: Author's elaboration).

is internalised in a continuous biological or technical cycle. What would happen if architecture followed this logic? How could we balance the economics of construction with the ecology of production? Every time we build a space, we deconstruct another, often in remote locations on the planet (MetaloCus n.d.).».

An ecological and low environmental impact approach to architectural and urban design must promote the enhancement of local production, sustainable land use and a balanced relationship between human settlements and natural systems. In this perspective, priority must be given to gradual and regenerative intervention strategies that avoid large-scale demolition and adopt an evolutionary rather than revolutionary approach.

The current construction system is one of the sectors that generates the most externalities: every time we build, extracting resources, consuming energy, marginalising local skills and producing pollution, we contribute to a profound imbalance between the buildings we construct and the territories we transform. Currently, the built environment is responsible for over 50% of the materials extracted in the EU, 40% of energy consumption, 40% of waste (EEA 2019) and 37% of greenhouse gas emissions (UNEP 2024b).

Until now, architecture has sought to respond through mitigation strategies, aiming to reduce the environmental impact of buildings. But this is no longer enough. The time has come to shift the focus from damage control to the urgent need to adapt.

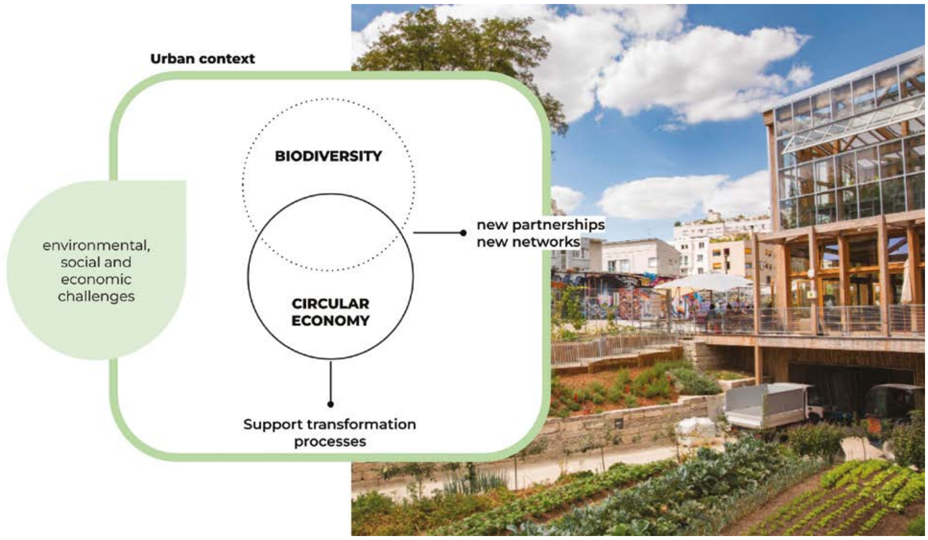

Fig. 2 – Operational research framework correlating aspects of biodiversity with those of circularity in urban transformation projects and processes (Source: Author's elaboration).

Adaptation means radically rethinking architectural design, imagining solutions capable of addressing the profound transformations already underway (Ratti C. 2025). Urban sites are complex, layered entities that are constantly evolving (Dovey 2010). Cities must therefore transform themselves over time in an adaptive manner, responding dynamically to contemporary environmental and social challenges (Geddes 1915).

In this context, there is a need to define guiding principles that integrate technological, environmental and systemic aspects into a circular and biodiverse vision capable of rebuilding the relationships between the natural environment, economic processes and urban and territorial transformations.

The project becomes a critical tool for rebalancing the internal relationships between ecologies and economies, intervening not only on the built environment, but also on design habits, supply chains and regulatory instruments, in order to build urban contexts that reduce waste production and maximise regeneration. The circular approach to resource management is one of the issues that the technological culture of architecture is called upon to address in order to overcome the linear approach to cities.

Current experiences promote the efficient use of resources, often managed within the urban perimeter, by recycling available materials or reusing building elements recovered from the context, considering the existing built environment as a source of supply. This contributes to "closing the loop", reversing the metabolic trend of urban areas from linear to circular (Ferrao and Fernández 2013).

3. Strategies for circular and regenerative technological and environmental design

Planning cities in the new Anthropocene, oriented towards circular metabolism, means accepting the challenge of an ecosystemic and networked approach, guided by an innovative vision but at the same time capable of recovering traditional knowledge and practices based on self-sufficiency and the conscious use of resources.

There are several approaches to circularity in architecture: these include the use of recycled products where possible, a focus on natural and local raw materials, adapting construction to the life cycles of components, and ensuring that component assemblies are reversible (McDonough and Braungart 2002; EMAF 2019).

Starting from the theoretical framework of the circular economy developed by the Ellen MacArthur Foundation (2012; 2017), which interprets urban systems as restorative and regenerative by intention and design, aimed at eliminating waste from production processes, regenerating degraded ecosystems and decoupling economic growth from the consumption of limited resources; the principles of circularity in the regeneration of critical urban areas derive from a screening of scientific literature and the analysis of demonstration and research projects at European level (Superuse studios, n.d.; Bauburo in situ, n.d.; Rotor, n.d.). Specifically, the processes that improve access to urban resources (Heisel et al. 2022) and make a concrete contribution to the recovery of the built environment and construction waste were examined in depth, interpreting the city as an urban stratification, an anthropogenic mine from which to draw on to promote infinite and regenerative production cycles. (Bender and Bilotta 2020).

The circular city can be understood as a complex and adaptive socio-ecological system, in which biophysical, social and institutional dimensions interact through circular flows of materials, energy and resources (Williams 2021). It integrates three fields of action: circular practices (recycling, reuse, recovery), regenerative interventions (restoration of ecosystems and ecosystem services) and adaptive processes (flexible design, co-creation, collective learning). This model is based on a transdisciplinary and multidimensional approach, capable of activating a structural relationship between the different spheres of sustainability — political, social, economic, ecological and territorial. This vision does not merely integrate these dimensions, but interconnects them in a unified framework, in which governance defines the rules, urban planning activates projects and evaluation guides and monitors processes. The interaction of these components supports the convergence between the economic (circular) dimension, the cultural and ecosophical dimension (generating a new urban metabolism) and the ecological dimension (fundamental to ensuring resilience). (Carta 2017)

The strategies that guide these models can be divided into five main areas that aim to achieve circularity in architecture and develop models inspired by ecological cycles and the regeneration of living systems.

4. Restoration of critical or abandoned buildings and infrastructure.

This strategy aims to avoid the intensive use of materials associated with the construction of new buildings by favouring the restoration and adaptive reuse of existing buildings. It promotes the continuity of value over time and space of existing building stock through construction measures that preserve and increase the value of buildings and infrastructure, such as maintenance, repair, and conversion, and significantly reduces emissions and resource consumption compared to demolition and new construction. (Stricker et al. 2022). This approach is integrated with the protection and enhancement of natural urban habitats by promoting land use that protects ecosystems, giving priority to construction on land that is already occupied or previously contaminated.

Adaptive reuse of building materials and components.

Don't throw anything away: work with what we have by promoting the reuse of waste from urban systems. Giving new life to existing materials or components available on site or from the urban mine is a key strategy in the circular regeneration process. Discarded building components embody the craftsmanship and design know-how that went into their creation; they therefore have an intrinsic value that goes beyond their simple value as scrap (Stricker E., et al. 2023). Identifying and utilising waste streams and mapping residual and reusable materials for reuse within projects is essential for keeping resources in the value chain. The built environment represents a resource of materials for urban transformation, offering great opportunities for circularity. In this sense, the planning process is based on the availability of resources (Stricker et al. 2022).

Development of a long-term design process.

"The main architect is time," says Stewart Brand, founder of the Whole Earth Catalog (1968-1998). Extending the useful life of a building is essential to minimising overall resource consumption. Integrating circularity principles into the built environment encourages designers to adopt a flexible design process that responds to the needs and uncertainties of available materials and adapts to different future uses to ensure space-sharing models aimed at maximising the use of existing buildings. The use of the building thus begins to create metabolic relationships with the surrounding environment in response to changing needs and available resources (EMAF 2019). This strategy aims to reduce initial resource consumption by maximising the use of space and avoiding periods of disuse in the building programme.

At the same time, designing buildings and components so that they can be easily dismantled and reused in the next cycle is a fundamental step towards circularity. This approach involves the use of flexible systems that can be dismantled and rebuilt over and over again for different needs in different locations (Superuse Studios n.d.).

Inclusive and ethical governance for circular design.

Promoting a collaborative, multi-stakeholder approach that actively involves citizens, administrations, professionals and businesses, encouraging co-design and shared management of urban spaces, promotes circularity and biodiversity. Participatory processes strengthen social cohesion and ensure that territorial transformations respond to local needs, integrating ethical and cultural values that recognise nature as a non-human stakeholder and adopt circular processes (Buijs et al. 2016).

Ecological enhancement of the built environment

This strategy aims to introduce regenerative and nature-positive actions into the building design process. By focusing more on the ecological value of urban sites, measures can be taken to maximise the restoration of biodiversity in the built environment. The approach is based on closing material cycles, reducing environmental impact and restoring vitality to urban ecosystems, thereby improving residents' quality of life. Integrating natural infrastructure from the early stages of planning and design allows for more sustainable urban development, promoting virtuous relationships between the built environment, ecosystems and quality of life (EC 2021).

5. Prospects for the circular regeneration project

We already have everything we need: the point is not to continue producing, but to learn to read what exists more carefully, to recognise its latent value and reactivate it. The built environment is not an exhausted resource, but a reservoir of potential: every building, every material used retains a residual value that can be regenerated. From this perspective, urban materials and spaces should no longer be considered waste or scrap, but part of a new form of urban stratification, a veritable "anthropogenic mine" capable of feeding regenerative production cycles. Everything is in a process of constant transformation or reconversion - structures, cities, spaces, images, identities (Schwarz 1949). The adaptive reuse and regeneration of existing urban resources are the foundations of a new culture of urban renewal. Architecture, therefore, is no longer an act of replacement, but a process of transformation that favours reuse, regeneration and re-integration of materials in situ, while supporting the reactivation of local economies.

The transition to a circular model is not limited to the choice of materials, but requires a radical rethinking of processes, value metrics and decision-making models

(Stricker et al. 2023). It is about extending the useful life of cities and territories, reversing the extractive logic that has characterised contemporary urban development. In this sense, adaptive reuse and regeneration of existing resources are the foundations of a new culture of urban renewal, guided by the principles of "zero volume" and "no net land take". Unused or underused spaces represent strategic potential, capable of activating sustainable urban policies and stimulating participatory processes of active citizenship and proximity. However, isolated practices are not enough: a holistic and multi-scale approach is needed that recognises territorial metabolism as a key principle of planning, recomposing today's fragmented material flows and reconnecting industrial, natural and cultural systems. Urban regeneration programmes should be conceived as urban recycling districts, supported by territorial laboratories, multi-stakeholder alliances and collaborative tools capable of strengthening administrative effectiveness and enabling shared processes in terms of planning, economics and management.

In this context, circular thinking is an essential framework for urban and territorial strategies, guiding active, adaptive and responsive design processes that can integrate spaces into new cycles, accelerate their regeneration and connect sectoral cycles. The city can thus evolve from a consumer of land and resources to an integrated ecosystem, capable of self-regeneration and ensuring social, economic and ecological resilience. Only with recycling and biocentric urban planning, capable of combining technical, social and moral dimensions (Carta 2017), will it be possible to face the challenge of the Neoanthropocene (Sijmons 2014) and guide the transition towards systemic, equitable and transformative models of governance, capable of rethinking the city as a true laboratory of sustainability.

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Biodiversity, resilience and well-being in urban projects: critical analysis on three case studies

Costanza Carbonari, Giulio Hasanaj, Lorenzo Nofroni

Abstract: The contribution investigates the systemic relationships between biodiversity, urban resilience, and human well-being within processes of territorial and environmental regeneration, through a comparative analysis of three European case studies: the Emscher Restoration Project (Germany), Lyon Confluence (France), and the North–South Green Corridor in Berlin, including *Park am Gleisdreieck* and *Natur Park Südgelände*. The main objective is to assess how biodiversity can serve as an operational parameter for the adaptive design of urban ecosystems, contributing to climate mitigation and the enhancement of urban liveability. The research adopts a critical and interdisciplinary methodology, combining morphological and environmental analysis with the examination of strategies for integrating green infrastructures, ecological networks, and public space systems. Three key analytical axes are identified: (1) the interactions between biodiversity, resilience, and well-being in urban projects; (2) the capacity of green infrastructures to generate multiple ecosystem services; and (3) the design awareness involved in creating shared habitats for human and non-human species. Findings highlight that the most effective strategies operate according to a systemic and multiscalar logic, integrating ecological, social, and climatic dimensions. The Emscher Restoration stands as a model of integrated ecological regeneration, where river restoration and landscape reconnection produce measurable effects on territorial resilience. Lyon Confluence demonstrates the potential of climate-oriented design for urban liveability, albeit showing limitations in ecological monitoring. The Berlin park system represents a paradigm of multi-species cohabitation, where spontaneous natural processes and deliberate planning coexist in a dynamic balance. The study concludes that urban sustainability should not be assessed through isolated performance indicators but through the ecosystemic integration capacity that defines the city as a complex adaptive system. This perspective opens new research directions on biodiversity as a strategic ecological infrastructure, capable of steering urban design towards socio-ecological resilience and widespread environmental well-being.

Keywords: Urban Biodiversity, Urban Resilience, Health and well-being, Integrated design.

1. Nature-based Thinking: a holistic approach to biodiversity, resilience and well-being in urban environments

Today, urban ecosystems face epochal challenges induced by climatic, economic, and social changes. Among these, first and foremost, is the attempt to moderate and reverse the trajectory that, over the last two centuries, has led to a clear and evident loss of biodiversity. In our times, this has compromised or risks compromising the very ability of ecosystems to reiterate and reproduce those functions necessary for the survival of living communities, including climate regulation, water and air quality, and food supply (IPBES 2019).

Concurrently, the impacts of climate change are manifesting with increasing severity, and ecosystems characterized by high levels of diversity show greater resilience to these impacts, enabling more effective adaptation and mitigation processes (Knapp et

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al. 2019; IPCC 2023). In this scenario, urban natures assume a pivotal role not only in maintaining climatic and environmental balances but also in directly influencing human health and well-being (EC 2021a; UN-Habitat 2022).

Human health is fundamentally dependent on healthy and diversified ecosystems, which support the essential conditions for life while offering protection against extreme climatic events and disease risks (WHO 2021). Faced with these challenges, the temptation is often to seek technological or "green" ready-to-use solutions, almost as if consulting a catalogue. However, when discussing Nature-based Solutions (NbS), it must be premised that a single solution, taken in isolation, is not sufficiently articulated to solve problems that are, by their nature, extremely complex. One cannot assume that installing a single green roof can solve the urban heat island problem, just as a single water retention area cannot manage the flood risk of an entire basin on its own.

As the case studies observed in this chapter suggest, the most effective responses do not stem from the application of a single NbS, but from an integrated strategy that considers the multiple interactions between ecological, social, and economic components. Precisely, it is essential to make a conceptual shift: moving from reductionist and mechanistic thinking - based on applying a linear cause-effect response model to complex problems - to thinking based on complexity, which is systemic and recursive: a Nature-based Thinking (NbThinking) (Randrup et al. 2020). While a reductionist view might lead to applying "green solutions" as mere technological artifices, a nature-based approach implies considering multifunctionality, ecological connectivity, and specific biodiversity, relating them to the place and the living community that inhabits it. The approach, therefore, defines the solution, and not vice versa. This "thinking" represents the true interpretive key for NbS; indeed, from this perspective, NbS are not the starting point, but the result of a design process that centers ecological processes. This is a mode of city planning and design that should, by its very nature, be truly integrated into the local system of habitats and ecosystems it addresses; multidisciplinary because it is complex and systemic; and participatory because it is capable of activating cultural and social processes.

An integrated project is one that considers the interdependencies between different objectives. As will be seen in the analysis of the case studies, the transformative potential of contemporary urban practices lies not in verifying biodiversity, resilience, or well-being as isolated factors, but in examining how their systemic integration generates innovative results. This chapter analyzes three case studies - described in section 3 - Emscher, Lyon La Confluence, and the North-South Green Belt in Berlin. Widely known and considered exemplary approaches to ecosystem regeneration, they are characterized by very different scopes of intervention and approaches. However, they are united by the attempt to integrate the feedback between biodiversity, resilience, and well-being in strongly anthropized environments; the relationship between ecosystem services and ecosystem functions; and the creation of habitats for other species beyond human-centric urban landscapes. The large-scale restoration of the Emscher basin in the Ruhr region constitutes a territorial laboratory where the reconstruction of river processes and the valorization of industrial heritage have generated new ecological and social balances. The Lyon La Confluence project, in contrast, interprets regeneration as an adaptive and incremental process, where green and blue infrastructures, energy innovation, and public participation contribute to redefining the relationship between the city and nature. Finally, the Berlin system connecting Park am Gleisdreieck and Natur-Park Südgelände embodies an approach based on the recognition and protection of spontaneous nature, transforming urban voids and former railway areas into spaces of multispecies coexistence. To critically analyze these emblematic examples, we did not limit ourselves to a description of the results, but used three specific "trace concepts" or interpretive keys - indicated in detail in section 2 - to examine them and investigate their conceptual and practical implications. Through these three analytical lenses, the chapter aims to offer a critical reflection - discussed in section 4 - on the role and potential of nature-based strategies and solutions. Beyond the selected case studies, which were chosen for their international relevance and their alignment with the main analytical parameters of the study, recent literature documents numerous additional examples demonstrating the potential of Nature-based Solutions (NbS) to address the interconnected challenges of climate change, biodiversity loss and human health (World Bank 2021). However, the present research focuses on three particularly significant cases, widely recognised at the global level, in order to undertake a critical investigation through different analytical lenses.

2. Keys to analysis for case studies

The selected case studies illustrated in the following section are emblematic projects of urban regeneration including ecosystem conservation and restoration; these successful examples have been described and analysed at length in literature, we therefore aim at focusing on specific analytical tools for a new and different key of examination of projects' results. The proposed keys to analysis are reported one by one in the following subsections, where the analytical criteria are defined in a general way, namely not declined into specific urban regeneration projects.

2.1. Feedbacks between biodiversity, resilience and well-being in urban environments

A first criterion for investigation of the case studies concerns the interdependence between biodiversity, climate resilience and human well-being in urban environments. Biodiversity loss undermines the capacity of ecosystems to provide essential services, including climate regulation, water and air quality, and food provision (IPBES 2019). Ecosystems characterised by high levels of diversity exhibit greater resilience to climate-related impacts, thereby enabling more effective processes of adaptation and mitigation (Knapp et al. 2019; IPCC 2023). Urban nature plays a pivotal role not only in maintaining climatic and environmental equilibrium but also in influencing human health and well-being directly, by supporting both physical and mental health (EC 2021a; UN-Habitat 2022). Human health is fundamentally dependent on healthy and diverse ecosystems, which sustain the essential conditions for life while simultaneously offering protection against extreme climatic events and disease risk (WHO 2021).

Building on these premises, the critical assessment of the case studies is structured around three interrelated dimensions:

Biodiversity: the analysis addresses strategies to reduce habitat fragmentation and enhance ecological connectivity, the promotion of native species – including pollinators – and the strengthening of both floristic and faunal diversity.

Climate resilience: attention is given to adaptive responses to climatic hazards, such as extreme precipitation events and the urban heat island effect, as well as to mitigation strategies that emphasise carbon sequestration through vegetation and soil storage.

Human well-being: the availability of inclusive and accessible public spaces is considered in relation to their capacity to foster physical activity and recreation, with demonstrable benefits for physical and mental health, stress reduction, and overall quality of life, alongside improvements in air and water quality.

From this perspective, the critical assessment of projects lies not in verifying biodiversity, resilience, or well-being as isolated factors, but in examining how their systemic integration generates innovative outcomes, or conversely, how their disjunction risks reducing interventions to partial solutions. The transformative potential of contemporary urban practices is thus revealed in the interplay of these three parameters, which determines their capacity to serve as models of sustainability.

2.2. Ecosystem services and ecosystem functions, when urban regeneration projects provide both

Sustainable urban regeneration is a broad process of transforming city areas to improve their liveability, resilience, and inclusivity by integrating environmental, social and economic interventions aiming to reduce environmental impact, enhance quality of life, and create long-term value for all stakeholders. Indeed, this holistic process integrates benefits from both human-derived and natural capital, and most importantly should provide not only enhanced ecosystem services, but also improved environmental and ecological conditions of urban spaces. Therefore, a key analytical tool for the assessment of urban regeneration projects consists in evaluate whether project outcomes include ecosystem conservation and restoration with resulting improved ecological functions and Nature-based Solutions' implementation with resulting improved ecosystem services, as these two concepts are not identical (Waylen et al. 2024, Carbonari and Solari 2025).

Ecosystem restoration is defined as "the process of halting and reversing degradation of ecosystems worldwide, resulting in improved ecosystem services and recovered biodiversity" (UNEP-WCMC 2021, IUCN 2021). Ecosystem restoration aims at the regeneration of natural processes through carefully planned interventions, primarily aimed at eliminating human-induced pressures. This approach involves a form of "assisted regeneration" that is largely guided by ecological objectives (Shackelford and McDougall 2023). This means that the main goal is ecosystem functions restoration together with enhancing habitat complexity and biodiversity, which are possible if anthropogenic stressors on the environment are reduced. This is actually an ecocentric perspective according to which ecological recovery and biodiversity gain are valorized for their intrinsic value besides ecosystem services (Carbonari and Solari 2025).

In addition to ecological restoration, there is the concept and implementation of NbS, which, while distinct from ecosystem restoration, share certain similarities (Carbonari and Solari 2025). The International Union for Conservation of Nature, IUCN, defines NbS as "actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature" (IUCN 2016). Therefore, in NbS, with respect to restoration, ecosystem services are more central with closer attention paid to people's needs: NbS address major societal challenges (IUCN 2020, Sowińska-Świerkosz and García 2022), thereby anthropocentric goals prevail and eco-health fades in the background. Dealing with NbS, even when particular care is devoted to interventions to tackle environmental degradation and biodiversity loss, such actions are often conceived to boost ecosystem services (Carbonari and Solari 2025), which serve society following an anthropocentric perspective (for instance, healthier freshwater ecosystems represent improved resources for primary production and provisioning services; many other examples in this sense can be found in literature (Basak et al. 2021, Buckley et al. 2024, among others)).

In light of the definition of NbS and ecological restoration, we can affirm that the main common element between the two is the goal and ensuing actions to restore natural processes; in case of NbS this is a co-benefit, while when dealing with ecosystem restoration this is the core benefit. In many cases, however, ecological restoration is properly designed and implemented alongside targeted efforts to provide additional ecosystem services, making it unclear whether the recovery of natural processes is the primary objective or merely an added benefit. Moreover, if the interventions are highly multipurpose and bring together multiple stakeholders including social and economic interests, such actions can be identified both as Nature-based Solutions and ecosystem restoration measures (Carbonari and Solari 2025). In these conditions, therefore, regeneration projects improve both ecosystem services and ecosystem functioning.

2.3. Setting-up habitats for other species rather than just human-centric urban landscapes

The third criterion on which the analysis of the case studies presented in this chapter is further developed aims to contribute to highlight how, and to what extent, there is an awareness of the role of human actions in creating habitats for other species within urban spaces. Consequently, we question if and how much this awareness is translated into oriented and intentional planning and design approaches. Indeed, in the evolution of the technical and scientific disciplines that study densely anthropized environments, the shift from an anthropocentric to an ecocentric perspective has allowed for a more in-depth investigation of the interaction processes between us and other living beings: a community with which we cohabit environments where our action is dominant but is neither the only one nor certainly the sole one. Over the last fifty years, we have witnessed an evolution that has taken territorial planning from an approach exclusively focused on designing spaces for functions specifically reserved for humans, to a growing sensitivity in recognizing, protecting, and restoring spaces for all species. In this regard, one must recall Ian L. McHarg, a pioneer of ecological urbanism and a prominent member of a generation of scholars strongly oriented towards recovering a harmonious relationship between humanity and the environment. In numerous publications, including his most famous work, Design with Nature (1969), he expressed an approach to planning founded on the knowledge of ecological processes and inspired by them for a harmonious coexistence with the entire biosphere. Sylvia Crowe, as a militant and passionate landscape architect, for all her long professional and academic career, urged public decision-makers, planners, designers, and society as a whole to recognize the plurality of life in the complex biocenoses of which we are a part, and to integrate our actions with observance and respect. In this vein, starting from the late 1970s, the perspective of the city as a complex mosaic of habitats began to consolidate, eventually being articulated into a distinct discipline: urban ecology. In recent times, the awareness of cohabitation in urban space between humans and other living beings has led to the development of possible conceptions and interpretive models, including "ecological urbanism" (Mostafavi, Doherty 2016), "multispecies urbanism" (Solomon, Nevejan 2019), "botanical city" (Gandy, Jasper 2020), and "biophilic city" (Beatley 2011). It is precisely from this last model that the concept of functional coexistence in the urban environment emerges with explicit clarity. According to this concept, the actions of humans are interrelated with and inseparable from the actions of other cohabiting species, and urban natures (Corrado, Lambertini 2011) are not merely a "remnant" of wild nature, but a complex and dynamic ecosystem that requires careful understanding and a more eco-conscious intention in satisfying our desires. The definition of coexistence modalities proposed by this conception is based on the pursuit of a common, pluralistic, and non-speciesist perception of the presence of other species. It also relies on the dissemination of an aesthetic that recognizes in everyday urban landscapes not only the habitats we can intentionally create for ourselves and other species, but also the unintentional ones, which are shaped by spontaneous naturalization processes and guided by unplanned ecological dynamics, a phenomenon that the ecologist Ingo Kovarik defines as "fourth nature" (Kovarik 2005; Kovarik 2013).

3. Selected case studies

3.1. Emscher Park: Systemic Ecological Restoration and Coexistence in a Post-Industrial Riverscape

3.1.1. Introduction to case study

The Emscher catchment restoration is a large-scale intervention on the entire basin of the Emscher River (Figure 1) in the "Ruhr Metropolitan Area" in North Rhine-Westphalia (Germany); the Emscher restoration intervention can be labelled as an integrated set of either riverscape NbS or river restoration measures (Carbonari and Solari 2025) also including urban and industrial regeneration. The Emscher River is a tributary of the Rhine River, its catchment covers 865 km² of urban and peri-urban areas densely populated (average 2775 inhabitants per square kilometer). The entire area presents a post-mining and post-industrial landscape. In 1990, the catchment was characterized

Fig. 1 – Biotope network along the Emscher river (Source: Emschergenossenschaft Emscher Future Master Plan, 2006).

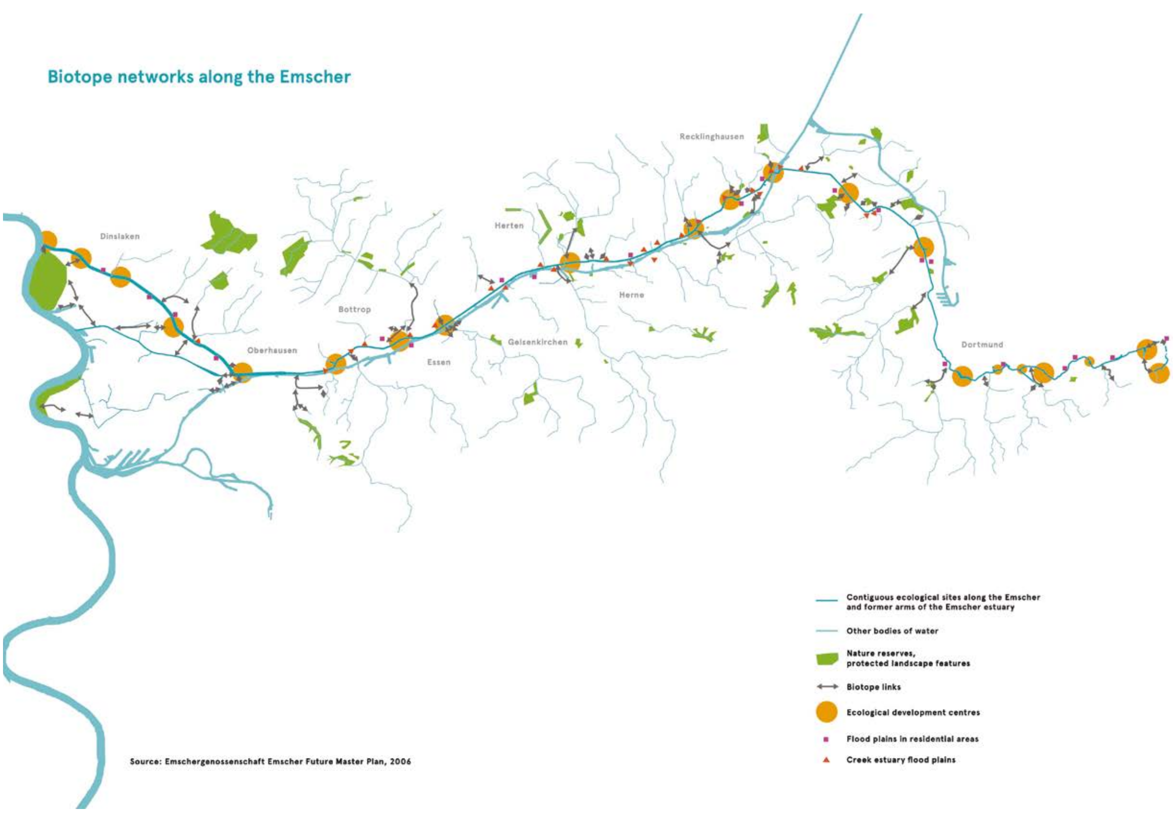

Fig. 2 – Testo Emscher river at Herne and Recklinghausen (Germany). In the background the electricity-museum (Source: Arnoldius 2006, Wiki Common CC By 4.0).

by abandoned mines and factories, along with extensive impermeable and artificial land surfaces. The Emscher River and its tributaries were not only channelized and paved but also served as direct conduits for wastewater. That same year, a 30-year, catchment-wide restoration project was launched with the goal of transforming the Emscher and its tributaries back into natural streams, establishing a separate sewage system, restoring and reconnecting the floodplain, and enhancing the resulting ecosystem services (Gerner

Fig. 3 – A view of Duisburg-Nord park. Design by Peter Latz 2016 (Source: Wiki Common, Autor: Zairon, 2016 CC By 4.0).

et al. 2018 2023). The restoration project started with the construction of a 423-kilometer underground sewer system to separate wastewater from river water, accompanied by the installation of phytoremediation basins. Subsequently, the concrete linings of the streams were dismantled, and the channel cross-sections were widened, including the reclamation of terraces and floodplain. Alongside the restoration of both vertical and lateral connectivity, the renaturation process also involved the establishment of riparian vegetation. The project also included the transformation of a post-industrial area into a permanent lake with flood mitigation objectives: this artificial basin is the Lake Phoenix (Dortmund), which stores 700,000 m^3 in normal weather and can accumulate an extra volume of 240,000 m^3 during flood events (Gerner et al. 2018).

In parallel with the hydrological and ecological interventions, the project also entailed extensive urban and landscape transformations. The restoration was closely integrated with urban planning strategies aimed at improving the quality and accessibility of public spaces along the river corridors. Former industrial areas were reconfigured into green-blue infrastructures, linear parks, and recreational paths connecting urban centers, while new landscape designs emphasized visual continuity between the watercourses and the surrounding built environment (Figures 2 and 3). These interventions redefined the spatial relationship between the river and the city, turning the restored river corridors into structuring elements of the metropolitan landscape (Wuppertal Institute 2017; Laser and Sørensen 2021).

3.1.2. Regenerating Post-Industrial Landscapes: The Emscher as a Laboratory of Biodiversity, Resilience and Well-being

The Emscher renaturation project constitutes an emblematic case for understanding how the full integration of biodiversity, climate resilience, and human well-being can generate innovative outcomes in territorial regeneration (Climate-ADAPT 2024). The restoration of approximately 170 km of watercourses and the reintroduction of complex fluvial morphologies – meanders, wetlands, and vegetated banks – not only re-established functional habitats and enriched biological diversity (with aquatic species rising from 170 to 300 and avifauna from 38 to 147 species), but also strengthened the system's capacity to absorb climate shocks, transforming ecological infrastructure into an active safeguard against floods and extreme events (Climate-ADAPT 2024; Gerner et al. 2018). At the same time, these processes created high-quality spaces for everyday life, demonstrating how biodiversity can be translated into social and health capital (Zimmermann and Lee 2021). The creation of over 300 hectares of water retention areas and natural floodplains, together with the desealing of urban soils, illustrates the inherently multi-functional nature of the interventions: measures designed to mitigate climate risks simultaneously fostered ecological habitats and enhanced urban liveability by reducing heat islands and expanding opportunities for collective use (Climate-ADAPT 2024; Zimmermann and Lee 2021). Similarly, the Emscher Landscape Park – a 70 km ecological corridor connecting 17 cities – demonstrates that green infrastructure can simultaneously serve as an ecological device, a resilience tool, and a social infrastructure, with direct impacts on health and territorial cohesion (EC 2022). The transformation of industrial heritage into parks, museums, and cultural centres further confirms that environmental regeneration gains strength when it is also translated into symbolic and community regeneration, restoring shared identities to post-industrial territories (Kaçar 2016; Labelle 2001). A critical reading of the case, however, highlights that disarticulation among the three parameters risks reducing the transformative scope of the intervention. The impossibility of fully restoring original ecosystems due to deep soil alterations, the structural dependence on engineered infrastructure such as sewers and pumping systems (Laser and Sørensen 2021), and the persistence of local inequalities in access to green spaces (Zimmermann and Lee 2021) reveal that biodiversity, resilience, and well-being are not always pursued in a balanced way. The innovative value of the project therefore lies not only in the outcomes achieved, but in its ability to weave together ecological, climatic, and social dimensions within an integrated framework. It is precisely in their interconnection – rather than in the sum of sectoral objectives – that the transformative capacity of contemporary regeneration practices can be measured (Gerner et al. 2024).

3.1.3. The Emscher intervention outcomes in both enhanced ecosystem services and ecological functioning

The Emscher interventions definitely met the goal of ecological restoration since the set of integrated measures goes beyond the setting-up of new green and blue areas. Indeed, river processes and ecological functioning were restored thanks to the achievement of the necessary prerequisite consisting in the mitigation and even removal of the anthropogenic stressors, for instance pollutants, which were the main cause of ecological degradation of both aquatic and terrestrial ecosystems. The extensive reafforestation of stream banks and floodplain reconnection allowed relevant nitrogen, phosphorus and carbon retention quantified in tonnes per year, comparing pre- and ex-post intervention conditions (Gerner et al. 2018). A similar quantitative analysis was conducted for habitat quality and species diversity, focusing on the increased number of watercourses' kilometers achieving good ecological status (as defined by the Water Framework Directive (European Parliament and Council of the European Union 2000, European Commission 2016)) and the rise in taxa richness (Gerner et al. 2018 2023). The Emscher catchment restoration also provided enhanced ecosystem services, which were designed and measured, together with ecological outcomes, all throughout implementation phases according to both biophysical and economic evaluation. For instance, the economic benefits of reducing flood risk due to the artificial Lake Phoenix are assessed in terms of avoided costs of flood damage, the rise in real estate value due to the natural amenities offered by the lakeshore, and the added opportunities for recreational and cultural ecosystem services. In general, ecosystem services were planned and assessed according to the DESSIN ESS Evaluation Framework (Anzaldua et al. 2018), a procedure developed within the European research project DESSIN (Demonstrate Ecosystem Services Enabling Innovation in the Water Sector 2014-2017) giving guidance to analyse the difference in value of Ecosystem ServiceS (ESS) in a system before and after restoration and management measures. Moreover, the Emscher case study can be labelled as a successful implementation of multiple and integrated NbS with a resulting improvement in ecosystem services delivery because the solutions adopted are highly multipurpose, also addressing social and economic needs, and present an extensive engagement of multiple stakeholders. Indeed, with respect to this last issue, the DESSIN ESS Evaluation Framework relates each case-relevant ecosystem service to local stakeholders (Anzaldua et al. 2018), in particular water board and residents; stakeholders are then informed and often actively involved in co-design since the beginning of the planning phase.

3.1.4. Emscher renaturation project and Duisburg-Nord park as a model for Ecological Coexistence

The widespread industrial decline of the twentieth century left a legacy of derelict, post-industrial landscapes often viewed as ecologically degraded and functionally obsolete (Loures and Panagopoulos 2007; Rahdar and Milani 2025). Traditional landscape design, frequently prioritizing aesthetics or singular functionality, has historically failed to address these complex sites, often overlooking their potential for ecological integrity (Rahdar and Milani 2025). In response to this failure, a paradigm of ecological landscape design has emerged, advocating for holistic approaches that integrate natural processes, biodiversity, and human social needs (Rahdar and Milani 2025). The Emscher renaturation project and the Landschaftspark Duisburg-Nord, designed by Latz and Partner, stands as a seminal exemplar of this philosophy. Rather than eradicating the site's industrial past, the project demonstrates how planning and design can leverage industrial remnants to create complex new habitats, fostering remarkable biodiversity and facilitating a functional coexistence between human activity and non-human species. The design strategy for Duisburg-Nord represents a radical departure from conventional reclamation, which typically involves remediation and erasure. The Latz approach was instead based on interpreting the existing fragmented layers of the site (Loures and Panagopoulos 2007). The architects fundamentally "accepted the dynamic nature of nature as the basis of their design" (Treib, in Latz 2016). This acceptance of industrial nature—the spontaneous vegetation and ecological processes already occurring on the derelict site (Keil 2019)—was the project's foundational principle. Instead of imposing a new, idealized "natural" landscape, the design aimed for a harmonious reclamation of both the natural and the built environments (Loures and Panagopoulos 2007). This methodology treats the industrial structures not as liabilities to be cleared, but as essential components of the new landscape, transforming the former steelworks into a multifunctional, socially engaging, and ecologically sustainable space (Rahdar and Milani 2025). A primary success of this approach is the park's function as a significant refuge for biodiversity. Industrial brownfield sites, contrary to perception, often form the "backbone of urban biodiversity" in post-industrial regions (Keil 2019). The structural variety of the Emscher renaturation project, with its disparate soils, railway embankments, concrete bunkers, and retaining walls, creates a mosaic of unusual microhabitats (Latz 2016; Keil 2019). This physical complexity supports an almost complete spectrum of successional stages, from pioneer communities on raw slag to established pioneer forests (Keil 2019). The park is now considered a "local hotspot for biodiversity," vital for the preservation of many rare and endangered species (Keil 2019). Areas where mining subsidence created inaccessible swamps, for example, were not restored but protected as valuable habitats, contributing to biodiversity by allowing natural processes to unfold without human interference (Latz 2016). Furthermore, the project pioneers favorable conditions for coexistence by integrating human-nature interaction directly into its ecological framework (Rahdar and Milani 2025). Emscher renaturation project and Duisburg-Nord are not a fenced-off nature preserve; they constitute a natural park that utilizes the industrial remains of past industry to create culturally stimulating landscapes (Loures and Panagopoulos 2007). Visitors are invited to experience this emergent industrial nature, climbing blast furnaces that overlook pioneer forests or walking on elevated structures above the wilderness (Latz 2016). The design facilitates coexistence through spatial separation that allows for observation without disturbance; the most wild areas are often inaccessible but remain visible from railway embankments (Latz 2016). The importance of the Emscher renaturation project and the Landschaftspark Duisburg-Nord lies in its successful synthesis of industrial heritage, ecological processes, and human social needs (Loures et al. 2006). It provides a powerful, practical precedent, demonstrating that ecological design can transform seemingly damaged landscapes into vital habitats for diverse species (Keil 2019; Latz 2016). By rejecting erasure and instead embracing the dynamic processes of industrial nature, the park creates the necessary conditions for a new form of coexistence, proving that post-industrial sites can be reclaimed not only for society and culture, but for the environment itself (Loures and Panagopoulos 2007).

3.2. Lyon Confluence: An Adaptive Landscape for Societal and Fluvial Resilience

3.2.1. Introduction to case study

The La Confluence district in Lyon is situated at the edge of the historic city, on the artificial peninsula located between the Rhône and Saône rivers. This area was urbanized in the 19th century, during the industrial revolution, to accommodate the river port, industrial zones, and rail and road infrastructure. Following the manufacturing sector crisis beginning in the late 1970s, the entire area, encompassing approximately 76 hectares, experienced extensive phenomena of dereliction resulting from progressive de-industrialization. In the late 1990s, the municipal administration defined an urban renewal program aimed at the urban reconversion of the district. An international competition was launched to acquire a strategic masterplan, and a public-private urban transformation company was subsequently established. The winning masterplan project, designed by Michel Desvigne and François Gréther, envisions a dynamic urban structure where the enhancement and reconversion of industrial infrastructure are integrated with an evolving system of gardens, the *jardins provisoire* (provisional gardens). This system is founded upon the action of *preverdissement* (pre-greening): a preventive planting strategy that supports the concept of establishing various temporal identities and configurations, oscillating between temporary and permanent states, for the new green spaces—totaling approximately 30 hectares. This strategy allows for the implementation of public spaces prior to the completion of construction interventions (residential buildings and offices), accompanying them according to an incremental logic. In the development of the masterplan (Figure 4), a 'two-speed' landscape is devised. Here, certain temporary elements—such as meadows, specific vegetated strips, and pioneer woods—are established preemptively within an open space system that

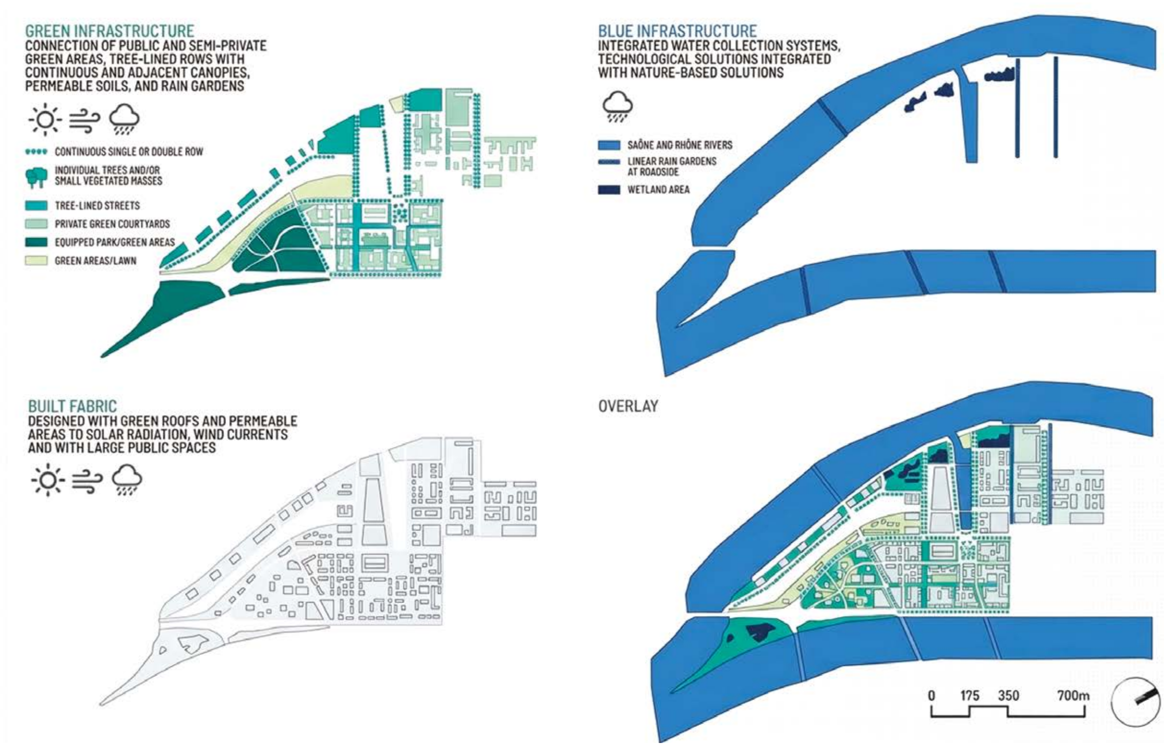

Fig. 4 – The Confluence masterplan conceived by Michel Desvigne and François Gréther (Graphic processing and image source: Lorenzo Nofroni, 2025)

Fig. 5 – Jardin du Musée des Confluences at the confluence of the Rhône and Saône rivers designed by Coop Himmelb(l)au and EGIS aménagement. (Source: Wiki Common, Autor: Guilhem Vellut, 2017 CC By 2.0).

Fig. 6 – Jardin Aquatique Ouagadougou at La Confluence – Lyon (Source: Wiki Commons, Author: Guilhem Vellut 2017 CC BY 2.0).

encircles areas awaiting construction. Conversely, the perennial elements, consisting of tree alignments, embankments, and infrastructure, are progressively constituted as the building interventions take shape, ultimately providing a structural and definitive vegetative configuration to the entire district. Particular attention is dedicated to the fluvial system and water management. Specifically, the project has resulted in a substantial transformation of the Saône's left bank, restoring this important ecotonal strip between the emerged land and the river to a pre-industrial conformation (Figure 5). Meanwhile, the new eco-district is situated within a dynamic context, influenced by the geomorphological processes of the two rivers. Wetlands, meadows, and forested areas ensure continuity of the green infrastructure (Figure 6), introducing high environmental value and increasing vegetal and animal biodiversity within the urban system. This is achieved through the reconstruction or spontaneous definition of numerous and diversified habitats suitable for marsh species, birds, insects, and aquatic animals. The Confluence project leverages the inherent instability of the area as a strength, implementing a strategy of progressive and evolutionary infiltration of vegetation that occupies the spaces and develops concurrently with the city's growth. This represents an exemplary intervention based on the rehabilitation of the fluvial ecosystem and a system of provisional parks, capable of accommodating all transformations without necessitating the completion of the ultimate grand design (Corner and Tiberghien 2009).

3.2.2. City, nature and community: the transformative capacity of La Confluence

The *La Confluence* project in Lyon stands as one of the most ambitious examples of urban regeneration in Europe, grounded in an integrated approach where biodiversity, climate resilience, and human well-being are treated as foundational principles rather than supplementary objectives (SPLLC 2019; Ferretti 2020). The reintroduction of nature – through the creation of a continuous green framework, large-scale soil remediation, and the development of diverse habitats – reconnected the new district to territorial ecological networks and initiated processes of ecosystem reconstruction (SPLLC 2019; Lyon Confluence 2025). These actions, however, extend beyond the ecological dimension: they also enhanced urban resilience by increasing rainwater retention, reducing urban heat islands, and improving microclimatic quality, thus demonstrating how biodiversity and resilience measures can generate cross-cutting co-benefits (GRAIE-OTHU 2025; Zimmermann and Lee 2021). At the same time, sustainability and energy strategies – such as the *Hikari* block, the first positive-energy mixed-use complex in Europe, equipped with a district-level smart grid – illustrate the interplay between resilience and well-being at both building and urban scale. Energy efficiency and microclimatic adaptation provide immediate benefits for residential comfort while contributing to broader goals of carbon neutrality (Darchen 2020; Morishita-Steffen et al. 2021). Similarly, SuDS installations function not only as technical devices for stormwater management but also as urban habitats that foster biodiversity while improving the usability and comfort of public space (Lyon Confluence 2025). Resident well-being emerges as the synthesis and the true measure of the project's transformative capacity. The provision of local green spaces, the emphasis on *mixité* and social housing (23%), design principles such as guaranteed solar access for each dwelling, and the development of health-oriented facilities such as the therapeutic garden within the *Eurêka* block show how biodiversity and resilience were also translated into instruments of inclusion, health promotion, and social cohesion (SPLLC 2019; Ferretti 2020). Public participation further reinforced this collective dimension: the initial exhibition attracted more than 24,000 visitors and over 1,000 comments, leading to revisions of the masterplan, while post-occupancy surveys continue to integrate user feedback into subsequent *Cahiers des Charges*, ensuring an iterative and adaptive design process (Lyon Confluence 2025). Nonetheless, a critical reading reveals limitations that arise when the three parameters are only partially integrated. While around 35 hectares of green space and 4,500 new trees were created, systematic ecological monitoring has not been implemented, limiting the ability to assess measurable biodiversity improvements (Carbonari and Solari 2025). Moreover, with only one-third of the district served by a separate sewer system, the intervention falls short of being considered true ecological restoration, as anthropogenic stressors have not been sufficiently reduced to achieve large-scale ecological recovery (Carbonari and Solari 2025). In conclusion, the transformative strength of *La Confluence* lies in the systemic interplay between biodiversity, resilience, and well-being: when these parameters are mutually reinforcing, they generate innovative outcomes capable of redefining the relationship between city and nature; when pursued unevenly, they risk producing a sum of sectoral actions that, while improving urban quality, fall short of full ecosystemic regeneration. The project demonstrates that the measure of urban sustainability rests on maintaining this systemic integration, avoiding the drift towards parallel but disconnected trajectories.

3.2.3. The Lyon Confluence regeneration, a case study successfully addressing societal challenges and overlooking environmental and ecological actions

The Lyon Confluence regeneration includes integrated and progressive interventions highly multipurpose and addressing several societal needs; the whole intervention is carried out through an effective and extensive cooperation between public and private sectors, complemented by a systematic and continuous involvement of the local community. The project brought off a diverse, inclusive, and sustainable district by developing a built environment with high functional diversity. By 2030, it will deliver 5000 new housing units, including social housing, and ensure buildings meet high energy performance standards. It also supports a vibrant and diverse economy, home to 1650 businesses, and features a wide range of educational, cultural, and recreational facilities. A key achievement is the successful transformation of the waterfront (Figure 5), which has restored natural features and improved access for residents. Notably, the Saône riverbanks have been redeveloped into Quai Rambaud, a five-kilometer continuous promenade now reconnected to the wider city and equipped with integrated infrastructure for soft mobility (SPL Lyon Confluence). With regard to ecological restoration, however, the measures undertaken are not as effective as the social, economic and urbanistic ones (Carbonari and Solari 2025). Actually, extensive green areas totaling 35 hectares have been developed, along with the planting of 4500 new trees; the blue-green spaces are spread across key areas, including the main Champ Park (Figure 6), three aquatic gardens, and several neighborhood gardens; tree species were carefully chosen to enhance biodiversity, and in 2011, a survey of the animal species inhabiting these blue-green spaces identified 32 different bird species (SPL Lyon Confluence). However, two main issues persist: i) the measures taken to reduce human-induced pressures contributing to ecological degradation have not been thoroughly or scientifically addressed, for example, less than one-third of the district is equipped with a separate sewage system for waste and grey water, and there is no documented evidence of improved water quality in the receiving bodies; ii) with respect to the new green-blue spaces there is no analytical assessment of ecological enhancement, for instance a consistent quantitative monitoring is not provided (i.e. absence of quantitative comparison pre-post intervention or restored-unrestored areas). Regarding this last point, it is emblematic that literature tends to assess the value of green-blue spaces of the district just in terms of boosted value of real estates (Roebeling et al. 2017).

3.2.4. Design a complex habitat system for a new model of coexistence among all species of the Lyon urban ecosystem

The primary objective of the masterplan (Figure 4), designed by Michel Desvigne and François Gréther, was to reconstruct the relationship between the city and its rivers. This vision translated into a complex environmental strategy that extends beyond a simple urban park system, aiming to reintroduce habitats for plant and animal species to create favourable conditions for coexistence between humans and all other species. The masterplan's greatest innovation is realizing a system of diffused parks and gardens as an ecological strategy to create a network of habitats and urban ecological corridors. The urban regeneration plan is thus conceived starting from the creation of a green infrastructure based on the connection between open spaces, including tree-lined rows with continuous and contiguous canopies that act as corridors for avifauna, and the widespread use of permeable soils and rain gardens. These fragmented yet connected elements create a mosaic of micro-habitats that allows fauna and flora to move and thrive within the urban fabric. To ensure the area's immediate vitality, the concept of a "two-speed" landscape was introduced: alongside perennial and long-term plantings, jardins provisoires (provisional gardens) were implemented. These allowed for the creation of favorable conditions for plant colonization in areas awaiting urban and building development, activating ecological cycles from the project's very first phases. In parallel, the project developed a sophisticated blue infrastructure, based on the renaturalization of the Rhône and Saône banks and the creation of numerous floodable open spaces. These rain gardens and infiltration basins not only prevent flooding and reduce the load on the sewer system but also create essential wetland habitats and become vital places for amphibians, aquatic insects, and specific hygrophilous flora, significantly diversifying the district's biodiversity. An emblematic example that translates the philosophy contained in the Desvigne and Gréther masterplan to a neighborhood project scale is the Champ de la Confluence (Figure 6), designed by the landscape architecture firm BASE. Described as the "missing piece" in the district's overall park strategy, it was envisioned as an urban woodland that functions as a cohabitation space among species. In this sense, the most relevant aspect of the BASE project is the fruitful designed configuration of spaces that replicates the logic of the river's geographical movements. In fact, instead of imposing a rigid design, the project mimics the site's natural processes; the streets themselves are designed to wander around buildings in an "alluvial nature." This process-based approach works with the nature of the place, creating varied topographies (mounds, swales) and utilizing post-industrial soil to encourage the spontaneous colonization of pioneer vegetation. This "alluvial nature" creates a dynamic, evolutionary landscape due to generates a mosaic of micro-climates and soil conditions (dry on the high points, wet in the basins) that maximizes the diversity of ecological niches—a system designed to trigger ecological processes that, over time, attract and support all species adapted to a river confluence environment.

3.3. From Park am Gleisdreieck to Natur Park Südgelände, the North-South green belt of Berlin: a rich and diversified system of open spaces for the urban ecosystem (Lorenzo)

3.3.1. Introduction to case study

The system of open spaces (map in Figure 7) situated between Park am Gleisdreieck (Figure 8), in central Berlin, and Natur Park Südgelände (Figure 9) in Schöneberg, represents a prime example of how a complex urban trajectory, structured by intricate social and environmental events, can transform into an open-air laboratory for experimenting with novel paradigms for interspecies coexistence within the urban environment. This instance, unique in certain respects due to its origins in the peculiar historical, geopolitical, and urban context of Berlin, has generated new contemporary urban landscapes for the Western city. These landscapes consist of hybrid and not entirely programmed spaces, where coexistence, diversity, resilience, and health

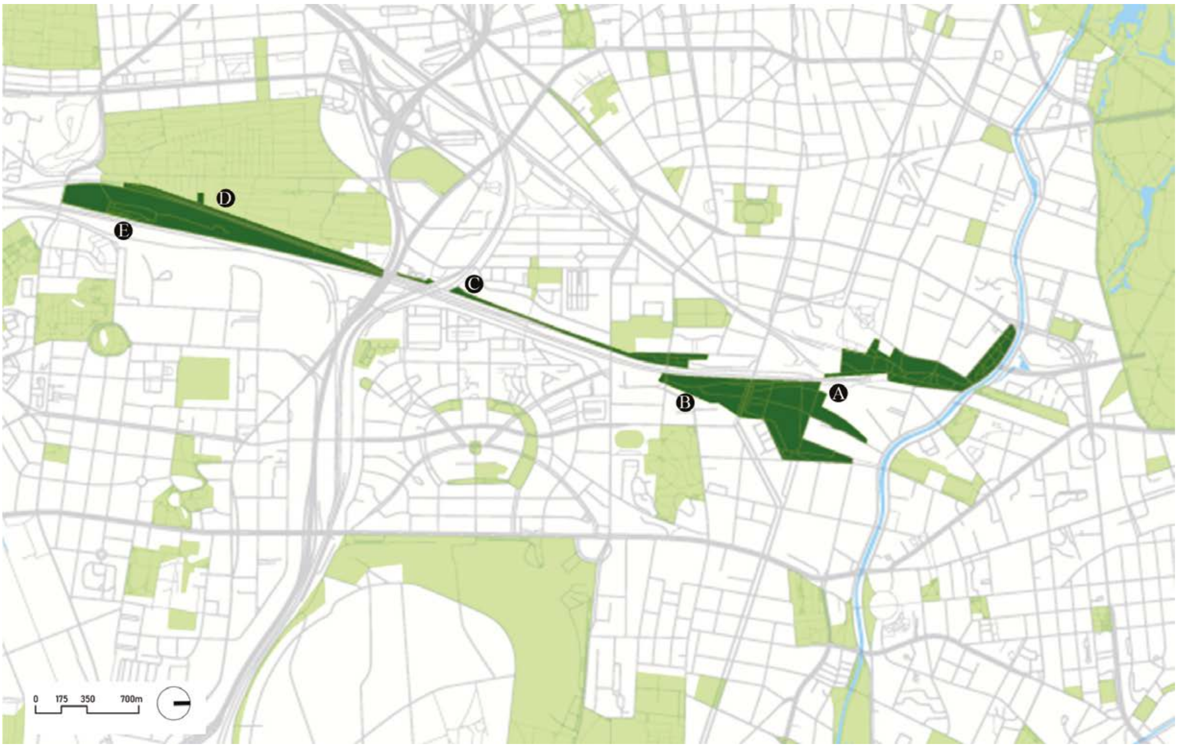

Fig. 7 – The park system, indicated by letters on the map: Park am Gleisdreieck (A), Dora-Dunker park (B), Nord-Süd-Grünzug (C), Parkbereich Insulaner (D), and Natur Park Südgelände (E). (Graphic processing and image source: Lorenzo Nofroni, 2025).

manifest as quotidian and infra-ordinary phenomena (Perec 1989). These phenomena transcend the wholly artificial critical threshold that separates our species from the remaining living organisms and occur across the entirety of the biocoenoses coexisting within this urban space. If a satellite image of central Berlin is observed, focusing on Potsdamer Platz and tracking the infrastructural alignment constituted by the railway bundle running from the center toward the southwest, a rarefied urban fabric is readily apparent. This fabric is characterized by extensive open spaces rich in vegetation which, despite minor discontinuities, collectively form an articulated and complex ensemble of urban parks spanning approximately 100 hectares. Encountered sequentially from north to south are the following components: Park am Gleisdreieck (26 ha), Dora-Dunker park (6 ha), the Nord-Süd-Grünzug—a linear park approximately 2 Km long, Hans-Baluschek Park (6 ha), Parkbereich Insulaner (16 ha), and Natur Park Südgelände (18 ha). This parks and open spaces system stands as an exceptional laboratory, in the unique context of Berlin, marked by wartime destruction and political division, resulted in the emergence of vast urban voids, most notably the extensive, abandoned railway yards (Figure 8 and 9) (Kowarik and Langer 2005). Left to undisturbed natural colonization processes for decades, especially in the isolated territory of West Berlin, these "iron landscapes" (Gandy 2020) became incubators for novel ecosystems. This phenomenon gave rise to a spontaneous and resilient ruderal vegetation, termed "urban wilderness" or "nature of the fourth kind" (Kowarik 2005, cited in Kowarik 2015). The park system connecting Park am Gleisdreieck and Natur-Park Schöneberger Südgelände is a direct product of Berlin's conscious decision to integrate rather than erase these unique ecological assets. This approach, formalized in planning instruments like the 1994 Landscape Program, treats spontaneous nature as a valuable component of the urban green infrastructure. The north-south

Fig. 8 – One of the clearings with grass and pioneer vegetation in the Park am Gleisdreieck (Source: Wiki Common, Autor: Lienhard Schulz, 2011 CC By 3.0).

Fig. 9 – Groups of shrubs and a pristine forest grew out of the former railway wasteland, all without human influence in the Natur Park Südgelände (Source: Wiki Common, Autor: Dirk Ingo Franke, 2009 CC By 2.0).

parks system represent distinct yet complementary strategies for managing this new wilderness. Natur-Park Schöneberger Südgelände, developed on a former freight yard, exemplifies a conservation-led approach. Here, the design preserves the spontaneous pioneer forest by "staging" it through minimal interventions, such as elevated walkways, effectively linking conservation with recreation (Kowarik and Langer 2005; Kapitza and Hofmeister 2020). Conversely, Park am Gleisdreieck, located near the central Potsdamer Platz, masterfully integrates high-value wilderness areas with intensive public use through sophisticated, deliberate zoning (Kowarik 2015). This park demonstrates how "urban wilderness" can be a core, branded component of a modern, highly-frequented park, not just a residual element (Kowarik 2015).

3.3.2. The urban ecological regeneration of Natur Park Schöneberg Südgelände between biodiversity, climate resilience and wellbeing

The Natur Park Schöneberg Südgelände (NPS) in Berlin represents an emblematic case of urban transformation capable of systematically integrating biodiversity, climate resilience, and human wellbeing, overcoming the fragmentation of sectoral approaches (Lambertini 2006; Kowarik 2022).

The project originated from the reclamation of a large disused railway area – the former Tempelhof freight yard – which had been abandoned for around fifty years, where residual infrastructural elements intertwine with established spontaneous vegetation (Kowarik and Langer 2005; Dellatorre 2022).

A critical analysis of the Südgelände highlights the virtuous interaction between these three dimensions and illustrates how an approach based on the coexistence between habitats and human use can generate innovative outcomes (Boschiero et al. 2022; CEREMA 2012).

Biodiversity constitutes the founding element of the project, which led to the site being recognised as an urban ecological reserve. The area hosts an extraordinarily rich ecosystem, which developed thanks to the long period of abandonment: more than 350 plant species, at least 30 breeding bird species, and 95 species of wild bees – including 34 protected ones – have been recorded (Kowarik and Langer 2005; Natur Park Südgelände 2025). The spontaneous vegetation originally present has been progressively enriched with alien species, recognised by the Berlin school of urban ecology as structural components of the urban ecological mosaic (Kowarik and Langer 2005; Dellatorre 2022).

The conservation of this area within a densely built context plays a crucial role in reducing ecological fragmentation and strengthening connectivity among different urban habitats, making the park a strategic node within Berlin's green network (CEREMA 2012; Wolff et al. 2023).

Spontaneous ecological processes are recognised as resources that contribute to climate change mitigation and adaptation. The species colonising these environments show a high degree of resilience, adapting to conditions of aridity, thermal stress, and poor soil (Kowarik 2022).

In this way, the site functions as a natural device for mitigating urban climatic hazards, such as the heat island effect. Although no quantitative data are available on carbon sequestration, the existing vegetation contributes to a diffuse green network, improving the carbon balance and mitigating the impacts of climate change (Annese, Mininni, and Scalera 2021).

The Südgelände was conceived as both an ecological and cultural infrastructure, returning to the community a place subtracted from the city for decades. The park provides spaces for leisure and physical activity, promoting psychophysical wellbeing and stress reduction, becoming a space for social interaction and direct contact with nature (Rinaldi 2024). The protection of spontaneous vegetation, valued for its ecological role, also contributes to the improvement of air quality and the urban microclimate. A distinctive architectural feature is the metal grating walkway, raised about 80 cm above the ground, allowing visitors to cross four hectares of protected natural reserve safely, ensuring public accessibility without compromising the habitat (Kowarik and Langer 2005).

Local artists have also reinterpreted the former railway tracks, blending art, ecology, and memory of place (Dellatorre 2022).

The innovation of the NPS does not stem from a single element but from the interdependence between conservation, adaptation, and public use. The project demonstrates how biodiversity can be enhanced through the protection of spontaneous habitats, even those partly inaccessible to humans, and how resilience emerges from ecological systems capable of adapting and evolving over time (Kowarik 2022). Similarly, the park's public experience is founded on a direct and respectful relationship with nature, in which human wellbeing and ecological integrity mutually reinforce one another (Annese, Mininni, and Scalera 2021; Rinaldi 2024). From this perspective, the Südgelände stands as a paradigm of ecological urban regeneration, successfully integrating nature, culture, and design (CEREMA 2012; Boschiero et al. 2022).

3.3.3. Berlin's parks network both improves ecosystem services and ecosystem functions, but cause-effect assessment of restoration outcomes and assessment of reduction of anthropic stressors are partial and scattered

Berlin's parks network is an emblematic example of urban rewilding, which restored, over decades and across large scales, natural habitats within city environments starting from degraded areas transformed into self-sustaining ecosystems with minimal long-term human intervention. German ecologists are indeed the initiators of urban ecology and since the 1970's they restored Berlin "wastelands" – former industrial sites colonized by novel mixtures of native and non-native species – according to the principles of rewilding (Kowarik 2018, Kowarik and Langer 2005, Kowarik 2019, Kowarik 2023).

The ecological outcomes of these rewilding processes and conservation of habitats has been widely mapped and monitored with interesting and even surprising results, like the one that non-native species are not necessarily ecologically harmful: in areas with prevalence of non-native species such as black locust trees from North America, many organisms, such as ground beetles and spiders, were as abundant as in areas dominated by indigenous plants; and also, less than 6% of Berlin's endangered plants are threatened by non-natives species (Kowarik 2019, Kowarik 2023). Ecology studies documenting ecological improvement in specific areas of Berlin's parks network are several. For instance, Kowarik and Langer (2005) documented in Natur-Park Südgelände (approximately 18 ha) the spontaneous doubling of woodland between 1981 and 1991 passing from 37 to 70% of the park area. This colonization was mainly carried out by pioneer species, such as birch and locust trees, then followed by maples. Another example of documented ecological results in specific areas of the park network is the one of a bird community in the Tiergarten (over 200 ha) illustrated in Felgentreff et al. (2024). The authors document number of species and functional richness of birds community from 1850 to 2022: in the years 1850, 1950 and 2022 the number of species passed from 53, to 16, to 59, respectively, and values of functional richness were 0.72, 0.28 and 0.82; the authors also state that a highly frequented park situated in a city center can shelter a high species richness. However, the research does not explicitly relate the time changes of bird population to vegetation changes, it just states that the park extension and the vegetation heterogeneity favour the good status of the bird community. In other words, a cause-effect assessment of ecological results is lacking. This is also missing in the previous example of plant colonization in Natur-Park Südgelände (Kowarik and Langer 2005): for instance, what are physical, chemical and biological changes in the soil matrix, which are clearly among the drivers of plant community changes? For example, it is acknowledged that nitrogen fixation is needed for the passage from pioneering trees to more demanding species (Kowarik and Langer 2005), but no quantitative measures of it are provided. Overall, ecology researches on Berlin's parks broadly lack a quantitative assessment of contaminants and other stressors trends, which are related to management changes of green areas, thus overlooking the changes of anthropic pressures that are among the primary regulators of ecological status.

Some ecosystem services (ES), in particular provisioning and regulatory ES such as air, soil and water purification and climate regulation, due to Berlin's parks are also poorly assessed in a quantitative way. For instance, scientific literature scarcely focuses on the microclimatic effects (e.g. heat waves, physiologically equivalent temperatures) of the parks (Langer et al. 2021) and rather places the parks in more global climatic trends to which the parks as well as the rest of the Berlin area are subject (Fenner et al. 2019, Mukherjee et al. 2025). Conversely, recreational and cultural ecosystem services are better assessed in the available literature (Rinaldi 2024, Mukherjee et al. 2025, among others).

Overall, the partial and scattered quantitative assessment of cause-effect relations in ecological results and of provisioning and regulatory ecosystem services is also due to the prevalence in literature on Berlin's parks and rewilding of disciplines such as urban planning and design, social sciences and urban studies, urban ecology; while environmental chemistry, water resources, atmospheric sciences are not quite so present. This results in an insufficient attention paid to the status of environmental matrices underpinning the outcomes of ecosystem restoration and ecosystem services. Finally, it is possible to affirm that Berlin's parks network both improves ecosystem services and ecosystem functions even if a complete transdisciplinary analysis is not available. Eventually, we recall that a deeper insight into cause-effect relationships and wider quantitative assessment are not the pretension of a one hundred percent deterministic understanding of complex realities, but rather an effort toward a systematic interpretation of changes drivers.

3.3.4. Between Gleisdreieck and Südgelände: A Laboratory for Staging New Wilderness for Urban Coexistence

The contemporary urban ecosystem is a paradox: while we are witnessing a dramatic impoverishment of global biodiversity, cities are unexpectedly revealing themselves as places of concentration for high biological diversity (Rinaldi 2024). This observation demands a radical reconsideration of the role of urban planning and design. No longer just actors in growth and the management of human flows, but fundamental mediators in the construction of new habitats and coexistence strategies among the species that inhabit urban ecosystems. Berlin represents, in this sense, an exceptional laboratory. Its unique 20th-century history—wartime destruction, the division of the Wall, and the consequent emergence of vast urban voids—created the conditions for the development of unique ecosystems. Decommissioned industrial areas, and particularly the vast railway yards, were left abandoned for decades. In these "no-man's lands," especially in isolated West Berlin, natural colonization processes took place undisturbed (Kowarik and Langer 2005). This phenomenon led to the birth of what has been defined as "nature of the fourth kind" (Kowarik 2005, cited in Kowarik 2015): a spontaneous, resilient nature that thrives on the debris and infrastructures of the Anthropocene, creating hybrid habitats of extraordinary ecological value. The fall of the Wall posed a crucial question: what to do with these "iron landscapes" (Gandy 2020)? The city's answer was not tabula rasa, but a conscious approach of integration and valorization. This awareness translated into cutting-edge planning tools. As early as 1994, reunified Berlin equipped itself with the Landscape Program (Landschaftsprogramm) and the Land Use Plan (Flächennutzungsplan), which assigned a central role to the open space system and the protection of diffuse naturalness. It is in this political and cultural context that the park system connecting Park am Gleisdreieck to Natur-Park Schöneberger Südgelände was born, transforming an infrastructural fracture line into an ecological backbone. The Natur-Park Schöneberger Südgelände is perhaps the most radical example of this vision. Developed on the former Tempelhof freight yard, the park is the result of planning aimed at “linking conservation and recreation” (Kowarik and Langer 2005). Instead of imposing a traditional design, the project opted to preserve the ecological succession already underway—a pioneer forest of birch and black locust trees that had grown spontaneously between the tracks. The design intervention was minimal and targeted: the insertion of a system of paths and a system of rules capable of gradually dosing and conditioning human accessibility, based on the degree of protection and respect for the ecological functions of the park’s different areas. This choice is a masterful coexistence strategy: humans are invited to enter in the wilderness as observers, to feel and interact with respect and a sense of community. The park is not tamed nature, but a hybrid nature carefully staged (Kapitza and Hofmeister 2020). The park’s management continues to follow this principle, balancing rigorous conservation of some areas with public access, fostering a co-evolution among the industrial vestiges, the flora and fauna, and the human visitors (Suhrhoff 2022). If Südgelände represents the pole of conservation, Park am Gleisdreieck, closer to the city’s beating heart (Potsdamer Platz), embodies the pole of intensive recreation (Kowarik 2015). The challenge here was complex: how to integrate the precious areas of ruderal vegetation—the urban wilderness—with the pressing public demand for space for sports, play, and leisure (Gandy 2020). The solution by Atelier Loidl, winner of the international competition and developer of the project drafted and implemented between 2006 and 2013, was a conscious and intelligent zoning. The park is divided into high-maintenance areas, intended for intensive human use (lawns, plazas, sports areas), and low-maintenance areas, where spontaneous vegetation has been not only preserved but actively integrated into the design (Kowarik 2015). These habitats are protected, but made visible and appreciable, an integral part of the park’s aesthetic experience. Gleisdreieck demonstrates how urban wilderness became possible within a highly-frequented park, not as a remnant, but as an essential and characteristic component of the park’s identity itself (Kowarik 2015). Ultimately, the park system developing along the railway axis between Potsdam and Schöneberg is the implementation of a possible response to the fundamental challenges facing the urban choices of many European cities. Among these is overcoming the public perception that sees uncultivated spaces as disorderly, dirty, or unsafe (Rinaldi 2024) and striving to leave a habitable environment for our descendants of different species (Lambertini 2022). They do so through the power of design. Landscape architecture acts as a cultural mediator, building “a balance between ecology and sentiment” (Rinaldi 2024). The walkways of Südgelände and the clear zoning of Gleisdreieck frame the wild, making it legible, accessible, and characteristic, rooted in the experience of an urban phenomenology that is found all around us. These projects define a “new ecological imaginary” (Gandy 2020) for the 21st-century city. They demonstrate that coexistence between humans and non-humans is not a utopia, but the result of intelligent design, far-sighted planning, and the political will to recognize the city, in its entirety, as a shared habitat. It is therefore a matter of asking how urban settlements can collaborate with other “terrestrials”, undertaking courageous exercises of imagination and embracing the wild as one of the constitutive components of diffuse naturalness and open spaces in current urban landscapes (Lambertini 2022).

4. Lessons learned from comparative case studies on application of Nature-based Solutions

The comparative analysis of the three case studies—Emscher, Lyon Confluence, and the Berlin North-South Green Corridor—through the thematic lenses of the interdependence between biodiversity, resilience, and well-being (topic 2.1); the relationship between ecosystem services and ecosystem functions (topic 2.2); and the creation of habitat and multi-species coexistence (topic 2.3), reveals how urban regeneration projects are evolving towards integrated approaches, albeit with distinct strategies and priorities. On the first topic, the cases demonstrate different models of integration. Emscher Park emerges as an emblematic example of near-total systemic integration. Here, biodiversity restoration has directly generated climate resilience and human well-being, demonstrating how the three elements can be synergistic and mutually reinforcing. In Lyon Confluence, while well-being and resilience are effectively integrated, we observed a less robust connection to biodiversity, highlighting a deficiency in systematic ecological monitoring to measure actual increases. The Berlin system achieves integration by balancing areas of high human use with the strict protection of spontaneous habitats, managing resilience through the inherent naturalness of the sites themselves. Regarding the second topic, a greater diversification of approaches emerges among the cases. In Emscher Park, a strong integration in the pursuit of both ecosystem services and ecosystem functions objectives is observed. Indeed, it can be described as a major ecological restoration strategy—removing anthropogenic stressors (pollutants) and reactivating fluvial processes—which is progressively implemented through a convincing quantification and valorization of ecosystem services, such as hydraulic risk reduction and increased recreational value. Lyon presents an excellent application of NbS focused on services to respond to social and economic challenges; however, the objective of functional restoration of the fluvial environments appears not yet fully achieved, as stressors (e.g., due to inappropriate sewage system) have not been completely removed, and an ecological assessment of actual recovery is lacking. Berlin, while promoting both aspects through rewilding, presents a quantitative assessment of functional restoration (e.g., pollutant reduction) that is partial and sparse. Finally, on the third topic, all cases move beyond an anthropocentric approach, but with different design philosophies. In Emscher, particularly at Duisburg-Nord, the post-industrial landscape is reinterpreted, utilizing its own rubble as a substrate for new, complex micro-habitats. Lyon adopts an adaptive and incremental strategy, activating early ecological cycles via "jardins provisoires" and weaving a network of blue-green corridors that develops with the city. Berlin offers the most radical model: the cultural legitimization of "fourth nature" (spontaneous wilderness). Here, the design of open spaces does not create the nature of the sites, but rather highlights it, making it legible and perceptible.

In conclusion, the three cases outline important reflections on the approaches and modalities for applying NbS for biodiversity in urban contexts. Specifically, it can be affirmed that no single model can be determined; diverse modalities exist because each ecosystem presents a unique geography and a unique history of the human-environment relationship that must be read, interpreted, and re-imagined. Safeguarding and enhancing biodiversity means, first and foremost, shifting from a sectoral to a multidisciplinary approach that involves different fields of knowledge, including through the active participation of inhabitants, as such action is primarily generated by a cultural process. Balancing services and functions—that is, making conscious decisions that posit a principle of ecological equity between what we demand and what we contribute to creating in the urban ecosystem—is therefore fundamental. In this sense, NbS acquires greater efficacy when employed downstream of nature-based approaches aimed at identifying criticalities and potentialities through the systemic observation of environments. This orientation must be directed not only toward well-being, resilience, or the services the environment can provide, but also and above all toward what we ourselves can contribute and achieve as an integral and integrated part of the bio-community, in a sentiment of renewed alliance and coexistence with all species.

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Public engagement for nature-based regeneration of the built environment

Maria Vittoria Arnetoli

Abstract: Cities are increasingly called upon to address the interconnected challenges of climate change, biodiversity loss and growing exposure to natural and anthropogenic hazards. In this context, Nature-based Solutions (NbS) are increasingly recognised as integrated approaches capable of combining ecological restoration, disaster resilience and human wellbeing through the active involvement of communities and living systems. However, their effective implementation requires stronger collaboration between institutions, researchers and citizens, as well as greater public awareness of environmental risks and opportunities for urban regeneration. Moving from an overview of the main international, European and Italian policy frameworks, the chapter investigates public engagement (PE) as a process that can encourage the integration of NbS within the transformation of the built environment. Particular attention is devoted to methodologies relevant to academic research, such as Citizen Science and knowledge co-production, and especially Urban, Environmental and Technological Design, such as co-governance and co-creation. The latter is analysed through a sequence of phases – stakeholder selection, co-design, co-implementation and co-monitoring – that engage communities throughout the entire life cycle of interventions, enabling them to become active agents of change. The contribution also discusses selected tools developed within European research projects aimed at supporting PE in NbS initiatives and highlights the importance of people-centred evaluation methods capable of capturing long-term impacts, particularly in terms of social inclusion and ecosystem services. Collaborative approaches are also central to the Third Mission of universities, which are increasingly called upon to engage with society. Within this framework, the "Code4Risk" project is discussed as an experimental design-based initiative in which knowledge sharing, co-design and self-construction activate the community as a collective architect capable of defining emergency preparedness strategies aligned with the biophilic and circular design principles. Finally, Urban Living Labs emerge as enabling environments where collective intelligence can support the co-creation of resilient and nature-positive urban futures.

Keywords: Nature-Based Solutions, Public Engagement, Co-creation, Multi-stakeholder Partnerships, Urban Living Labs.

1. Cross-cutting cooperation fostering synergies between climate, nature and society

With a 70% probability that the temperature increase will exceed the Paris Agreement threshold of 1.5 °C (WMO 2025)[1], the interconnections between the climate crisis and biodiversity loss are clearly acknowledged, and directly impact the liveability, health and safety conditions of urban environments. Cities, both major contributors to and victims of climate change (CC), are at the same time laboratories of innovation (UN-HABITAT 2024) for the mainstreaming of NbS.

The co-benefits of NbS are recognised as key resources to jointly respond to environmental degradation and social poverty, however, demonstrating these benefits is far from self-evident (EC 2023): while some results are short-term, direct and local, oth-

[1] Available at: https://wmo.int/publication-series/wmo-global-annual-decadal-climate-update-2025-2029?access-token=pNLbdBu8q2rFHbkLrdh9YE5cold58Ic7lc47kQiUg4U

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ers may emerge in the long-term, with indirect impacts at a large scale (Kabisch et al. 2022). Furthermore, although the benefits of NbS are well recognised within the scientific community, the same cannot be said for technicians, practitioners and citizens.

With regard to public perception, the data provided by Eurobarometer surveys are relevant: 85% of Europeans believe that CC[2] is a serious problem and a priority for improving the quality of life (2025); while with regard to biodiversity[3] (2018), if about seven out of ten have heard the term "biodiversity", only four out of ten know its meaning. At the national level, ISTAT data on environmental concerns (2024) show that 58.1% of the population expresses worry about the climate crisis.

Dealing with the complexity of the interacting socio-environmental crises that shape our societies requires not only overcoming the boundaries between disciplines and sectors, but also adopting approaches that hybridise top-down and bottom-up logics. Therefore, promoting NbS with a cooperative approach, aligned with the "One Health" vision (WMO[4]) not only raises consciousness and thus reduces social vulnerability, but also ensures that interventions are better tailored to the specific characteristics of the context and helps avoid undesirable effects such as maladaptation or green gentrification.

Philippe Tulkens, Deputy Mission Manager of the EU Mission on Adaptation to CC, emphasises, on the occasion of the *European Climate Change Adaptation Conference* (ECCA 2025), the urgent need to redesign the chain of knowledge transfer from researchers, national and local authorities to citizens. Communities are not passive recipients but active partners in accelerating the ecological transition, which must be founded on trust between people and institutions, listening skills and opportunities for co-creation. Co-creation in the architectural field can be understood as «any act of collective creativity» (Sanders and Stappers 2008, 6): understanding creativity as a collaborative practice can help consolidate NbS within the collective imagination.

Among others, the siloed organisation of urban policies, the competition between different priorities and the limited participation of residents (UN-HABITAT 2024) prevent NbS projects from expressing their full potential. In response, it is necessary to adopt flexible and adaptable tools that raise the understanding of the interconnections between the ecological crisis and daily issues such as poverty, health issues and inequalities, counteracting apathy and scepticism through knowledge-sharing practices.

To this end, universities are called upon to play a fundamental social role as facilitators, opening up to society and finding in public engagement (PE) a driver for cultural and social innovation. Today, the Third Mission assumes strategic value in academia (Claudi de Saint Mihel 2019) and sees the university engaged in strengthening cooperation between institutions and local communities.

In particular, design disciplines can provide both technical expertise and visionary capacities to support the co-development of sustainable and shared future scenarios.

2. Promoting nature-based solutions through participatory approaches: from global agendas to local practices

Enhancing NbS through PE is strongly promoted by a wide range of policies, programmes and regulations at multiple governance levels, from the international to the city level.

[2] Available at: https://eccoclimate.org/it/italiani-ed-europei-sono-a-favore-dellazione-per-il-clima-lo-dice-l-eurobarometro/

[3] Available at: https://europa.eu/eurobarometer/surveys/detail/2194

[4] Available at: One health

At the international level, several global agendas emphasise the importance of PE in responding to climate-related and ecological pressures. In particular, the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity encourage the implementation of NbS through community-based processes. Similarly, the 2030 Agenda for Sustainable Development, in particular SDG 11 in its target 11.3 "Enhance inclusive and sustainable urbanization and capacity for participatory planning", calls for strengthening PE in urban regeneration processes.

At the European level, the active involvement of communities in environmental decision-making is rooted in the Aarhus Convention (1998, in force since 2001), subsequently incorporated into the European legislation through Directive 2003/35/EC. More recently, the European Green Deal encourages the active involvement of citizens and stakeholders in shaping climate adaptation and environmental transformation processes. More specifically, both the EU Strategy on Adaptation to Climate Change (2021) and the EU Biodiversity Strategy for 2030 (2020), which paved the way for the EU Nature Restoration Law, establish clear commitments to multi-level collaboration in the implementation of NbS.

In the Italian context, the National Strategy for Adaptation to Climate Change (2015), states that PE in adaptation processes ensures greater public understanding and social acceptance of adaptation measures and highlights the need for collaboration with the scientific community.

Concerning the specific issue of PE in urban planning, the transparency and public availability of planning and territorial governance documents, including plans and their variations, are mandatory under Law 1150/1942, Legislative Decree 33/2013 on administrative transparency and, more broadly, the principles of participation established by Law 241/1990, followed by the regulations of the individual regions. At the local level, some regional planning frameworks – particularly in the Tuscany Region (Regional Law 65/2014) – have introduced the role of the "Information and Participation Supervisor" (*Garante dell'Informazione e della Partecipazione*), whose functions are regulated by municipalities through specific regulations. Engagement is therefore mainly conceived as an information and transparency mechanism, while the development of structured PE practices remains only partially regulated within planning procedures.

Despite the growing recognition of PE as a key enabler for the effective implementation of NbS in urban contexts, the policy framework outlined above suggests the need for a more structured integration of participatory processes, which could be addressed through the definition of specific provisions.

3. Public engagement as a process: methodologies, phases and tools for co-creation

Like other urban transformation processes, NbS intervention are not inherently inclusive or participatory. However, the active involvement from the outset of a multiplicity of stakeholders, and thus a wide range of perceptions, needs and expectations, helps to ensure greater alignment with local needs, facilitating greater acceptance and also nurturing a sense of belonging and ownership. Especially co-ownership, by fostering emotional connections between people and places, generates commitment to the long-term care of the intervention (Brown and Katz 2011).

As Esteban (2020) states, in order to balance the interests of different social groups and local concerns with broader societal objectives, participation cannot be treated as an additional measure but must become a structural and routine component of urban regeneration processes, based on mutual sharing and learning.

3.1. Methodologies

PE can encompass a wide range of initiatives, among which Citizen Science and the co-production of knowledge are of particular interest for academic activities.

Citizen Science (CS) (Capineri et al. 2025) is reshaping scientific research as a societal common good, in the spirit of Open Science. By involving citizens not only in data collection but also in the identification and analysis of local community priorities, CS innovates the ways in which knowledge is produced and used (Hecker et al. 2018) and contributes to the democratization of science (Irwin 1995).

The co-production of knowledge recognises civil society as an active driver of knowledge generation and experimentation. The exchange of different forms of knowledge among citizens, stakeholders and institutions, facilitated by universities, enables decision-makers to gather input from the daily users of spaces, neighbourhoods and services, while allowing people to gain new expertise.

Furthermore, within the fields of Urban Planning and Environmental and Technological Design, co-governance and co-creation, which represent closely interrelated processes, are of particular interest.

Co-governance or collaborative governance refers to «mechanisms in which citizens take part in the decision-making processes alongside local authorities and public or private stakeholders» (EC 2023, 46). Although the bureaucratic structure of public administrations still limits participation today, the ecological crises require the adoption of the "whole of society" approach (World Bank[5]) within «open, multi-phased, iterative, inclusive, flexible and adaptable» processes (Mahmoud et al. 2021).

Co-creation, understood as «the process of participation, interaction, collaboration, or co-production with citizens (organised or unorganised), political representatives, public officers, private stakeholders, and researchers» (EC 2023, 18), represents an emerging domain within the design field, whose phases and tools are discussed below.

3.2. Phases

Based on the literature on PE, the co-creation process can be structured into the following four main phases.

3.2.1. Stakeholder selection

Involving a plurality of actors from the outset helps limit potential conflicts, counteract scepticism and build motivation (Zingraff-Hamed et al. 2020). The "ecologically sensitive" Fifth Helix model (Carayannis et al. 2012), identifies the following key actors to be involved: academia, industry, government, culture, environment. Yet, in this first step of the PE process, the key question is: «How to engage all stakeholders and not only the "usual suspects"?» (UN-HABITAT 2024, 25). To prevent urban projects from reproducing, exacerbating or creating inequalities, and thus to ensure a "just transition" (UNDP[6]), it is necessary to give a voice to the most vulnerable groups: the elderly, women, children, and ethnic and religious minorities. In this regard, the Re-

[5] Available at: https://blogs.worldbank.org/en/arabvoices/how-can-governments-develop-a-whole-of-society-approach-to-address-the-climate-crisis

[6] Available at: https://climatepromise.undp.org/news-and-stories/what-just-transition-and-why-it-important

silience for Communities programme[7] identifies three factors to fairly select the target community: exposure to risks, access to resources and services, and socio-economic and institutional conditions. Useful tools for conducting fair stakeholder mapping include the RESIN guide, suggested by the Climate-ADAPT web portal, which adopts an influence-interest matrix (high/low influence, high/low interest), while the RACI matrix classifies actors as responsible, accountable, consulted and informed.

3.2.2. Co-design

Co-design (CD) is a collaborative design method in which experts, technicians, architects and facilitators work together with stakeholders and citizens (Holmlid 2009), thereby strengthening the communities themselves. The Engage2020 project identifies art, modelling, photography, graphics, mood boards, map making and scale modelling as tools. Through visioning and forecasting activities, starting from the requirements framework, the project is developed through the creation of one or more shared and collectively accepted scenarios. The design process unfolds through cycles of «divergency, selection, convergence, synthesis and analysis» (EC 2023, 36). CD may lead to longer timeframes and higher costs compared to "expert-led" processes. However, the benefits in terms of environmental and cultural compatibility and social acceptance of the adopted solutions may far outweigh the initial investment in the long run. One of the key outcomes of CD is "mutual learning" (Simonsen and Robertson 2013), which becomes "social learning" when referring to the co-creation of strategies (Sanders and Stappers 2008). Finally, "design as learning" occurs, i.e. that «learning happens within the design process itself» (EC 2023, 40).

3.2.3. Co-implementation

Co-implementation is the phase where «local residents can leave their mark on the land» (EC 2023, 43). Although involving people in site work is a complex challenge, since it requires specific preparation and the use of work and safety equipment, physically realising the intervention helps build a sense of belonging and shared ownership of the space (Lydon and Garcia 2015). People can actively contribute to shaping the outcome, for instance by defining the location of equipment or taking responsibility for small areas, planting vegetation, colouring or adding details, or participating in the choice of materials and urban furniture. Concerning the physical transformation of the urban space, co-implementation is perhaps the phase that plays the strongest role as a catalyst for positive change. Furthermore, training activities can stimulate new micro-economies supporting the most disadvantaged groups.

3.2.4. Co-monitoring

The European Commission's handbook for NbS practitioners (EC 2021) states that monitoring must be central to every NbS project, emphasising that developing it in a participatory way enhances its value as an awareness-raising and accountability activity. Collaborative data collection and dissemination activities on NbS performance can be classified into four types with different levels of participation (Lawrence 2006, 290): consultative, functional, collaborative, transformative. EU-funded projects on NbS have developed and

[7] Available at: https://resilientcitiesnetwork.org/downloadable_resources/Programs/R4C_CommunitySelectionGuide.pdf

tested numerous monitoring methodologies: participatory assessment (CONEXUS[8]); social monitoring (CLEVER Cities[9]); comprehensive framework for NbS assessment (PHUSICOS[10]); reflexive monitoring (Connecting Nature[11]). Of particular interest are the four phases identified by the CONEXUS project: 1) defining shared monitoring goals and objectives; 2) indicator selection; 3) data collection; 4) data analysis and evaluation. Among the categories of data used by the CLEVER Cities project in social monitoring, the synergies between nature and wellbeing are investigated in relation to the use of spaces, sense of belonging, social interactions, psychological issues and perceptions of safety and security.

3.3. Tools

The following is a selection of decision-making tools developed within European projects that promote NbS through PE processes and are considered particularly relevant for the research.

ClimateAdapt's "Do-it-yourself" handbook"[12] is a step-by-step guide for regional and local authorities to identify the most suitable participatory activities for their purposes, encouraging the establishment of a "community of practice".

The GrowGreen project's "Co-design Guide"[13] is aimed at policymakers responsible for NbS projects and includes 3 steps: 1) data collection, target setting and impact assessment of the identified alternatives; 2) definition of the financial framework; 3) collaborative monitoring of results.

The NATURE4CITIES open-source platform[14] provides digital tools for creating, evaluating and implementing NbS projects, such as the NbS explorer, Geocluster4NbS, the Environmental Assessment Tool and the "Step-by-step guide on Engagement strategies and tools".

The NATURVATION project's "Book on Citizen Engagement"[15] matches different PE methodologies with the type of promoter or stakeholders involved: for municipalities, round tables, co-design workshops and citizen panels; for associations, neighbourhood forums, district-based community work, environmental education; for the inclusion of marginalised groups, advocacy planning and community organisation.

The URBiNAT project developed an interactive co-selection and co-creation catalogue of NbS[16], by categorising the solutions into 4 groups: territorial, technological, social and solidarity economy and participatory.

The AGORA project[17] created the interactive platform "Agora Community Hub" which shares needs, knowledge and experiences on adaptive communities and aims to define a roadmap to scale up stakeholder and citizen involvement in Europe.

Although these tools differ in scope and methodology, they collectively reflect the growing integration of participatory practice within NbS implementation frameworks.

[8] Available at: https://www.conexusnbs.com/
[9] Available at: https://clever-guidance.urbanbynature.eu/
[10] Available at: www.phusicos.eu
[11] Available at: https://connectingnature.eu/
[12] Available at: https://climate-pact.europa.eu/eu-climate-action-academy/resources/do-it-yourself-diy-manual-mobilising-and-engaging-stakeholders-and-citizens-climate-change_en
[13] Available at: https://growgreenproject.eu/wp-content/uploads/2022/11/NbS-Codesign-guide-Bipolaire-22.pdf
[14] Available at: https://www.nature4cities.eu/results
[15] Available at: https://naturvation.eu/sites/default/files/result/files/citizen_engagement_handbook.pdf
[16] Available at: https://urbinat.ces.uc.pt/nbs-catalogue/
[17] Available at: https://adaptationagora.eu/outputs/

4. Code4Risk: a design-based community engagement project

Within the PE framework for NbS outlined above, the "Code4Risk" project is proposed as an experimental application of design-based PE to foster community awareness and co-creation processes for urban resilience. Winner of the call for Third Mission projects "UNIFI EXTRA 2024", the project was promoted by the Department of Architecture (DIDA) and the Civil Protection Centre (CPC) of the University of Florence, and implemented with the support of the Civil Protection Office of the Municipality of Florence and with the collaboration of Sociolab in the conception and facilitation of the activities and of "TEMP- ETS" for the cultural background.

Consistent with the fragility of Italian territories, and specifically the context of Florence, "Code4Risk" adopts a multi-risk approach combining hydrogeological and seismic hazards (earthquake and flooding) and climate-related hazards (heat islands, heat waves and extreme rainfall).

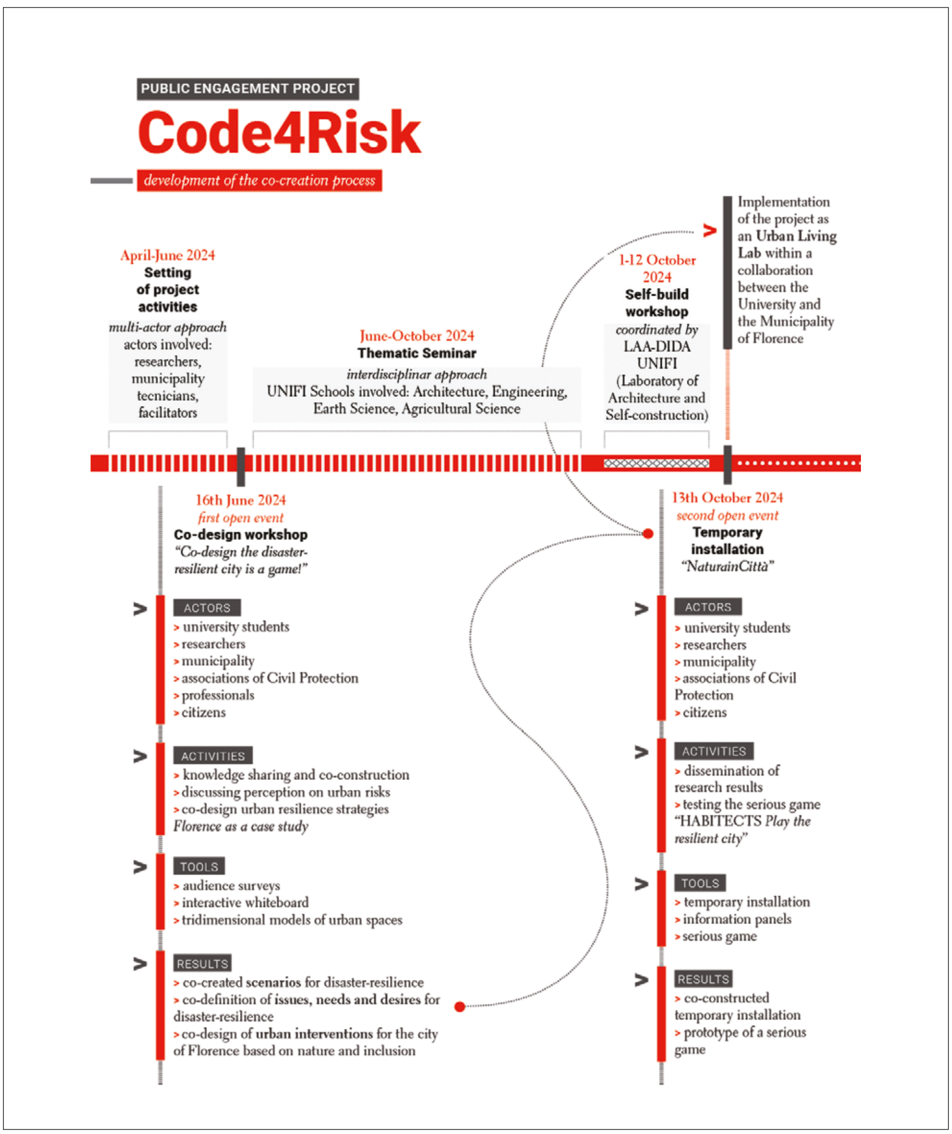

Fig. 1 – "Code4Risk" co-creation process. (Diagram by the Author).

Fig. 2 – Multi-stakeholder discussion during the co-design workshops of the "Code4Risk" public engagement project (16/06/2024, "Le Murate" Florence). (Photo by the Author).

Fig. 3 – Interactive white-boards where facilitators documented key insights from the discussions using post-it notes, drawings, and diagrams during the co-design workshops of the "Code4Risk" public engagement project (16/06/2024, "Le Murate" Florence). (Photo by the Author).

Aiming to boost synergies between the sustainability goals of the 2030 Agenda and Disaster Risk Reduction, the project brings together emergency preparedness with climate adaptation, biodiversity protection, and the liveability of urban spaces, placing the design perspective at the centre according to a collaborative, circular, and biophilic approach.

The initiative took place in Florence between June and October 2024 and was structured into 3 phases (see Figg. 1-4): a co-design workshop (16/06/2024) (Arnetoli et al. 2025), the first open event, which involved technicians, volunteers, citizens and university

Fig. 4 – Opening of the "NaturainCittà" installation and the presentation and first testing of the serious game "HABITECTS. Play the Resilient City®" (13/10/2024, "Le Murate" Florence). (Photo by the Author).

students in thematic discussions on risk perception, co-production of knowledge and co-design of urban resilience strategies through the use of 3D models representing architectural elements (house, street, square); a self-build workshop (October 2024), in which the DIDA-UNIFI Architecture and Self-Construction Laboratory coordinated the design and construction of a temporary installation together with an interdisciplinary group of university students, turning the intervention into an open construction site with strong educational value; the "*NaturaInCittà*" installation (13/10/2024), the second open event, organised as part of the National Civil Protection campaign "*Io non rischio*", which hosted information material on natural hazards and nature-based resilience strategies.

The opening of the installation was also an opportunity to test the serious game "HABITECTS. Play the Resilient City®" developed from the results of the co-design workshop, which subsequently led to the establishment of a collaboration with the Municipality of Florence to test the application of NbS as a tool to reconnect fragmented and degraded urban spaces through participative approaches, within the framework of an Urban Living Lab.

5. Urban Living Labs as spaces for collective thinking and design

Implementing the transition from disaster-prone to disaster-resilient cities in a fair and inclusive way requires citizens who are aware of the severity of the ecological crisis and practitioners trained to implement NbS.

> Living in a city can disconnect us from nature, but we remain dependent on many ecosystem services [...]. It is critical that policymakers and citizens work together, to better understand, value and protect the crucial relationship between cities and nature, as well as how urban nature-based solutions can facilitate more resilient urban environments (Jennifer Lenhart, global lead of WWF's One Planet Cities).

PE constitutes a deliberative activity that contributes to building trust between citizens and institutions and thus forms a key component of democratic systems (Willis et al. 2022; Jacobs et al. 2009). Co-creation and co-governance make society – understood as the 'software' component that enables the urban 'hardware' to function – an active designer, builder and manager of ecosystem-based regeneration processes.

Accordingly, Living Labs (LLs) represent socio-cultural networks where the diverse components of the community can become active and collaborate in the transformation of society and, consequently, of its physical environment. The European Network of Living Labs[18] (ENoLL) gathers experiences and resources with the aim of globally promoting LLs as «user-driven open innovation ecosystems». The Joint Programming Initiative (JPI) Urban Europe[19], introduced the term Urban Living Labs (ULLs), defining them as a forum for innovation. ULLs therefore represent a privileged public arena in which collective thinking can be translated into collective design.

Through his work and reflections, Carlo Ratti (2025) highlights how the myth of the architect as a Promethean figure still survives today, personified by a solitary creator – or archistar – who is convinced of his genius and his power to save society, while architecture has remained one of the few sectors «still largely immune to the gravitational pull of participation» (Ratti 2025, 80). On the contrary, the history of architecture, to quote Ratti again

> Is an epic, never told, of anonymous architecture: spontaneous or vernacular architecture, without a name, is the cultural expression of the human need to have not only shelter, but also a position, an identity, pleasures (Ratti 2025, 20).

In this sense, ULLs constitute a hybrid environment that hosts and encourages that *continuum* of small acts of design that, throughout human history, have produced cities as collective works of art. Placed in the tradition of Bernard Rudofsky's exhibition "Architecture without Architects" (MoMA, New York, 1964-65), ULLs become contemporary spaces in which the "orchestrating architect" is replaced by an orchestra of collective

[18] Available at: https://enoll.org/

[19] Available at: https://jpi-urbaneurope.eu/urbanlivinglabs/

intelligences, allowing the reactivation «of the ancient settlement process in which the act of living and the built form are a single entity» (Habraken 2013). In Marco Romano's thought, this corresponds to reconnecting "moral citizenship" with "material citizenship".

To encourage the institutionalisation of PE in urban regeneration processes, it is necessary to develop robust economic and people-centred evaluative frameworks capable of capturing both the tangible and intangible benefits generated by participatory approaches, particularly in the implementation of NbS. This includes the integration of cost–benefit analysis, impact assessment and co-benefit evaluation, supported by tools such as Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), in order to capture the long-term environmental, social and economic value of NbS. Such approaches can help highlight benefits that extend beyond immediate economic returns, including community empowerment, ecosystem services, human wellbeing and urban resilience.

In conclusion, the PE gives shape to a renewed form of Tomas Maldonado's (2022) "design hope", grounded in a shared cultural matrix that allows the "human environment", the anthropic subsystem through which human activities continuously transform the planet to coexist again with nature. In this perspective, ULLs emerge as fertile environments in which PE can co-create NBS projects to shape more resilient and inclusive urban transitions.

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SECTION 3

Application tools

The NbS CataTool of the National Biodiversity Future Center

Chiara Catalano

Abstract: Nature-based Solutions (NbS) represent a strategic approach to tackling the climate crisis, biodiversity loss, and other societal challenges in an integrated manner. This chapter retraces the evolution of the NbS concept, from the initial definitions by the European Commission and IUCN to the most recent UNEA formulation. It highlights how the growing relevance of NbS within European policies—including the Green Deal, the Nature Restoration Regulation, and Horizon research programs—has driven the need for decision-support systems (DSS) and monitoring initiatives. The NbS CataTool is a DSS developed within the National Biodiversity Future Center (NBFC) to facilitate the selection, implementation, and mainstreaming of NbS across urban, terrestrial, and marine environments in the Mediterranean context. Built upon a standardised taxonomy of over 100 NbS and an interconnected database of case studies, the tool integrates scientific evidence with practical decision-making needs. The DSS operates through three main functionalities: (1) an NbS Selection Tool, which guides users through a stepwise process based on NbS types, environmental domains, implementation contexts, and societal challenges; (2) a Learning Tool enabling open exploration of NbS through solution attributes; and (3) a Case Study Finder providing georeferenced, metadata-rich examples evaluated through a shared performance framework. Both solutions and case studies are provided with synthetic cards, detailed sheets, and expert-based evaluations linked to 12 global societal challenges. Distinguishing itself from existing DSS, the NbS CataTool offers a comprehensive, evidence-based, cross-domain NbS nomenclature and a harmonised evaluation structure aligned with European policies and standards.

Keywords: NbS Nomenclature, Landscape and Urban Planning, Biodiversity Strategy, Nature Restoration Regulation, Evaluation Framework.

1. Why are NbS important for people and nature?

Nature-based Solutions (NbS) were introduced in the early years of this century (World Bank 2008) and implemented within the European Commission (EC) Research and Innovation (R&I) policies over the past decade (European Commission 2015; 2025; Faivre et al. 2017) as a concrete answer to both the climatic and biodiversity crises, while generating environmental, economic, and social benefits (Dunlop et al. 2024). As introduced in Chapter *Nature and Artifice. An holistic approach to environmental and technological design*, NbS is an 'umbrella-concept' encompassing and derived from various ecosystem-based approaches such as bioengineering, agroforestry, green and blue infrastructure, all desirably working in synergy (Seddon et al. 2021). The path leading to the contemporary understanding of NbS is characterised by several milestones, starting from the first time they were mentioned in the early 2000s and continuing with their definition at the institutional level, as well as the publication of relevant reports, regulations, and resolutions that have supported their adoption in recent policies (Figure 1).

The different NbS definitions mirror the growing importance that biodiversity and ecosystems functioning have gained over time in shaping the concept of NbS, alongside their fundamental role in improving human-wellbeing (Table 1). Initially, according to

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Fig. 1 – Timeline of the development of the NbS concept and key milestones at EU and global levels. Modified and expanded from Cohen-Shacham et al. (2016) and Somarakis et al. (2019).

the definition introduced by the EC (European Commission 2015) and refined successively by the EC (European Commission, n.d.), NbS are conceived as actions inspired by and supported by nature, excluding solutions that merely imitate natural processes (Bianciardi et al. 2023). Subsequently, with the IUCN definition (Cohen-Shacham et al. 2016), further developed by the United Nations Environment Assembly (UNEA) (Nature-Based Solutions for Supporting Sustainable Development 2022), NbS came to encompass actions aimed at protecting, restoring and sustainably managing natural or modified ecosystems, to simultaneously address economic, environmental, and social challenges, thereby generating benefits for both people and nature. Despite these evolutionary shifts, a clear commonality emerges across definitions: the need to tackle social challenges through the implementation of multifunctional NbS capable of delivering multiple ecosystem services (Nesshöver et al. 2017), either individually or in combination with other nature-inspired or -derived approaches (Cohen-Shacham et al. 2019; IUCN 2020a).

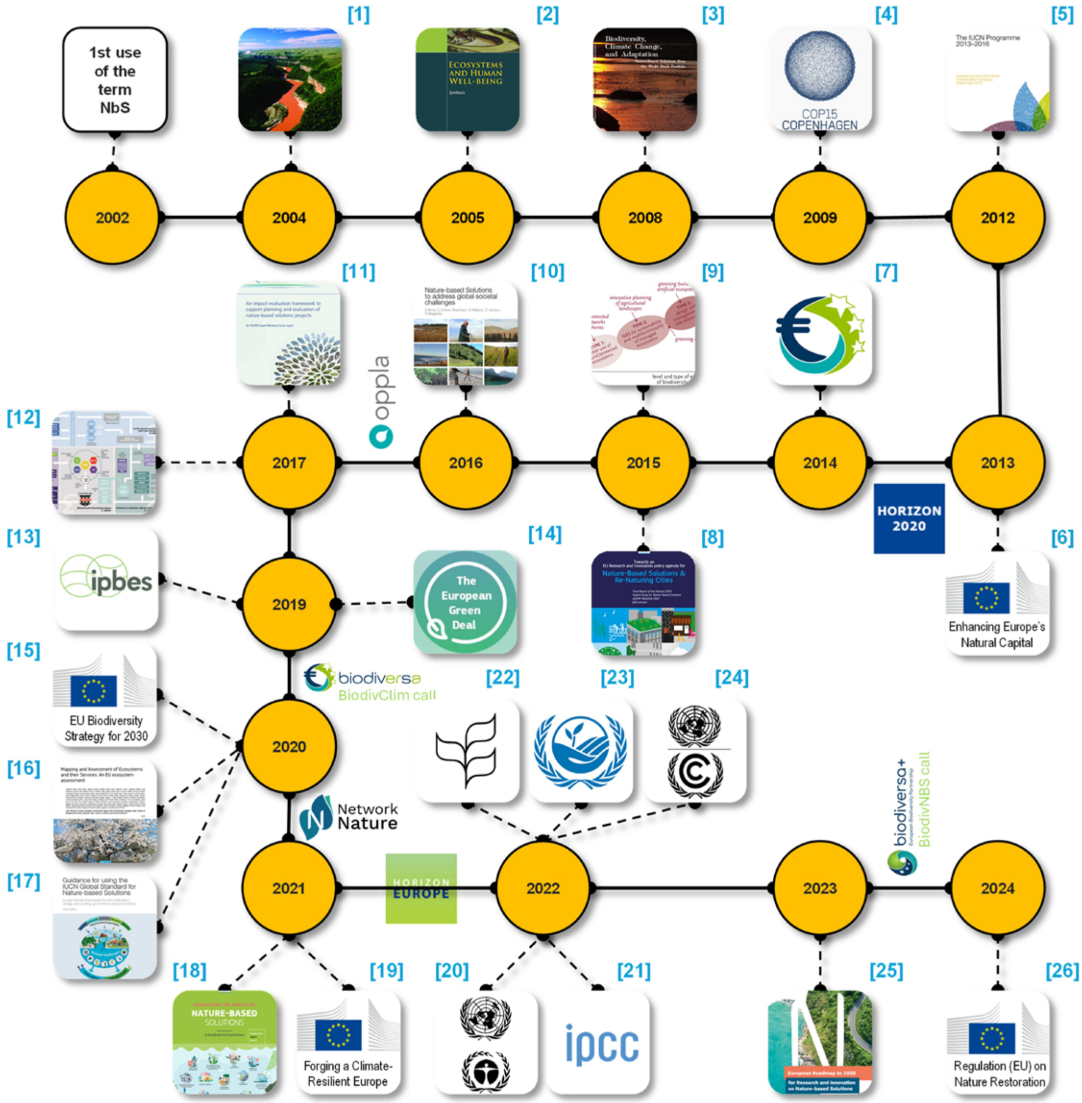
Table 1– Comparison among NbS definitions provided by the European Commission (EC), the International Union for Conservation of Nature (IUCN), and the United Nations Environment Assembly (UNEA). In orange, concepts which changed or gained more weight across definitions; in green, the commonalities across definitions.

EC 2015	EC 2025	IUCN 2016*	UNEA 2022**
"Actions which are inspired by, supported by or copied from nature. Some involve using and enhancing existing natural solutions to challenges, while others are exploring more novel solutions, for example mimicking how non-human organisms and communities cope with environmental extremes. Nature-based solutions use the features and complex system processes of nature […] to achieve desired outcomes […]. These nature-based solutions are ideally energy and resource-efficient, and resilient to change, but to be successful they must be adapted to local conditions".	"Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions".	"Actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits". 	"Actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits. […] 

*IUCN definition infographic can be found at IUCN (2020b)
**UNEA definition infographic can be found at https://www.conexusnbs.com/nbs-definition-infographics

The evolution of the definitions is closely related to the adoption of NbS at legislative and operational levels[1] (Figure 1). NbS have been recognised as essential by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

[1] See also Chapter *Policies and regulatory frameworks for urban and riverine nature restoration* for more information on regulatory frameworks.



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[26] Regulation (EU) on Nature Restoration, 2024/1991, European Parliament (2024).

(IPBES) for achieving the Sustainable Development Goals within and beyond cities (IPBES 2019), and by the Intergovernmental Panel on Climate Change (IPCC) as key to enabling climate-resilient development (IPCC 2022).

Furthermore, NbS as defined by UNEA (Nature-Based Solutions for Supporting Sustainable Development 2022) have been incorporated across the three Rio Conventions[2]: the *Sharm el-Sheikh Implementation Plan* of the UN Climate Change COP27 (Sharm El-Sheikh Implementation Plan 2023) which calls to reverse forest cover and carbon losses; the *Kunming-Montreal Global Biodiversity Framework* of CBF COP15 (Kunming-Montreal Global Biodiversity Framework 2022), which aims to reduce impacts on biodiversity (target 8) while restoring nature's contribution to people (target 11); and the UNCCD COP 15 (Action Taken by the Conference of the Parties at Its Fifteenth Session 2022) where NbS are highlighted as a means of sustainable land management. An important milestone achieved at the COP27 was the launch of the ENACT (Enhancing Nature-based Solutions for an Accelerated Climate Transformation) partnership: a voluntary coalition co-chaired by Egypt and Germany and coordinated by IUCN to contributing shaping a global agenda on NbS and across the Rio Conventions (ENACT 2024). Another significant step forward, is the entry in force of the EU *Nature Restoration Regulation* (NRR) on the 18th August 2024 (Regulation (EU) 2024/1991 2024). The NRR acknowledges the central role of NbS – and other ecosystem-based approaches – within broader policy landscape including the CBD global biodiversity framework, the EU Climate Law on climate neutrality (Regulation (EU) 2021/1119 2021), and the EU Strategy on Adaptation to Climate Change (Forging a Climate-Resilient Europe - the New EU Strategy on Adaptation to Climate Change 2021). It also promotes NbS as a means to increase urban green areas and trees cover in line with the EU biodiversity strategy (EU Biodiversity Strategy for 2030 2020), which calls on European town and cities with at least 20 000 inhabitants to develop Urban Nature Plans (previously named Urban Greening Plans). The policies outlined above were established to advance the targets set by The European Geen Deal[3] (The European Green Deal 2019) which aspires to safeguard and restore ecosystems, halt biodiversity loss, and achieve a climate-resilient Europe by 2050.

Together with the issuing of both binding and facultative policies, the uptake of NbS has been further enabled through substantial EU investments, particularly via Horizon 2020 (2014-2020) and Horizon Europe (2021-2027) Research and Innovation programs. These frameworks have supported more than 100 NbS-related projects within cluster 6: Food, Bioeconomy, Natural Resources, Agriculture and Environment[4], as well as EU-Missions[5] (European Commission 2025). In addition to these funding instruments, the implementation, upscaling and mainstreaming of NbS have been sig-

[2] The three Rio Conventions tackle the interconnected challenges of Climate Change, Desertification and Biodiversity Loss, respectively in the United Nations Framework Convention on Climate Change (UNFCCC), United Nations Convention to Combat Desertification (UNCCD), and Convention on Biological Diversity (CBD).

[3] Further information on the European Green Deal at https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

[4] Further information on Cluster 6 at https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/cluster-6-food-bioeconomy-natural-resources-agriculture-and-environment_en

[5] Further information on EU Missions at https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/learn-more-about-eu-missions_en

nificantly supported by the European co-funded partnership Biodiversa (2015-2022)[6] and Biodiversa+ (2021-2028) in cooperation with NetworkNature[7]. This partnership played from the beginning a pivotal role in shaping the conceptual foundation of NbS and in their mainstreaming into science-driven policies, while fostering stakeholders' engagement across sectors (Balian et al. 2014). Collectively, these initiatives contribute to the long-term vision that by 2050, "people are living in harmony with Nature" (Eggermont et al. 2021; Lemaître and Le Roux 2021).

2. Aims and functions of the NbS CataTool

The complex scenario and the ambitious targets set by the latest EU policies, as outlined in the previous paragraph, pose challenges at the operational level where the implementation of NbS must address context-specific conditions. In this regard, interactive multi-stakeholder tools are essential for enabling evidence-based decision-making and fostering cooperation among different sectors. For example, tools integrating standards and case studies together with reliable monitoring data can enhance citizens' awareness and knowledge while supporting co-design and co-governance initiatives, thereby strengthening NbS credibility and fostering their effective uptake (Catalano et al. 2024; Voskamp et al. 2021).

The National Biodiversity Future Center (NBFC), funded by the NextGeneration EU (European Commission 2021) as part of the Italian National Recovery and Resilience Plan (RRP), has invested substantial efforts in advancing the uptake of NbS through several interconnected activities carried out by the NBFC spokes[8]. Integrating scientific research with innovation and implementation of nature-based solutions, the NBFC aimed to position biodiversity as a central element for sustainable development, addressing global challenges through Monitoring, Conservation, Restoration, and Valorisation (MCRV). This mission is in line with the NbS approach outlined in the previous paragraph and the NbS-Types proposed by Eggermont et al. (2015), which considers the level and type of engineering as a discriminant among NbS (Figure 2).

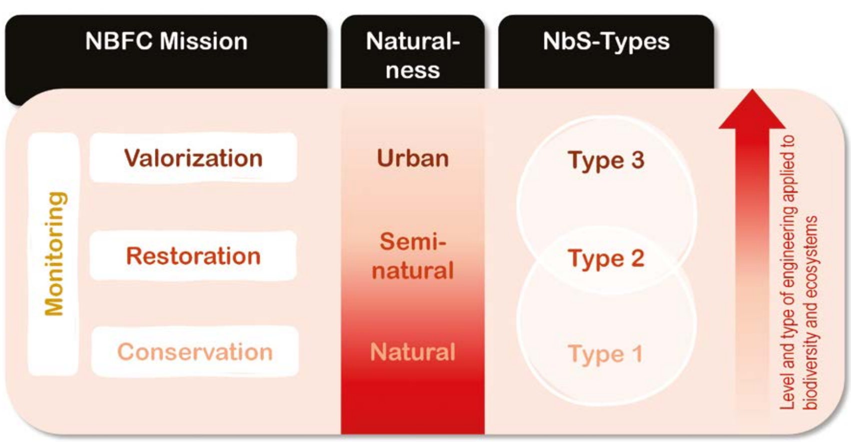


Fig. 2 – Relationship between the MCRV mission of the NBFC, the degree of Naturalness, and the NbS types (as defined by Eggermont et al. 2015).

[6] Details on Biodiversa and Biodiversa+ EU funded project can be found respectively at https://cordis.europa.eu/project/id/642420 and https://cordis.europa.eu/project/id/101052342

[7] Details on NetworkNature and NetworkNature+ can be found respectively at https://cordis.europa.eu/project/id/887396 and https://cordis.europa.eu/project/id/101082213/it

[8] For more information NBFC structure see Introduction of this book

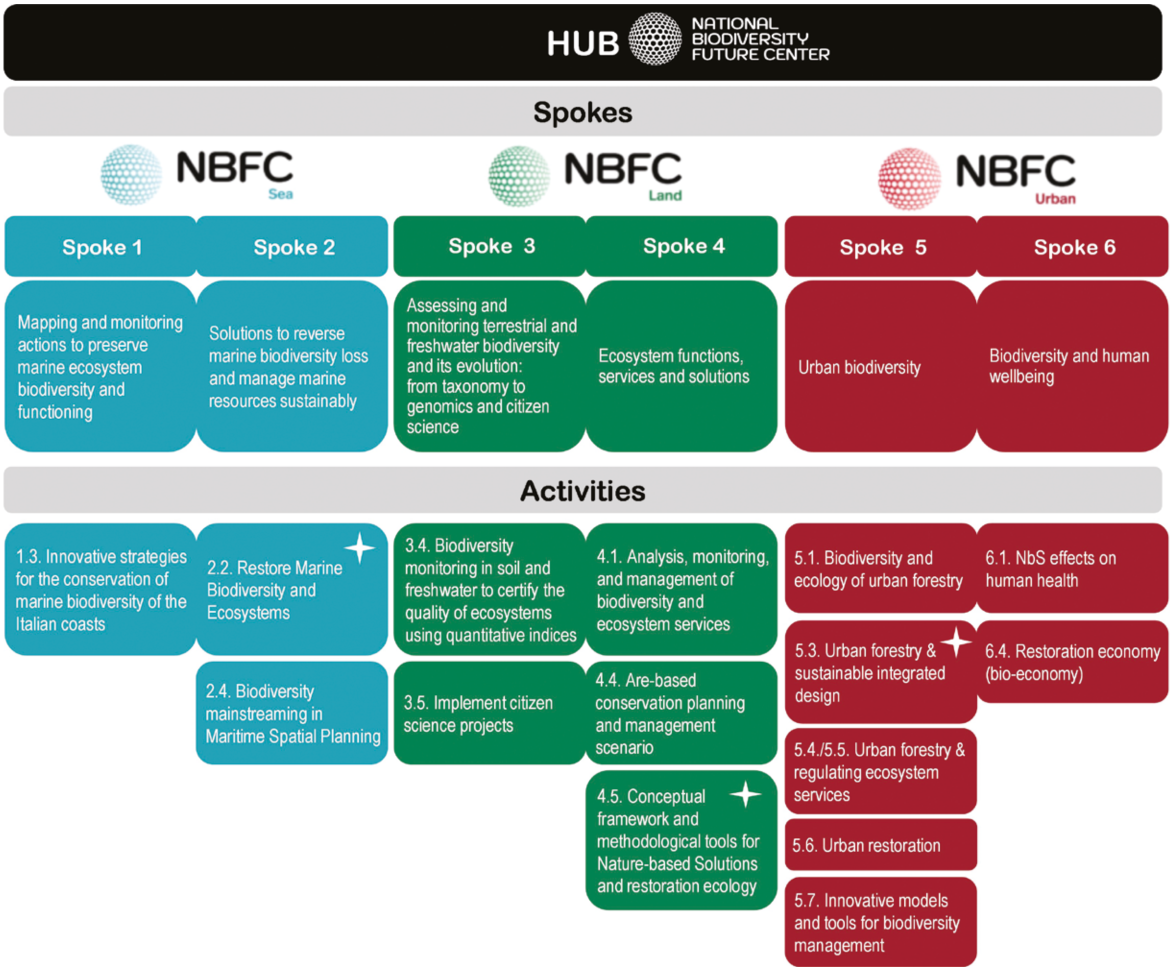


Fig. 3 – Sea, Land and Urban spokes of the National Biodiversity Future Center (NBFC). Stars indicate the activities involved in the development of the NbS CataTool.

This vision also represents the common denominator among the interlinked activities carried out across spokes 5 (Urban), 4 (Land), and 2 (Sea) related to NbS (Figure 3). A key crossing-cut outcome of these activities is the development of the NbS CataTool: a Decision Support System (DSS) aiming at facilitating the implementation and mainstreaming of NbS within the Mediterranean context. The tool encompasses solutions spanning different degrees of naturalness and anthropogenic impact across ecosystems, ranging from urban to natural contexts.

The DSS is an interactive online tool[9] that operates as (1) an *NbS selection tool*, (2) a *Learning tool*, and (3) a *Case study finder*. These functionalities build upon two databases, namely the **NbS database** and the **Case Study database**, which are linked through a shared taxonomy and evaluation framework (Figure 4a).

The *NbS selection tool* allows users to identify a range of NbS following a stepwise procedure (Figure 4b):

[9] The NbS CataTool is freely accessible online (https://tinyurl.com/CataTool) among the digital solution for biodiversity on the Biodiversity Gateway platform of the NBFC (https://www.biodiversitygateway.it/servizi-per-la-biodiversita/servizi-digitali-per-la-gestione-della-biodiversita/).

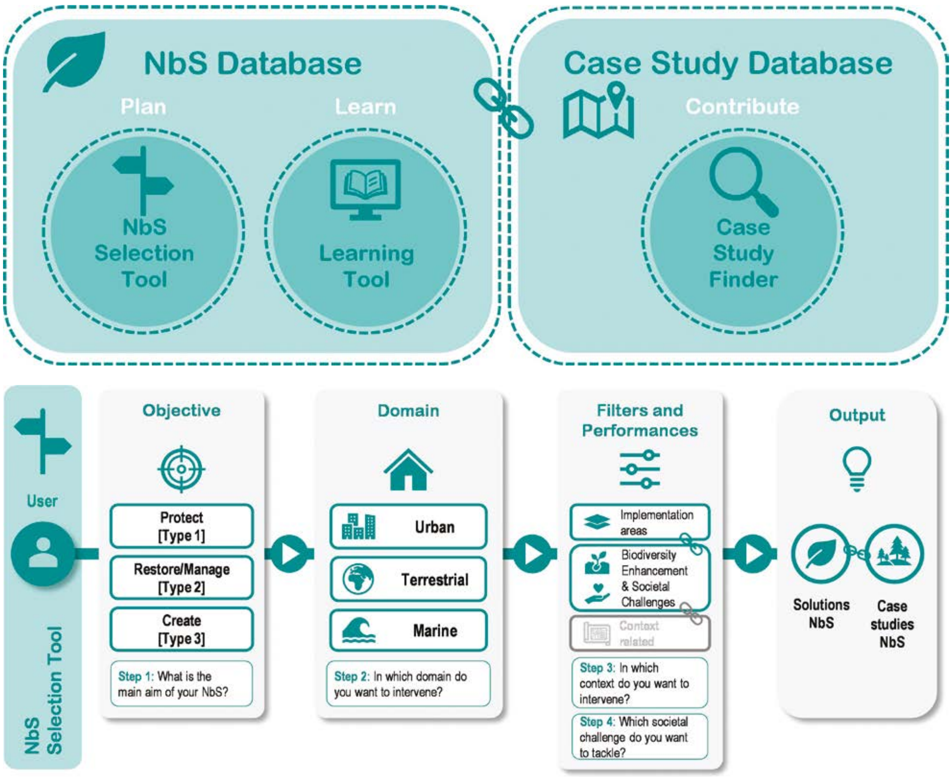
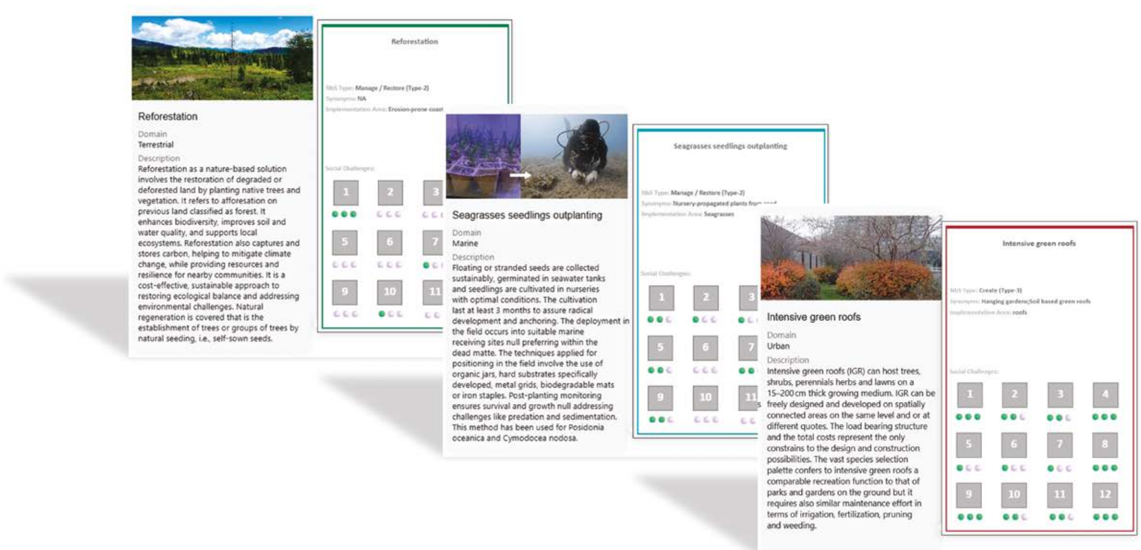


Fig. 4 – Graphical representation of the structure and functionalities of the NbS CataTool (above) and of the NbS Selection tool stepwise procedure (below); in grey the future planned development of the DSS.

Step 1: Define the object of the intervention. Users first select among the possible intervention options which follows the NbS-type classification Eggermont et al. 2015: Type 1, NbS for the protection and conservation of natural ecosystems (requiring minimal or no intervention); Type 2, NbS for the restoration, enhancement and management of natural or modified ecosystems (requiring moderate level of intervention); and Type 3, creation of new ecosystems (requiring high level of engineering effort) (see also Figure 2).

Step 2: Select the domain of intervention. Users must select among the urban, terrestrial, and marine domains. The first domain refers to urbanised environments extending beyond the urban matrix or political boundaries (e.g., transport infrastructure), characterised by novel ecosystems (from the green roofs and walls to road verges and private gardens), diverse habitat patches, and high anthropic pressure (e.g., soil sealing, pollution). Within the terrestrial domain figure protected and managed terrestrial environments including freshwater ecosystems both subjected to human impact (e.g., row material extraction and energy production) as well as climatic and natural hazards (e.g., fires, landslides, floods). The marine domain encompasses subtidal coastal and deep-sea ecosystems impacted also by human activities, exploited for fishery, aquaculture, recreation, mining and subjected to related impacts (e.g., pollution, acidification), biodiversity loss as well as other hazards (e.g., temperature and sea-level rise).

Step 3: Implementation area selection. Implementation areas are related to the context or conditions of the area of intervention, are domain-specific, and are tailored to the practice of different stakeholders involved in NbS planning. These includes landscape and urban planners (primarily operating in the urban domain), as well as envi-



double-sided cards of common urban, terrestrial and marine domains showing: on the front the description, representative photo; on the back the type, synonyms, implementation areas, and the expected performance towards the 12 societal challenges of the European Roadmap on NbS (EL Harrak and Lemaitre 2023).

ronmental engineers and ecologists (acting mostly in terrestrial and marine domains). For this reason, implementation areas in the urban domain are defined by scale and functions (e.g., building-scale solutions such as roofs and walls, or linear infrastructure such as roads and railways); in the terrestrial domain they are defined by hazard- and disturbances (e.g., erosion prone-areas); while in the marine domain they follow ecosystem categories (e.g., macroalgal forests, oyster reefs).

Step 4: Societal challenge selection. Finally, users shall select the societal challenges – beyond enhancing biodiversity, which is, by definition, inherent to all NbS – that the NbS intervention aims to address. The 12 global challenges[10] derive from the NetworkNature roadmap (EL Harrak and Lemaître 2023) resulting from the integration of the IUCN (2020b) and the EC (Dumitru and Wendling 2021) frameworks.

The outcome of the stepwise procedure is a list of ranked theoretical NbS (displaying scores from 1 to 3) relative to the selected societal challenges. The ranking is based on an expert-based, semi-quantitative evaluation based on a shared framework developed for both theoretical solutions and case studies, and consisting of three key performance indicators (KPI) for each of the 12 challenges. These indicators were adapted from the EC handbook (Cardinali et al. 2021) to ensure comparability among all the NbS across the different domains (urban, terrestrial, marine). The identified NbS are also presented as synthetic double-sided cards (Figure 5) whose front side provides a brief description and a representative photograph of a real case study, while the reverse includes information on NbS-type, implementation areas, synonyms, and the performance scores towards all 12 societal challenges (ranging from 0 to 3).

[10] The societal challenges as listed in the NetworkNature EU Roadmap to 2030 (EL Harrak and Lemaître 2023) are: 1) Climate Resilience, 2) Water Management, 3) Food Security, 4) Social Justice and Social Cohesion, 5) New Economic Opportunities and Green Jobs, 6) Participatory Planning and Governance, 7) Natural and Climate Hazards, 8) Health, Well-being and Air Quality, 9) Green Space Management, 10) Place Regeneration, 11) Knowledge and Social Capacity Building for Sustainable Urban Transformation, 12) Biodiversity enhancement.

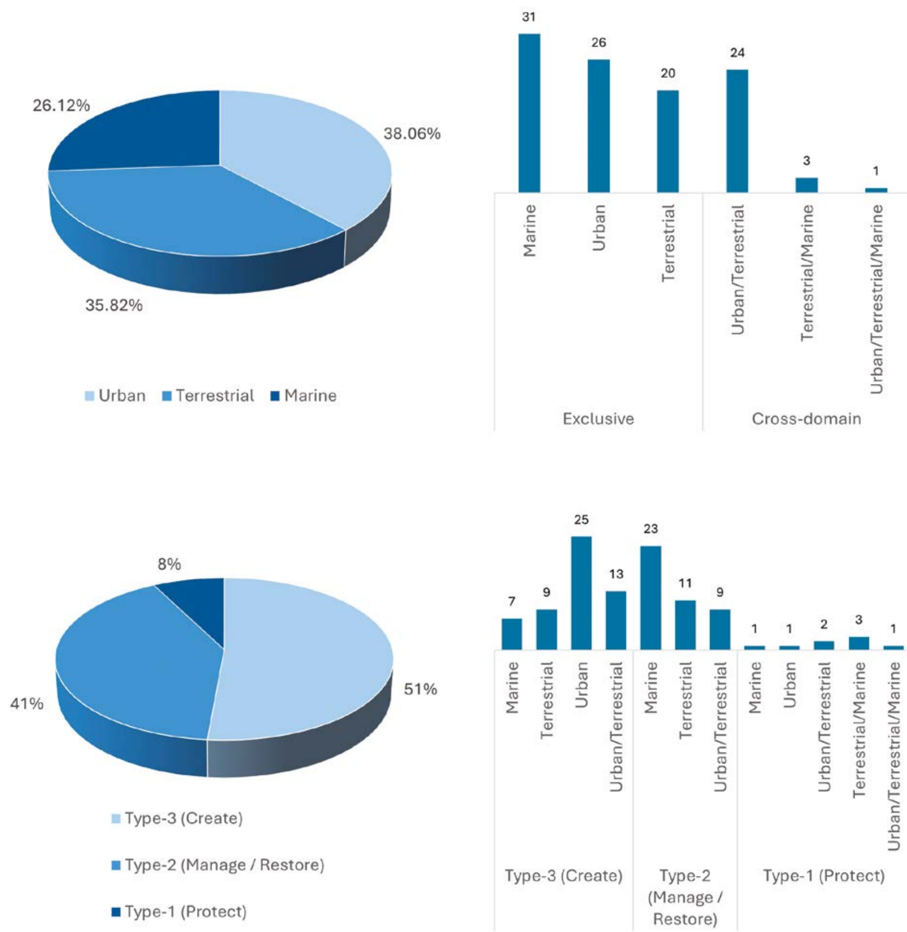


Fig. 6 – Theoretical NbS (a) grouped according to domains, (b) disentangled into exclusive (belonging to one domain only) and cross-domains (belonging to multiple domains), and (c) grouped according to NbS-types, (d) disentangled into NbS-types, domains and cross-domains.

Each NbS is further documented in detail, providing, in-depth description, the associated ecosystems[11], and an explanation behind the expert-based evaluation for all positively scored challenges. Additionally, the detailed sheet provides the link to available case studies, a reference list, and the contact details of the 'curators' responsible for compiling both the synthetic card and the detailed sheet for the corresponding NbS.

All the parameters used to characterise each NbS serve as screening fields within the *learning tool* functionality, which enables users to navigate the contents and search for specific NbS without constraints, for example by using NbS names, synonyms, or associated ecosystems. This functionality is intended to support students, citizens, and planners, particularly in co-design processes, by offering accessible and flexible exploration options.

These two functionalities – the NbS selection tool and Learning tool – are enabled by a structured NbS taxonomy encompassing more than 100 solutions, categorised by NbS-types and domains, which forms the core of the NbS database. The DSS tax-

[11] The classification of the ecosystems follows Maes et al. (2020) and El Harrak and Lemaitre (2023) and consists of 10 ecosystems: urban ecosystem; open ocean; costal ecosystems; rivers, lakes and ponds; forests; grasslands; croplands; wetlands; heathlands and shrubs; sparsely vegetated lands

onomy is the result of a comparative analysis of existing and widely recognised NbS catalogues (Castellar et al. 2021; Debele et al. 2023; Dumitru and Wendling 2021; Eisenberg et al. 2022; Nature4cities 2018; NWRM 2015; Riisager-Simonsen et al. 2022; Somarakis et al. 2019; URBAN GreenUP 2018; World Bank 2021), which has been further expanded drawing on the expert knowledge contributed by the domain-specific working groups (WGs).

Most of the NbS included in the DSS belong to the Marine domain (Figure 6a), whereas cross-domain NbS were largely associated with Urban-Terrestrial systems (Figure 6b), emphasising the strong connection between terrestrial and urban NbS, but a relative disconnection between these and the Marine domain. The majority of classified NbS were of type 3 (create), followed by type 2 (restore/enhance/manage) and type 1 (protect/conserve) (Figure 6c). Most of the type 2 NbS, were predominantly associated with the Marine domain, while type 3 NbS were mostly with the Urban domain, highlighting the hybrid nature of NbS across terrestrial ecosystems, where actions for the restoration or creation occur in nearly equal numbers (Figure 6d).

Finally, the third functionality of the DSS is the *case study finder,* which is based on the Case Studies Database: a comprehensive collection of national NbS real-world examples[12] drawn from well-established repositories such as Oppla and NetworkNature' shared database[13], and GeoIKP, as well as from pilot projects conducted within the NB-FC. The case studies can be freely explored using various screening criteria such as the NbS name following the DSS taxonomy, the associated ecosystem, domain and implementation areas, consistent with the metadata structure of the NbS database. They can also be selected directly on a map by clicking on georeferenced points.

Each case is presented, similarly to the theoretical NbS, through a synthetic card and detailed sheet providing further information. Moreover, in the case of monitoring data, implemented NbS are evaluated using the same framework applied for the theoretical NbS by providing information on their impact level, namely 'no impact' (=0), 'positive impact' (1), 'negative impact' (-1), and 'not addressed' (= NA). This evaluation is accompanied by a reasoned justification on the detailed sheet, along with links to data repositories or a contact person for data access, and in some cases, to the IUCN self-assessment evaluation[14] (IUCN 2020b).

3. Conclusive remarks and further developments

The NbS CataTool was conceived as a technological and digital solution that supports the design of efficient and resilient NbS, grounded in evidence and scientific research and aligned with the major European initiatives, such as NetworkNature, IUCN, and Biodiversa partnership. In addition, it can serve as an operational tool to support the implementation of the EU Nature Restoration Regulation and the EU Biodiversity Strategy, for both national restoration and urban nature plans (European Union 2025).

The presented DSS is a product of the NBFC, developed with the involvement of 70 researchers from 19 institutions and harmonised by a central team (activity coordinators) responsible for both the conceptual framework and the coordination of the

[12] Case studies are shown on the NbS Italy hub webpage and are continuously being collected thanks to users and interested partners https://www.nbsitalyhub.it/en/nbs-case-studies/

[13] The case study database is available either on Oppla https://oppla.eu/case-study-finder or NetworkNature https://networknature.eu/networknature/resources/networknature-case-studies websites

[14] IUCN self-assessment tool is available at https://nbs-sat.iucn.org/

Fig. 7 – Institutions involved in the coordination and development of the NbS CataTool Decision Support System.

domain-specific expert WGs (Figure 7). The WG members (i.e., NbS and case study curators) contributed up-to-date content (e.g., NbS descriptions and case studies collection) and evaluated both theoretical NbS and case studies.

Compared to similar online DSS, such as the GeoIKP NbS toolkit[15], ClimateApp[16] and the NbS Performance Assessment Tool[17], the NbS CataTool is a unique example of a comprehensive, evidence-based nomenclature standardisation effort (Bologna and Hasanaj 2023). It integrates solutions across urban, terrestrial and marine domains and related ecosystems, with a focus on the Mediterranean area, and it is built upon a wide corpus of scientific research (e.g., reference lists included in the detailed sheets). Moreover, it is a solid prototype adopting a simplified evaluation framework centred on global environmental, social, and economic challenges, thereby aligning with both the UNEA definition of NbS (Nature-Based Solutions for Supporting Sustainable Development 2022) and the IUCN global standard for NbS (IUCN 2020b). By contrast, other DSS, despite offering other relevant information (e.g., costs and policies) and useful functionalities (e.g., spatially explicit background data), cover a narrower scope. For example, the GeoIKP platform and toolkit focus exclusively on risk reduction (e.g., erosion, flood, drought and landslide), while both ClimateApp and NbS Performance Assessment Tool focus solely on solutions for the urban context, ranked respectively according to adaptation targets (i.e. flooding, heat, drought) and to ecosystem services (i.e., regulating, cultural, supporting, and provisioning).

To conclude, the presented product is continuously evolving prototype that can be further expanded with more advanced functionalities developed in collaboration with diverse stakeholders. For example, case studies could be regularly updated with monitoring data to provide information on the performance related to context-specific challenges, and associated costs. The NbS Selection Tool could be strengthened by

[15] GeoIKP toolkit can be accessed at https://geoikp.operandum-project.eu/nbs/toolkit

[16] Climateapp tool can be accessed at https://climateapp.nl/

[17] The nature-based solutions performance assessment can be accessed at https://icra.shinyapps.io/nbs-list/

adding practical and technical guidance and by ensuring interoperability with external platforms to integrate spatial data, public datasets, and spatial analysis models for identifying suitable intervention areas. Finally, the inclusion of a plant species selection functionality would offer more practical, context-specific recommendations, supported by contributions from nurseries and firms.

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Nature-based Solutions for the building system

Giulio Hasanaj, Chiara Catalano

Abstract: Nature-based Solutions (NbS) applied to the building system represent a key strategy to address urban environmental challenges while improving the quality of life and guiding the planning, design and sustainable management processes of future cities. NbS play a fundamental role in the climatic and environmental balance of urban areas and are an indispensable component of the ecological transition. The integration of NbS in roofs and walls offers multiple ecosystem benefits and are fundamental tools for increasing biodiversity, climate adaptation and ecological integration of the built environment, contributing to the transition towards more resilient and liveable cities. The chapter analyse and present NbS for the building system with a specific focus on roofs and walls. In the case of roofs, different types of green solutions are analysed: 1) extensive green roofs, which are light and low-maintenance; 2) intensive green roofs, characterised by a greater depth of substrate and more diverse vegetation; 3) semi-intensive roofs, which combine features of both; 4) biosolar roofs, which integrate vegetation and photovoltaic panels to maximise energy yield; 5) biodiverse green roofs, designed to host native species and promote urban habitats; and finally 6) blue-green roofs, which combine water tanks and typical green roof built-up improving the water management aspect. Regarding walls, the solutions analysed include 1) green facades which consist of climbing vegetation on supports; 2) green walls which integrate modular systems with plants rooted in artificial substrates; 3) planter green walls that are systems installed in containers integrated into the building façade. The mentioned building related NbS are synthesized in factsheets containing a) general description, b) technical and design parameters for the adequate implementation, and c) indicators for biodiversity enhancement, climate resilience, and health, well-being and air quality.

Keywords: Nature-based Solution, Urban biodiversity, Building System, Green roofs, Green walls.

The contribution of green roofs and green façades to urban biodiversity

Cities are today the places where we live (Mancuso 2023, p. 6). Urban areas are afflicted by the disruptive impacts of climate change (IPCC 2023), air, soil and water pollution (WHO 2024), and the progressive loss of biodiversity (IPBES 2019). Such phenomena are exacerbated by the degradation of green infrastructure, the loss of ecosystem services and urban expansion, which reduce soil naturalness and adaptive capacity, while increasing climatic, ecological and environmental vulnerability (WHO 2016; IPCC 2022).

«The way in which settlements and key infrastructure are planned, designed and maintained determines patterns of exposure, social and physical vulnerability, and resilience capacity (IPCC 2022, p. 1289)». In this regard, natural spaces – and particularly green and blue infrastructure – play a crucial role, as they influence the climatic and environmental balance of urban areas and are an essential component for halting biodiversity loss, mitigating climate change, and improving public health (EC 2013; EC 2021).

Nature-based Solutions (NbS), in particular, represent a key resource for guiding the planning, design and sustainable management of the cities of the future (UN-Habitat

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2022, p. XXII). NbS are recognised for their ability to pursue environmental, social and economic objectives simultaneously, acting as transformative levers for equitable and sustainable urban development (EC 2022; Xie et al. 2022).

However, the presence of natural spaces within urban areas remains limited compared to artificial surfaces. The proportion of green areas in European cities covers less than 16% of urbanised land, and only 3% of these spaces are publicly accessible (EEA 2021). In Italy, the availability of public green space is in some cases even more limited, with public green areas often accounting for less than 5% of the total municipal area (SNPA 2022).

The World Health Organization (WHO) recommends that cities should provide at least one accessible green space of 5,000 m^2 within 300 metres of residential areas (WHO 2016). Each citizen should have access to a minimum of 9 square metres of safe and functional urban green space, while the ideal amount of urban greenery is estimated at 50 square metres per person (Maryanti et al. 2016). Despite these recommendations, more than 60% of the urban population in Europe lives in areas with insufficient green spaces (Pereira Barboza et al. 2021).

NbS are receiving increasing attention for their potential to enhance the sustainability, resilience and biodiversity of urban environments, and are being implemented in many cities (Goodwin et al. 2023). However, their application is mostly concentrated at ground level or within urban open spaces (Almaaitah and Joksimovic 2022), while only a limited share concerns buildings. In several international contexts, green roofs and living walls have been tested, generating interest among citizens but often receiving limited attention within urban planning processes (Kandel et al. 2024).

Considering that the building stock constitutes a critical element in advancing both climate adaptation and the enhancement of urban biodiversity, it is essential to identify the NbS that can be effectively applied to buildings. Evaluating the key performance indicators emerging from existing evidence, defining the appropriate technical, construction and maintenance requirements, analysing the associated co-benefits, and recognising the principal knowledge gaps enable the consolidation of current understanding and inform future research on the implementation of NbS in urban environments (Kandel et al. 2024). Moreover, such an approach contributes to building a robust knowledge base to support the integration of NbS within architectural design and urban planning practices.

This contribution outlines NbS applied at the building scale included among the solutions of the urban domain of the NbS CataTool Decision Support System (DSS) (See Chapter *The NbS CataTool of the National Biodiversity Future Center*) and considered as key instruments for supporting the urban ecological transition. The work focuses particularly on green roofs and green walls, describing their various types — including extensive, intensive, semi-intensive, biosolar, biodiverse and blue-green roofs, as well as green façades, living walls, and planter walls — and presenting relevant scientific knowladge references for biodiversity, climate resilience, health and environmental quality.

By expanding the contents already present within the DSS, the work also provides a technological and typological analysis of these solutions. Each NbS is summarized in a technical data sheet that includes: a general description, design and construction parameters, maintenance requirements, and co-benefits in response to the challenges of biodiversity, resilience, health and wellbeing. This organisation makes it possible to translate scientific and technical knowledge into operational tools for designers, local authorities and policy makers.

Extensive green roof

Section A - General Description

Fig. 1 – Extensive green roof in Basel (Source: Catalano 2013).

Description

Extensive green roofs (EGR) are near-natural greened surfaces hosting mosses, succulents, forbs (including bulbs and tubers) and some grasses on an average 6-15 cm thick growing medium (Catalano et al. 2018; FLL 2018; Madre et al. 2013). Plant species able to grow on EGR with little maintenance and irrigation are stress tolerant, mostly annuals and low growing or creeping perennials capable of regenerating themselves and propagate easily (Madre et al. 2013; Thuring and Dunnett 2014). On such roofs, spontaneous colonization shall be favoured for resilient EGR over time (Vidaller et al. 2023) and not be considered a failure (Schrieke et al. 2021); also diverse plant assemblage perform better than monoculture (Tran et al. 2019). EGR represent most of the case studies due to the lower costs related to the installation and maintenance compared to the other kind of green roofs; they also possess the lower species richness due to the harsher conditions (higher drought, lower space for roots, stronger wind effect) and a more uniform structure (Madre et al. 2013). However, these conditions favour endangered and rare species typical of arid or very dry habitats, which tolerate or have adapted to harsh environmental conditions, thereby promoting pioneer vegetation (Pétremand et al. 2018). However, building height negatively influences arthropods biodiversity (Madre et al. 2013) while size is not necessarily linked to higher diversity (Mayrand and Clergeau 2018) thus even small EGR are a good mean to support biodiversity in dense urban areas.

Synonyms

Sedum roofs; mosses roofs; eco-roofs

Section B - Technical details

Implementation conditions

The construction of an extensive green roof is subject to a range of structural and climatic conditions. From a structural perspective, the load-bearing system must be designed to support an additional load varying between 60 and 150 kg/m^2 under water-saturated conditions, with higher values possible in specific configurations (ENEA 2024; ZinCo 2024). An extensive roof must include root-resistant certified waterproofing and a minimum slope of at least 1–2%, with appropriate drainage systems to prevent water stagnation that could damage the vegetation (FLL 2018; Peck and Kuhn 2003). On steeply sloping roofs, exceeding 25–30%, containment elements must be incorporated to prevent substrate slippage (Peck and Kuhn 2003).

Despite their limited substrate depth, extensive green roofs should ensure a minimum water retention capacity of 25 L/m^2 and achieve at least 95% vegetation cover within three years of installation (Eisenberg et al. 2022).

Local climatic conditions have a strong influence on design choices. In arid climates, for example, it is advisable to provide emergency irrigation systems that can be activated during periods of extreme drought (Eisenberg et al. 2022). In temperate and humid climates, by contrast, drainage management becomes particularly important, as the substrate can easily become saturated, thereby reducing the efficiency of its thermo-hygrometric functions (Elliott et al. 2016). In Mediterranean climates, it is recommended to use a soil layer thicker than 15 cm (composed mainly of fine-grained materials) to ensure optimal colonisation by plant species (Chenot et al. 2017).

Design features

The typical stratigraphy of an extensive green roof includes: 1) root-resistant waterproof membrane; 2) drainage layer made of gravel or plastic honeycomb panels; 3) geotextile filter fabric; 4) lightweight growing substrate with a predominantly mineral composition (such as lapillus, pumice and sand) and a limited organic component; 5) vegetation, usually consisting of non-woody plants (e.g. mosses, sedums, ground covers, hardy perennial herbs and grasses), although a wide variety of species can be employed (ENEA 2024; ZinCo 2024).

Plants suitable for extensive green roofs are low-growing and slow-developing species with rapid propagation, shallow root systems, or hardy perennials — including succulents — capable of surviving with minimal nutrient input and without additional irrigation (Eisenberg et al. 2022).

Extensive green roofs are often implemented on existing buildings, as they are generally lighter in weight, require less water and lower investment, and, with the appropriate technical supports, can also be installed on steeply sloping surfaces (Eisenberg et al. 2022).

Along the roof edges, gravel strips are typically incorporated, which, in addition to serving as firebreaks, improve perimeter drainage and facilitate access for inspection and maintenance (FLL 2018).

The extensive green roof represents a well-established technical solution which, with relatively simple design requirements (limited weight and minimal maintenance), offers multiple benefits: thermal and acoustic insulation (up to 8 dB), reduction of atmospheric pollutants, rainwater management, enhancement of biodiversity and mitigation of the urban microclimate. However, it is essential to comply with design criteria suited to the climatic and structural context, to follow an appropriate stratigraphy using suitable materials, and to ensure a minimum level of periodic maintenance (Berardi et al. 2014; ENEA 2024).

Maintenance

Once established, an extensive green roof requires only limited maintenance (generally one to two interventions per year) (ZinCo 2024; ENEA 2024). Routine maintenance includes the removal of unwanted vegetation (such as tree seedlings carried by the wind), the periodic cleaning of outlets and drainage systems from leaves and debris, and occasional applications of slow-release fertilisers to replenish nutrients within the substrate (FLL 2018; Eisenberg et al. 2022).

During the initial post-installation phase, greater attention is required, with regular irrigation until the vegetation is fully established and frequent inspections to promptly remove any emerging weeds (Peck and Kuhn 2003).

Irrigation is generally not required; however, although xerophilous species can tolerate prolonged periods without water, supplementary irrigation may become necessary under conditions of extreme drought (Woods-Ballard 2015). Pruning and mowing are not required (ZinCo 2024). These simple maintenance practices ensure a healthy and long-lasting vegetative cover, preventing the accumulation of dry biomass that could increase the risk of fire and compromise the ecosystem benefits of the extensive green roof (Climate-ADAPT 2020).

Section C - Societal challenges

Biodiversity enhancement

Integrating extensive green roofs in urban spatial planning strategies has great potential to increase the connectivity among green spaces (Braaker et al. 2014). Extensive green roofs community composition of high-mobility arthropod groups (bees and weevils) were mainly shaped by habitat connectivity, while low-mobility arthropod groups (carabids and spiders) were more influenced by local environmental conditions. For the first group of arthropods, green roof communities are connected by the frequent exchange of individuals among surrounding green roofs. On the other hand, low-mobility species communities on green roofs are more likely connected to ground sites than to other green roofs (Braaker et al. 2014).

Extensive green roofs are highly likely to provide habitat for a greater abundance and diversity of both plants and animals than conventional roofs which are spontaneously colonized (Williams et al. 2014). Even if other types of green roofs are more biodiverse, extensive green roofs, if they are left to spontaneous colonization, can act as refugia for species adapted to poor, sandy and dry environments (Muratet 2024).

Extensive green roofs can make a significant contribution to maintaining and enhancing the local diversity of species. A study conducted on eight extensive green roofs located in Hamburg revealed a remarkable species richness of arthropods. A positive correlation was observed between vegetation cover and species richness, highlighting that even relatively thin substrates, when appropriately vegetated, can support an ecologically diverse community. These findings suggest that the structure and complexity of vegetation are key factors influencing the establishment of different species, even in highly anthropized urban environments (Nevermann et al. 2025).

Extensive green roofs designed with the objective of conserving biodiversity, including those with shallow substrates typical of extensive systems, promote the presence of rare or uncommon plant species within urban environments. Floristic diversity can be enhanced through the targeted selection of plant species and by configuring the substrate to create differentiated microhabitats (Muratet 2024).

Climate Resilience

Extensive green roofs, characterised by lightweight substrates and species requiring low maintenance, represent an effective solution for mitigating climate change in urban environments. These Nature-based Solutions can capture atmospheric carbon through photosynthesis, contributing to the reduction of greenhouse gas (GHG) emissions and the improvement of air quality (Getter et al. 2009). Moreover, extensive green roofs enhance the energy efficiency of buildings due to their insulating properties, reducing the need for heating in winter and cooling in summer. In certain configurations (such as Biosolar green roof), integration with photovoltaic panels can also lead to increased energy production, as the more favourable microclimate created by the vegetation helps to improve solar panel performance (ENEA 2024).

An extensive green roof can enhance the performance of the building envelope by increasing thermal and acoustic insulation, mitigating surface temperature peaks, and improving indoor comfort. During the summer, the vegetation and substrate contribute to reducing surface temperatures by up to 25 °C compared with a conventional roof, resulting in energy savings for cooling (ENEA 2024). At the same time, the solution improves the sustainable management of stormwater, retaining on average between 50% and 90% of precipitation and delaying runoff, with positive effects on the urban drainage network (Berardi et al. 2014).

Health, Well-being and Air Quality

Living and working in a green environment has a positive effect on both mental and physical health, providing psychological relaxation and reducing stress (Hedblom et al. 2019). Health and wellbeing benefits can also be achieved without the physical use of green spaces, as a positive psychological effect may arise from the simple visual perception of greenery, even when such spaces are not directly accessible (WHO 2016). Therefore, green roofs and walls can serve as tools to promote citizens' health and wellbeing.

Although, by definition, an extensive green roof is not intended for intensive recreational use, many projects adopt a mixed solution to maximise health and wellbeing benefits. This configuration typically includes peripheral areas of a flat roof with extensive vegetation (offering visual appeal, as well as thermal and hydrological benefits) and a central walkable section (such as a paved deck or pergola), or vice versa. In such cases, particular care must be taken to separate the planted and pedestrian zones (through edging and dedicated drainage), and to provide localised irrigation for the green areas where these adjoin accessible spaces.

Intensive green roof

Section A - General Description

Fig. 2 – Intensive Green Roof at Manifattura Tabacchi in Florence (Source: Hasanaj 2025).

Description

Intensive green roofs (IGR) are highly engineered systems capable of supporting a wide variety of vegetation types, including trees, shrubs, perennial herbs, and lawns, within a growing medium typically ranging from 15 to 200 cm in depth (FLL 2018). These systems offer significant design flexibility and can be developed across large, contiguous roof surfaces, either on a single level or spanning multiple elevations. The main limitations are the structural load capacity of the building and associated construction and maintenance costs. Due to their substantial substrate depth and broad palette of plant species, IGRs can replicate the aesthetic and recreational functions of ground-level parks and gardens, providing valuable green spaces in dense urban settings. However, this complexity also entails high maintenance demands, including regular irrigation, fertilization, pruning, and weeding, making ongoing care essential for long-term functionality and ecological performance (Catalano et al. 2018).

Synonyms

Hanging gardens; soil based green roofs

Section B - Technical details

Implementation conditions

The implementation of an intensive green roof requires a suitably designed building structure capable of supporting the substantial loads arising from the saturated substrate, vegetation and any furnishing elements. The permanent load can range from 250 to over 1,000 kg/m², depending on the substrate depth and the type of vegetation used (FLL 2018; ENEA 2024). For existing buildings, a preliminary structural assessment is therefore essential, and, where necessary, reinforcement of structural elements should be undertaken.

Unlike extensive roofs, intensive green roofs are comparable to constructing a ground-level garden on a roof, making them suitable for accommodating a wide variety of vegetation, including trees and shrubs (ZinCo 2024; ENEA 2024).

The planning and design phase begins with an assessment of the building's structural condition, particularly the roof slab, to determine its load-bearing capacity. It is essential to carry out a feasibility analysis that includes a study and calculation of the slab's structural integrity in order to certify the maximum sustainable load. When calculating the overall static load, it is necessary to take into account the maximum weight that the structure may reach under full water saturation, as well as additional loads such as snow or those arising from maintenance activities (ENEA 2024).

From a technical perspective, the roof must be completely waterproofed using membranes that are resistant to root penetration (FLL 2018; Woods-Ballard 2015). It is also essential to provide an efficient drainage system and an automated irrigation system, as intensive vegetation requires a constant water supply, particularly during the summer months (METRO ADAPT 2019).

Local environmental conditions — such as solar exposure, wind intensity and urban microclimate — should guide the selection of the substrate and plant species, with a preference for native species that are resilient to water stress (Catalano et al. 2018; ENEA 2024). The detailed design and planning phase must also ensure ease of access for maintenance and safety (FLL 2018).

Other crucial aspects of implementation include the provision of a water supply connection on the roof to enable essential irrigation (ENEA 2024).

Design features

The functional stratigraphy of an intensive green roof consists of a sequence of technical layers, each with a specific role. The Italian standard UNI 11235:2015 outlines the elements that must always be included: 1) structural support; 2) root-resistant waterproofing; 3) mechanical protection layer; 4) drainage layer (gravel, plastic honeycomb elements, or modular drainage panels) that allows excess water to be discharged while retaining a portion useful for root absorption; 5) filter fabric to prevent the passage of fine particles; 6) growing substrate; 7) vegetation (FLL 2018; ENEA 2024; ZinCo 2024).

The root-resistant layer is always mandatory. If the existing waterproofing system does not fulfil this function, an additional membrane must be installed to protect the structure from root penetration (ENEA 2024).

The substrate depth is the defining feature of an intensive green roof and can range from 15 cm to 100 cm or more (FLL 2018). The water retention capacity of the substrate is typically between 50 and 150 litres per square metre, and it is essential that it remains biologically active and healthy to ensure optimal plant growth. The substrate is composed of lightweight, well-draining mixtures, generally consisting of pumice, expanded clay, and composted organic matter.

The drainage layer must ensure the rapid and effective removal of excess water and should be designed according to local climatic and hydraulic conditions (ENEA 2024).

The selection of plant species is extensive — including perennials, shrubs and trees — and must take into account the interaction between substrate depth, solar exposure, climate, water availability and the intended function (Catalano et al. 2018). In the case of shrubs and trees, the use of non-grafted plants grown in predominantly mineral substrates is recommended (FLL 2018).

The irrigation system (whether drip, sprinkler, or sub-irrigation) is an essential component to ensure the survival of vegetation during dry periods (Woods-Ballard 2015). Some systems incorporate integrated drainage modules that retain water and release it through capillary action, thereby improving water efficiency (Daku 2024; ZinCo 2024).

From a construction perspective, the intensive green roof is a dynamic system in which the proper dimensioning of each layer ensures durability, hydraulic performance and microclimatic comfort (Eisenberg et al. 2022). The design process must therefore integrate architectural, engineering, landscape and agronomic expertise within a multidisciplinary framework.

Maintenance

Maintenance represents a key determinant of the long-term functionality and performance of intensive green roofs. Such systems require management practices comparable to those of conventional gardens, including regular irrigation, pruning of shrubs and trees, mowing of lawns, fertilisation, and phytosanitary monitoring to control pests and diseases. Larger plant species have greater nutrient requirements, necessitating annual fertilisation in spring during the first three to five years, along with a basic chemical analysis of the substrate (pH, NPK) on an annual or biennial basis (ENEA 2024).

Routine maintenance also includes the periodic inspection of drainage systems, the removal of weeds, and the verification of the condition of waterproofing membranes. Extraordinary maintenance may involve the replacement of damaged substrate or vegetation, as well as the inspection and repair of the irrigation system (FLL 2018; ENEA 2024).

The level of maintenance required depends on the vegetative complexity and the intended use of the space. Accessible roofs featuring paved areas and trees may require up to 25–30 hours of maintenance per 100 m^2 annually (METRO ADAPT 2019). However, careful vegetation planning and the selection of native species can significantly reduce both water demand and maintenance needs (Catalano et al. 2018).

Finally, maintenance should be incorporated within a long-term management plan that includes seasonal inspections, performance reporting, and corrective actions (Woods-Ballard 2015). The maintenance cost of an intensive green roof can be up to ten times higher than that of an extensive one (ENEA 2024).

Section C - Societal challenges

Biodiversity enhancement

Intensive green roofs, due to their greater substrate depth and diversity of microhabitats, offer significant potential for enhancing urban biodiversity (Catalano et al. 2018).

They can host a wide range of plant species, supporting the presence of pollinating insects, birds and small invertebrates (Fernández-Cañero and González-Redondo 2010; ENEA 2024). However, the level of biodiversity is closely dependent on design choices: the selection of native species adapted to local climatic conditions increases ecological resilience and reduces maintenance requirements (Catalano et al. 2018; FLL 2018).

European guidelines emphasise the importance of viewing green roofs not merely as technological devices for water management or thermal insulation, but as semi-natural ecosystems that contribute to the urban ecological network (Eisenberg et al. 2022; Kandel and Frantzeskaki 2024). The inclusion of heterogeneous elements - such as temporary wet areas, differentiated substrates, logs or stone features - can enhance habitat diversity and improve the overall ecological function (Woods-Ballard 2015). Conversely, an excessive degree of human intervention or an overly artificial vegetation layout may reduce the naturalness of the habitat (Catalano et al. 2018). In this sense, integrated design involving architects, ecologists and botanists is essential to balance aesthetics, functionality and biological sustainability in intensive green roofs.

Climate Resilience

Intensive green roofs mitigate high temperatures, addressing the phenomenon of urban heat islands. They act effectively on the improvement of the urban microclimate through the natural evapotranspiration effect of the vegetation, via low reflectivity and high absorption of solar radiation required for photosynthesis. The temperatures of green roofs can be 16-22°C lower than those of conventional roofs (EPA 2008). The widespread implementation of green roofs on between 80% and 90% of a city's rooftops can lead to a reduction in average air temperature ranging from 0.3 °C to 3 °C, depending on climatic conditions, vegetation type, and surface reflectance. This effect arises from plant transpiration and the increase in surface albedo, both of which decrease the amount of sensible heat flux released into the urban atmosphere (Santamouris 2014). Intensive green roofs can reduce a building's energy consumption. Thanks to their thermal mass layer, they insulate the building, allowing heating and cooling systems to work more efficiently, leading to a significant reduction in energy consumption (Oliveira Santos et al. 2024).

Intensive green roofs reduce the hydraulic load generated by extreme rainfall by collecting and retaining large volumes of water and delaying its entry into the sewer network, thereby preventing hydraulic overload. However, their hydrological performance depends on the season: in summer, evapotranspiration promotes water retention, whereas in winter the substrate often remains saturated, causing the vegetated roof to behave like an impermeable surface. Under extreme conditions, once the soil has reached saturation, effectiveness depends on the resilience of the urban drainage system and on the presence of complementary strategies. Intensive green roofs can retain between 41% and 75% of rainfall over a two-hour period (Liu et al. 2020). Approximately 44% of water from heavy rainfall events is retained within the roof structure (Kolasa-Więcek et al. 2021). Moreover, they contribute to water quality improvement through filtration, absorption and biodegradation processes, being effective in removing suspended solids and heavy metals (Woods-Ballard 2015).

Health, Well-being and Air Quality

The presence of low vegetation, grassy areas and trees covering building surfaces provides shaded spaces for users to rest. Urban green areas have a positive psychological effect. Intensive green roofs can be used for physical exercise, gardening and social interaction, all of which are positive factors for public health (Andreucci et al. 2019; Gehrels et al. 2016).

The use of intensive green roofs allows the creation of true outdoor social spaces on building rooftops, sheltered from the noise and vehicle traffic of urban streets. These spaces can include furniture elements such as benches, shelters, lampposts, etc., and can be used for recreational activities, including sports, leisure, relaxation, urban farming (related to the cultivation and production of food), or gardening (World Bank 2021).

Intensive green roofs provide areas for recreation and opportunities to enjoy outdoor living spaces, contribute to local food production and boost the local economy creating jobs in many sectors (Susca et al. 2011; Whittinghill and Rowe 2012).

Intensive green roofs are important sources of information about the environment. They can serve as classrooms for local schools, providing a space for observation and experimentation for students interested in nature, biology, and the environment (Hop and Hiemstra 2012).

Semi-intensive green roof

Section A - General description

Fig. 3 – Semi-intensive Green Roof of the Water Filtration Plant in Wollishofen, Zurich, Switzerland (Source: Chiara Catalano 2013).

Description

Semi-intensive green roofs are a hybrid solution between extensive and intensive green roof systems. They typically support shrubs, perennial herbs, and lawns, planted in a growing medium ranging from 12 to 100 cm in depth (Catalano et al. 2018). This type of green roof retains much of the biodiversity and multifunctionality potential of intensive systems while significantly reducing structural load, installation complexity, and maintenance costs. Unlike extensive green roofs, which are limited to low-growing, drought-tolerant vegetation due to shallow substrates, simple-intensive systems allow for a wider range of plant species and more diverse habitat structures. The spatial design and vegetation selection are like those used in traditional intensive roofs, enabling aesthetic, recreational, and ecological benefits. However, by optimizing substrate thickness and simplifying irrigation and drainage systems, simple-intensive roofs offer a cost-effective and flexible approach for enhancing urban green infrastructure.

Synonyms

Simple-intensive green roofs; light-intensive green roofs

Section B - Technical details

Implementation conditions

Semi-intensive green roofs (SIGR) are an intermediate stage between extensive and intensive green roofs, thought to be visited and used also for recreation purposes. The substrate thickness varies according to the plant growing form, that is from 12 cm up to 40 cm for grass or herbaceous plants and up to and 60 cm for perennials and shrubs, from

15 cm up to 50 cm for woody shrubs and perennials, and up to 100 cm for bushes (FLL 2018, Pérez and Coma 2018). In mediterranean climate, irrigation is needed mostly during prolonged periods of drought, or limited precipitations, generally during summer. During the other time of the year, while the deeper substrate allows greater water retention than extensive roofs, efficient drainage is still necessary to avoid waterlogging and to maintain root health. Compared to extensive green roofs, SIGR provides higher thermal resistance due to the higher substrate thickness but requires a higher loading capacity of the roof structure considering all the layers in saturated weight, the vegetation and the people visiting the roof, beside maintenance. Considering for example a thickness between 10-25 cm with herbs, grasses and shrubs, the weight at maximum water capacity ranges between 120-350 Kg/m2 (Pérez and Coma 2018).

Design features

The built up, as for the other green roofs types with exception of blue-green roofs, consists of the following layers above the roof structure (FLL 2018; Catalano et al. 2018): 1) root-resistant waterproofing; 2) mechanical protection layer; 3) drainage layer (gravel, plastic honeycomb elements, or modular drainage panels) that allows excess water to be discharged while retaining a portion useful for root absorption; 4) filter fabric to prevent the passage of fine particles; 5) growing substrate; 6) vegetation. In addition, due to fire safety and a better water management, gravel border is required along the perimeter and roof outlets. Regarding the plant species selection, it is possible to select different growth forms, from small herbaceous to perennial ground covers, but also bulbs, grasses and small shrubs, which require moderate maintenance (occasional pruning) and occasional irrigation (Vacek et al. 2017). For higher substrate up to 100 cm at punctual areas, it is possible to use woody plants (FLL 2018).

Maintenance

Semi-intensive roofs demand moderate but regular maintenance. This includes seasonal pruning for bushes and other woody species, periodic fertilization and weed removal for lawns, but also inspection of irrigation components. Though higher in maintenance compared with extensive roofs, this green roof system also provides the potential for a formal garden effect and/or potentially greater ecological benefits. As all green roofs plants can dry out in hot summers, thus objects that can generate sparks, glass (e.g. bottles) or cigarette ends must be avoided. However, the risk of spreading fire through wind is limited because the biomass is relatively small and the mineral substrate layer is reducing the potential inflammability risk. Exceptions are grass roofs because dry conditions increases the risk of fire propagation (i.e., if in summer the substrate is not moisturized by irrigation for example). Therefore, grass-dominated green roofs require targeted maintenance interventions (e. g., mowing and removal of aboveground biomass) to reduce fire hazard and prevent excessive accumulation of organic matter in the substrate, which can promote nutrient leaching and subsequent runoff water pollution.

Section C - Societal challenges

Biodiversity enhancement

Semi-intensive Green Roofs (SIGR) have a wide palette of plant and therefore can better support biodiversity both flora and fauna (including pedo-fauna); if maintenance is reduced to the minimum, for example for grass dominated vegetation one time late mowing, and the spontaneous colonisation is not arrested, except for invasive exotic plants, it can represents an enhanced natural form of vegetation, often self-sustaining and evolving. This typology can be considered a good mean of compensation, partially restoring the environmental footprint of the building by increasing biodiversity and restore water cycle. Over time, without or minimal irrigation, and allowing spontaneous species to colonise the roof, SIGR can mirror local surrounding communities (metapopulations) acting as stepping stones for natural habitats harnessing the enhanced soil-plant-insect relationships (Frisk and Hanslin 2025). In these conditions, species diversity of roofs communities is influenced positively by surrounding natural habitat proving their mutual beneficial relationship (Muratet et al. 2024). Additionally, the larger, the older and the deeper substrate, the higher the capacity of green roofs to support biodiversity due to a positive species/area ratio as in the case of the Wollishofen Water Filtration Plant in Zurich which hosts a great variety of species (including orchids) typical of semi-dry grasslands of temperate Europe (Landolt 2001). The way species are brought on roofs is relevant for species conservation, for example employing seeds or plants grown of the same ecotype by using the hay transfer method or hay seeds collected by vacuum or by hands, is increasing the potential biodiversity. Moreover, plant diversity is positively correlated with wildlife diversity but also CO_2 sequestration and stormwater capture and the resiliency to environmental stressors such as temperature, wind and water drought (Ndayambaje et al. 2024).

Climate Resilience and Water management

Green roofs contribute to the reduction of Urban Heat Island (UHI) effect cooling the air, but also reducing both roof temperature and ambient temperature compared to conventional roofs, thus reducing indoor cooling and heating needs. The vegetation layer (which can be simplified as foliage and ambient air) has a relevant impact on the mitigation of the UHI and it is characterized and influenced by many environmental parameters and thermal processes, such as: (1) solar radiation absorbed by the foliage; (2) long-wave radiation emitted by foliage into the ambient air and exchanged between the foliage and the air as well as the soil; (3) convective heat transfer phenomena occurring between the air and the foliage as well as between the soil surface and the ambient air of the canopy layer; (4) evapotranspiration and shading occurring in the foliage; and (5) convective heat transfer phenomena between the canopy and the ambient air (Mihalakakou et al. 2023). The substrate depth influences also the capacity of filtering stormwater with deeper substrate having higher water retention capacity thus a more effective means for water management purposes. Also plant diversity plays a role in both storing carbon and reducing carbon loss enhancing also the ability of the soil to absorb carbon (Speak et al. 2012). As all green roofs, one of the primary strengths is their ability to detain, retain, and slow the flow of stormwater, mitigating stress placed on sewers and water treatment facilities and local water cycles. Green roofs unlock the potential of the capture and reuse of untreated rainwater for irrigation and maintenance purposes, relieving pressure on freshwater systems.

Health, Well-being and Air Quality

Green roofs contribute significantly to CO_2 reduction and to the overall decrease of atmospheric pollution and greenhouse gas emissions. By moderating building temperatures, they help keep indoor environments at more stable levels (indoor temperature reduction up to 15°C), which in turn reduces the demand for air-conditioning (Mihalakakou et al. 2023). Lower energy consumption (cooling load reduction up to 70%) directly translates into a decrease in carbon dioxide emissions and other air-polluting criteria. Through this mechanism, green roof technology plays a relevant role in mitigating air pollution and limiting the release of greenhouse gases, thereby delivering both immediate and long-term benefits for the atmosphere and for human health. In addition, green roofs help prevent and reduce a wide range of air and pollutants (e.g., $PM_{2.5}$, PM_{10}, O_3, NO_2), enhancing environmental quality in densely populated urban areas. The carbon sequestration is performed by the plants and substrates and indirectly by energy savings due to the reduction of the building energy consumption both depending on the substrates' type and depth as well as the plant species richness and plant functional diversity (e.g. grasses, bushes, succulents), density and cover. To this regard, semi-intensive green roofs with grasses and forbs perform better than extensive green roofs with succulents. The thermal comfort associated with green roofs may also have indirect positive effects on those living or working inside the buildings they cover. Occupants of greener buildings often report higher levels of relaxation and well-being, which can be reflected in reduced absenteeism and improved workplace satisfaction. In this way, green roofs support not only environmental sustainability but also healthier, more comfortable, and more productive urban lifestyles. Beyond their environmental impact, SIGR also provides a variety of social and health-related benefits: visual and physical contact with natural greenery has been shown to offer a wide range of direct and indirect advantages for people, including improvements in both physical and mental health. Exposure to green space can support reductions in heart rate and blood pressure, alleviate respiratory health problems, and promote overall well-being. The presence of high-quality natural landscapes in urban areas can also influence how people feel, behave, and work. By lowering stress levels and counteracting feelings of sadness, additional greenery can improve mood and enhance productivity.

Biodiverse roof

Section A - General description

Fig. 4 – Biodiverse roof on a multi-level parking building in Manarola, Liguria, Italy (Source: Riccardo Guarino 2016).

Description

Biodiverse green roof (BGR) or 'brown roofs' were developed, respectively, in Switzerland and the United Kingdom to create urban areas with biodiversity conservation potential, by replicating near-natural habitats and host rare plants and animals, and relatively undisturbed (Baumann 2006; Brenneisen 2006; Dunnett 2015; Grant 2006). The genesis of biodiverse roofs took origin from long-term monitoring studies on extensive green roof where it was noticed that species establishment and succession was affected by the substrate kind and thickness, climatic conditions and of course time. For instance, on the traditional roofs constructed in Germany at the beginning of the 19th century and characterised by a coat of sand and gravel protecting the waterproof membrane, the first stadium (couple of years) was dominated by commensal species, while in the following 10 to 30 years, by meadows species in deeper substrate or shaded areas, or mosses and Crassulaceae species in shallow substrate and fully exposed areas (Thuring and Grant 2016). The fundamental design criterion for the construction of green roofs for biodiversity, consisted in creating micro-mosaic of different contiguous habitats capable to host different biological forms of plants and animals. The most relevant design characteristics distinguishing BGRs from conventional GRs are (Catalano et al. 2016a): 1) the creation of high spatial heterogeneity by varying substrate thickness and type, and adding extra features such as small temporary ponds, dead wood and other biodiversity shelters; 2) the selection of autochthonous plant species of the same ecotype or biogeographical region to foster local species dispersion also across cities (stepping-stones and metapopulation); the low maintenance and limited disturbance.

Synonyms

Brown roofs; ruderal green roofs; biotope roofs; soil-based green roofs

Section B - Technical details

Implementation conditions

When designing green roofs, it is necessary to correctly identify the permanent load, which must be assessed in relation to the materials comprising the individual layers and elements and, for safety reasons, to the fact that these elements may be completely saturated with water. Therefore, the values considered for static evaluation must be the densities under saturation conditions of all the individual layers or elements used in the built-up. An important factor to consider when designing any green roof is the dead load capacity (or weight) that the roof exerts onto a building. New buildings can be designed to ensure that they can withstand the weight of a green roof, while, when retrofitting onto an existing building the maximum load and carrying capacity of the roof structure mut be assessed by a structural engineer prior to installation. Generally, Biodiverse green roofs possessing the features of both extensive and simple-intensive roofs and a substrate which varies between 8 cm and 20 cm, therefore loads vary from about 100 Kg/m2 (typical of extensive green roofs) and about 400 Kg/m2 of semi-intensive green roofs. Biodiverse green roofs are based on shallow, low nutrient substrates (an average depth of 13 cm) and have low maintenance requirements; by varying substrate depth, the roof can support a greater diversity of plants and therefore biodiversity: mosses, succulents, herbaceous plants and grasses together with arthropods. Since the creation of habitat patches is one of the key design features, in retrofitting cases, the higher substrate thickness or heavier materials can be situated in correspondence of the pillars sustaining the roofs.

Design features

Similarly to all green roofs, the built up is the same as other conventional green roofs (FLL 2018; Catalano et al. 2018): 1) structural support; 2) root-resistant waterproofing; 3) mechanical protection layer; 4) drainage layer (gravel, plastic honeycomb elements, or modular drainage panels) that allows excess water to be discharged while retaining a portion useful for root absorption; 5) filter fabric to prevent the passage of fine particles; 6) growing substrate; 7) vegetation. Both irrigation and fertilisation are not required because resiliency and the low resources consumption is the requisite of all biodiverse green roof. The major difference to the other kind of green roofs is related to the substrate layer and therefore the vegetation. Keys design features are (Catalano et al. 2016a; 2018): (1) spatial heterogeneity, (2) use of autochthonous plant species of the same biogeographical region and (3) low maintenance and disturbance. As for the first point, fine-grained patchwork of different, contiguous habitats capable of hosting different biocoenoses can be obtained by varying the substrate thickness and kind, adding extra biodiversity-aiding structures such as stones, trunks, branches or other biodiversity shelters, and creating temporary ponds to offer water source for insects and birds while favouring the establishment of ephemeral hygrophilous biocenoses. As for the second point, the selection of plant species belonging of the same biogeographical region shall favour species already adapted to local conditions thus enhancing the resilience of these novel ecosystems (SIA 2013). In turn, the vegetation should also attract pollinators and support them with food, nesting places and reproduction sites. As for the third point, it is known from applied ecology that to a moderate disturbance correspond to a higher biodiversity (Bellini et al. 2025; Catalano et al. 2016b). Therefore, biodiverse green roofs require only a minimum maintenance limited to eradication of unwanted invasive species or trees juveniles. In practice, for example, could consist in planting shrubs on deeper substrate of 15 cm, sowing herbs on lower substrate depth of 10 cm, and spreading Sedum sprouts on the thinnest substrate depth of 6-8 cm, finally leaving open surfaces (beside the drainage outlets) free from vegetation for arthropods (sand patches or stripes). A critical phase is the dry period, normally in summer, which can cause the death of green roofs dwellers (both flora and fauna). For this, the installation of extra designed features such as dead woods and stones can provide cooler micro-conditions where species can find refugia.

Maintenance

Maintenance on this roof is comparable to extensive green roofs, considering that the area with grasses is not homogeneous and, in any case, works as refugia for species during more extreme conditions and should be kept in place. In case of temporary pond installation, the membrane used to detain water shall be periodically checked. In general, considering that to moderate disturbance often corresponds to a higher biodiversity, these roofs only need low yearly maintenance (eradication of unwonted seedlings and saplings of woody species which might be eventually too heavy for the roof structure or can damage the waterproof membrane). However, the low maintenance regime required for these kinds of GR systems should not influence the periodical check-up of the technical and structural parts.

Section C - Societal challenges

Biodiversity enhancement

Biodiverse green roofs are created to increase urban bio permeability, by mimicking nearby natural habitat sharing similar conditions that on roofs. For example, it would be possible to mimic dry grassland also belonging to priority habitat (Catalano et al. 2016a) such as that of 6220 (Pseudo-steppe with grasses and annuals of the *Thero-Brachypodietea*) of the Natura 2000 Directive (Council Directive 92/43/EEC), but also ruderal habitats (Dunnett 2015). The selection of plant species belonging to the regional species pool and therefore already adapted to local conditions enhances the resilience of these novel ecosystems (SIA 2013). In this way, green roofs can improve the ecological network as they can host metapopulations of targeted species (Ksiazek-Mikenas et al. 2019). To select the right species, Lundholm (2006) introduced the habitat template approach aiming at finding habitat analogues (Lundholm and Richardson 2010) to be imitated on GRs, while Catalano et al. (2021) suggested a phytosociological approach to select the species that grow together in shared environmental condition. In any circumstances on biodiverse green roofs, spontaneous colonization shall be encouraged (Muratet et al. 2024), except for invasive species or trees juveniles. When biodiversity conservation is concerned, the use of local soil (topsoil) is also encouraged because of the seed bank, microorganisms and fungi contained in it (Best et al. 2015; Van Der Kolk et al. 2023). In some countries the creation of biodiverse roofs is considered as a compensation measure by law (Ishimatsu and Ito 2013) when favouring specific endangered species (as in the case of the black redstart in UK, and the lapwing in Switzerland).

Climate Resilience and Water management

Regarding both the performance of biodiverse green roofs, possessing both the characteristics of extensive and semi-intensive green roofs, they have an intermediate performance regarding their benefits towards the challenges of climate resilience and water management. However, they contribute in mitigating UHI water quality. The benefits offered by GR can be categorized as follows

Energy benefits directly expressed through the reduction of the cooling and heating load depend strongly on building characteristics and heat transfer processes

Water management services provided by GRs depend on the plant species composition, plant strategy to uptake water, substrate type and thickness (water storage capacity), as well as the intensity of the rain event, where the role of spontaneous colonising vegetation is in this type of green roof quite relevant (Schrieke et al. 2023).

Health, Well-being and Air Quality

As the other green roof types, biodiverse green roofs (BGR) contribute to improve air quality by direct thanks to both plant and soil, in an intermediate level compared to extensive and semi-intensive green roofs. BGR are not thought to be visited by people to keep the disturbance of the biotope at minimum level. Nevertheless, such roofs can be used for education purposes in schools to increase awareness for biodiversity but also towards nexus among ecosystem services and biodiversity (Cole et al. 2024).

Biosolar roof

Section A - General description

Fig. 5 – Biosolar roof on Hallenbad roof (Muttenz, Basel) (Source: Catalano 2014).

Description

Biosolar roofs integrate photovoltaic (PV) panels on green roofs (generally extensive green roofs with an average substrate depth of approximately 12 cm) enhancing the multifunctionality of green roofs by producing electricity (up to 5 %) as well as increasing biodiversity, reducing pollution and other ecosystem services compared to conventional roofing systems (Ciriminna et al. 2019; Fleck et al. 2022; Irga et al. 2023; Lamnatou and Chemisana 2015; Singh and Brar 2020; Schindler et al. 2016). Plant species/PV interaction showed to increase the electricity yield depending also on other factors such as climatic conditions, evapotranspiration and albedo. Higher albedo and evapotranspiration can be obtained at higher plant coverage and can be increased using plants with light-coloured (or with silver hairs) leaves and light watering regime during summer. Succulents (such as *Sedum* spp.) showed to perform better than other forbs not only for the dense cover but also for the relatively low hight thus reducing the risk of shading the panels (Lamnatou and Chemisana 2015). However, *Sedum* species have a reduced evapotranspiration during hot sunny days, therefore also other species can perform well on biosolar roofs such as pulvinate, and prostrate plants (Catalano and Baumann 2017). From biodiversity perspective, PV increase niche diversity than same green roof without PV sheltering plants and animals (Nash et al. 2016). Compared with the combination of PV systems and white or cool roofs (i.e., reflective coatings or materials), biosolar roofs are recommended by multi-criteria decision frameworks that account for both the multiple ecosystem services provided by green roofs and stakeholder preferences (Maurer et al., 2023). By integrating vegetation and photovoltaic systems, biosolar roofs optimize overall performance while maximizing benefits for buildings (e.g., thermal insulation and energy generation) and the environment (e.g., biodiversity enhancement) (Rousset-Rouvière et al., 2025).

Synonyms

Photovoltaic-green roof; Bio Solar Terrace

Section B - Technical details

Implementation conditions

The design of Biosolar roofs must take into consideration both vegetation requirements and panels' energy productivity. In fact, PV modify both the microclimatic conditions beneath and behind them due to the casted shadow, and the way rainwater reach the ground due to the shield effect. Nevertheless, this creates a range of possible niches for species tolerating temporary shading and needing protection from direct sun exposure. Before deciding plant species, take into consideration the expectant maximum height that the plant can reach because tall growing plants can shade the panels and are less able to withstand strong wind. Rainwater accumulated more at the bottom edges of the modules, and it is transmitted through the substrate by capillarity, or it is actively diverted under the panels with capillarity fleeces below the modules. The distribution of water beneath the panels will also depend on the slope of the roof. If the slope of the whole roof area is less than 2%, an appropriately dimensioned and hydraulic effective drainage must be implemented. If the slope exceeds 9%, the waterproofing/root protection must be prevented from slipping off. Besides water storage in the substrate itself, further irrigation systems can be installed, depending on the resources, needs and region (also cooling the air thus increasing panels performance and energy yield). Regarding the statics, the main difference between biosolar roofs compared with other extensive green roofs is the weight of the photovoltaic or thermal panels together with the wind actions which generate extra load.

Design features

The built up of Biosolar green roofs depends on the type and structure holding the solar: Solar systems need to be securely fixed to the roof either weighted down (ballast) or anchored to some the roof of building structure to prevent wind lift effect; the substrate can provide ballast to the structure of PV. Nevertheless, the built up below the substate is the same as conventional green roofs (FLL 2018; Catalano et al. 2018): 1) structural support; 2) root-resistant waterproofing; 3) mechanical protection layer; 4) drainage layer (gravel, plastic honeycomb elements, or modular drainage panels) that allows excess water to be discharged while retaining a portion useful for root absorption; 5) filter fabric to prevent the passage of fine particles; 6) growing substrate; 7) vegetation. As well as biodiverse green roofs, provide spatial heterogeneity through its varying substrate thickness: in front of the panels, where the conditions favour low growing species and succulents, the recommended thickness is 5-7 cm for a length of 50cm. At the back of the panels, where the conditions favour plant growth and biomass, the recommended thickness is 15 cm which can be increased up to 20 cm with the distance to the previous solar array is wider (to 80 cm). It is also advisable to increase the area free from vegetation at the edge and at the water outlets to favour xeric insects. As the substrate constitutes a ballast for the solar panel structure against the wind, the use of excavation soil mixed with sandy gravel from local pits is recommended. There are opportunities to create different habitats of various plant associations within the solar panels' arrays and water percolation strategies (it is also important that the water necessary for plant growth can reach the area below the panels), because the variation of the substrate thickness and the shade of the panels support plant species with different adaptabilities. Drought and stress tolerant species can be planted at the front of the panels while at the back where conditions are shaded and humid, competitive and ruderal species are recommended. What is important is that the plants do not shade the panels thus affecting the energy production; therefore, pulvinate, creeping and prostrate plants should be preferred. More recently, bifacial photovoltaic modules have been implemented on roofs. These modules generate electricity from direct solar radiation incident on the front surface as well as from reflected (indirect) radiation captured on the rear surface. The backside of bifacial modules is typically transparent, allowing the solar cells to harvest light from both sides (Rousset-Rouvière et al. 2025). Their energy yield can be further enhanced when integrated with green roofs, due to increased light reflectance and improved microclimatic conditions (Baumann et al. 2019).

Maintenance

Maintenance of biosolar green consists of regular cleaning, debris removal and when necessary, prune the vegetation in front and between the panels to keep the power outputs at the maximum, but also as for other green roofs, eradicate phanerophytes and invasive weeds. Mowing is typically not required; however, it may be necessary in areas adjacent to the panels. In these cases, removal of aboveground biomass is essential to avoid excessive nutrient accumulation in the substrate. It is also necessary to verify that the vegetation is healthy and the soil is not eroded or moved by winds exposing underlying layers working as ballast for the PV. Supplementary or electronic devices such as irrigation and drainage systems but also inverters and electric wires, should be also checked to prevent floods or fires or reduce the performance of the PV. Finally, as all extensive green roofs plants can dry out in hot summers, thus objects that can generate sparks, glass (e.g. bottles) or cigarette ends must be avoided. However, the risk of spreading fire through wind is limited because the biomass is relatively small and the mineral substrate layer is reducing the potential inflammability risk.

Section C - Societal Challenges

Biodiversity enhancement

Biosolar roofs are a win-win solution for both the building and biodiversity as the presence of panels creates different micro climatic conditions below and between the panels for insects and plants favoured by shading or the protection from wind (Rousset-Rouvière et al. 2025). The installation of a solar systems on green roof can mitigate some of the harsh conditions typical of extensive green roofs: high temperatures, higher winds, constant sun exposure, high evaporation. In fact, panels or collectors shade against wind and sun creating more favourable conditions for plant which generally increase in density and diversity, but also an increased water retention as the rate of evapotranspiration ratio is reduced. Thus, biosolar roofs are richer in species (both flora and fauna) than conventional extensive green roofs due to the diverse ecological niches and habitats created by the panels (Nash et al. 2016).

Climate Resilience and Water management

The cooling effect of green roofs through evapotranspiration can benefit an integrated solar system by reducing not just the surrounding air temperature, but panel temperatures as well: the milder micro-climate due to the presence of the vegetation can help reduce the operating temperature, keeping PV closer to their optimal working temperature. The degree to which this effect increases electricity generation ranges from 2 to 8% annually (Catalano and Baumann 2017; Shafique et al. 2020). These benefits will depend on several factors including the climate, the panel height from the substrate, the plant species used and their density (cover), and the presence of irrigation. For example, panels that are mounted too close to the substrate will limit the circulation of air underneath, reducing the cooling effect. Similarly, different plant species transpire at different rates, therefore plant communities have a different impact on cooling. A broad plant palette will provide a broader array of performance and benefit, along with enhancing biodiversity. By employing bifacial photovoltaic modules (which generate electricity on both sides of the panel), albedo plays a crucial role: PV can have a 17% higher yield due to the higher albedo provided, for example, by silver-leaved plants or light-coloured substrates, when compared with standard green roof (Rousset-Rouvière et al. 2025).

Health, Well-being and Air Quality

As other green roofs, plants on roofs bind and absorb fine dust and other particulates, filtering them out of circulation. Similarly, green roofs bind and store carbon over time, in growing media and plants, storing and utilizing it for photosynthesis. Finally, the harvesting of green roof derived biomass can be used to contribute to regenerative energy concepts on a district scale.

Blue-green roof

Section A - General Description

Fig. 6 – Blue-green roof in Nevio Scala Winery in Lozzo (Source: DAKU Italia 2025).

Description

Blue and green roofs are characterised by vegetated roofs that collect, store and reuse rainwater. These roofs prevent water wastage, ensure proper water management during periods of drought and protect against heavy rainfall (Haer et al. 2022). A distinctive feature of the blue and green roof is its double cavity underneath to collect and retain rainwater. The first cavity collects and retains every raindrop of the water. The second cavity collects excess water from the first cavity, which is then used for irrigation. Irrigation water, instead of being delivered by traditional systems, is released slowly to the substrate from bottom to top, favouring horizontal diffusion and working by capillarity. Using sensors, an IoT system controls the release of water collected between the two cavities to manage rainfall loads in a balanced manner in relation to the weather forecast (DAKU 2024; Eisemberg et al. 2022).

Synonyms

Smart roof, stormwater management roof, capillar smart roof

Section B - Technical details

Implementation conditions

The successful implementation of a blue-green roof requires the integration of specific structural, hydraulic, ecological, and management conditions, all of which are crucial to ensure the proper functioning and long-term performance of the system.

From a structural standpoint, the roof must provide sufficient load-bearing capacity to support the combined weight of the saturated substrate and retained water - often exceeding 200 kg/m^2 - and must incorporate a waterproof and root-resistant membrane that complies with recognised standards of durability and impermeability (Almaaitah and Joksimovic 2022).

In hydraulic terms, the system should include a storage layer designed to retain between 20 and 80 L/m^2 of rainwater, coupled with a controlled drainage mechanism. In advanced systems, this may be automated through smart valves operating on weather-forecast-based management, which can reduce runoff by up to 90% during extreme rainfall events (Busker et al. 2022; Haer et al. 2022).

From an ecological perspective, the use of plant species tolerant to alternating hydric stress is essential, along with a lightweight substrate (8-25 cm thick) capable of ensuring adequate water retention, root aeration, and mechanical stability (Cristiano et al. 2022).

The management component requires periodic maintenance and, in more advanced configurations, the integration of monitoring sensors to measure water levels and vegetation health, thereby optimising the functional response of the roof (Richter et al. 2023).

Finally, urban and climatic conditions must guarantee compliance with local runoff regulations and adaptation to site-specific rainfall patterns, in order to maximise flood-risk mitigation and enhance the roof's microclimatic contribution within the urban environment (Richter et al. 2023).

Design features

From a constructional perspective, the blue-green roof is configured as a multi-layered system, in which each layer performs a specific and interdependent function. Above the load-bearing structure lies the waterproof and root-resistant membrane, typically made of PVC, EPDM, or modified bitumen, combined with a protective geotextile layer that distributes loads and prevents mechanical damage (Cristiano et al. 2022).

The blue layer, the technological core of the system, consists of cellular or modular units made of HDPE or recycled polypropylene, with a height ranging from 5 to 12 cm and a storage capacity between 20 and 80 L/m^2. This component enables the temporary retention of rainwater and its gradual release through manual or automated control devices (Busker et al. 2022; Haer et al. 2022).

Above the hydraulic layer, a geotextile filter prevents the migration of fine particles and preserves the system's permeability. The green layer, or growing medium, consists of a lightweight and porous substrate composed of materials such as pumice, perlite, expanded clay, and organic compost, with a thickness of 8–25 cm, providing adequate water retention, root aeration, and mechanical stability.

The vegetative cover includes species adapted to the local climate and ecological objectives of the project, mainly sedum, grasses, and aromatic plants capable of withstanding alternating hydric stress (Richter et al. 2023). In more advanced systems, integrated IoT sensors monitor water levels, substrate moisture, and surface temperature, enabling adaptive and predictive management of drainage and irrigation (Busker et al. 2022). In this configuration, the blue-green roof functions as a technical-ecological device that combines hydraulic efficiency, thermal comfort, and urban environmental value.

Maintenance

Regular maintenance represents a critical aspect in ensuring the long-term durability and operational efficiency of blue-green roofs. The main activities concern the hydraulic, vegetative, and structural domains. From a hydraulic perspective, it is essential to periodically verify the performance of drainage and storage devices, clean control valves, and check sensor functionality to prevent blockages and maintain the system's designed water retention capacity (Busker et al. 2022; Haer et al. 2022).

Vegetative maintenance involves the removal of invasive species, replacement of deteriorated plants, and reintegration of the substrate every three to five years. In arid or Mediterranean climates, seasonal supplementary irrigation may be required to preserve vegetation health and coverage uniformity (Cristiano et al. 2022).

On the structural level, an annual inspection of the waterproofing membrane and verification of static loads are essential, particularly in intensive roof systems where accumulated water and mature vegetation may significantly increase weight (Richter et al. 2023).

Finally, the integration of digital monitoring systems enables a predictive maintenance approach, improving water management efficiency, anticipating performance issues, and reducing long-term operational costs (Almaaitah and Joksimovic 2022).

Section C - Societal challenges

Biodiversity enhancement

Blue-green roofs serve as habitats and ecological corridors for urban wildlife (Ndayambaje et al. 2024). Numerous studies highlight their role as biodiversity refuges by mimicking natural habitats. Bird species have been observed using green roofs for feeding and nesting (Washburn et al. 2016). Some cities actively promote rooftop biodiversity through policies. For instance, Basel (Switzerland) requires native plants and soil (Kazmierczak and Carter 2010), Toronto offers biodiversity guidelines (Torrance et al. 2013), and London mandates green roofs to support biodiversity and related benefits (Williams et al. 2014). Species richness on roofs depends on factors like vegetation diversity, roof age, and structural complexity. Higher plant diversity often correlates with greater biomass and more niches, supporting a wider range of species (Cook-Patton 2015; Dinnage et al. 2012). This diversity can also benefit trophic levels beyond biomass, increased plant variety boosts faunal diversity (Brenneisen 2006), with notable rises in animal abundance on roofs featuring complex vegetation layers, from moss/sedum to woody shrubs (Madre et al. 2013). Arthropod diversity also peaks where vegetation is most structurally diverse (Gedge and Kadas 2004). Ultimately, plant diversity creates habitats that attract and sustain diverse insect and wildlife communities (Köhler and Ksiazek-Mikenas 2018).

Climate Resilience

Blue-green roofs decrease CO_2 levels through photosynthesis and storing carbon in plants and roots (Kavehei 2018). Researchers propose that increasing vegetation density in green roof systems can improve their capacity to absorb carbon (Charoenkit and Yiemwattana 2017). Variety of plant species on roofs can significantly impact CO_2 sequestration. For example, plant diversity plays a role in both carbon storage and reducing carbon loss in the short term and further found that a higher diversity of grassland species and specific plant characteristics enhance the absorption of carbon into the soil, increase storage of carbon (Steinbeiss et al. 2008). Consequently, ecosystems with diversity have the potential to facilitate the movement of carbon from the atmosphere to the soil. The impact of plant diversity on carbon sequestration on roofs with different vegetation (sedum, annual plants and a combination of sedum and annual plants) exceeds the decrease in CO_2 concentrations compared to monoculture plantation (Agra et al. 2017).

Urban runoff from surfaces like rooftops is known to contribute to water pollution (Lapointe et al. 2022). Having a variety of plant species on roofs can help address these issues by absorbing stormwater, reducing runoff, and aiding water infiltration (Lundholm et al. 2010). Plant diversity helps to improve the retention of stormwater by developing a range of canopy structures that catch rain, root systems that enhance soil absorption, growth patterns that optimize water uptake in different seasons and efficient use of nutrients to support greater plant growth and water absorption (Dunnett et al. 2008). Plant mixtures outperform monocultures in terms of water retention capabilities (Lundholm et al. 2010). The efficiency in reducing rainwater runoff can be improved by including both annuals and sedum (Maclvor and Lundholm 2011). While sedum is not the most effective at absorbing water and preventing runoff compared to higher diversity plantings, it is resilient and can survive drought conditions without irrigation. Having plants that can quickly absorb moisture between rain events in the season can enhance the water management capabilities of roofs. Recognizing the roles of green roofs for water mangement, it is suggested to use plant combinations to enhance water interception, absorption, and infiltration. Particularly, combinations that include sedum are noted for their ability to withstand disturbances, offering an approach to maximizing the functions of green roofs (Vasl et al. 2017).

Health, Well-being and Air Quality

Blue-green roofs in an urban setting can be beneficial to mental health by decreasing stress and anxiety just from observing them in an urban setting (Wang et al. 2016), while improving cognitive function (Lee et al. 2015), as well as overall wellbeing (Rezaei et al. 2021).

Blue and green roofs are great places for communities to meet and can become attractive places for intergenerational activities, social interaction, and collaboration (World Bank 2021). In addition, blue and green roofs provide recreational spaces encouraging community participation in green projects and fostering a sense of happiness and connection with nature, among city residents (Ndayambaje et al. 2024).

Rooftop agricultural entrepreneurship can create much needed low skill and part-time jobs and engage local communities on cooperative production (World Bank 2021). Moreover, blue-green roofs systems give benefits in terms of energy efficiency, building resilience and property value enhancement (Ndayambaje et al. 2024). They also contribute economically by increasing property value (Manso et al. 2021), sometimes by as much as 16 % (Ichihara and Cohen 2011).

Green façade

Section A - General Description

Fig. 7 – Green façade in Budapest at Bastya Park (Source: Hasanaj 2024).

Description

Green façades are characterised by extensive vegetation that develops vertically and maintains its roots in the ground. The development of green façades occurs in two forms: direct and indirect systems. Direct systems concern with free growth, thanks to the contact of the plants with the building façade or with the aid of anchoring systems inserted into the wall. Indirect systems works with the use of modular and/or tensile systems (grid or linear). Green façades include climbing plants, with long, folding, slender, drooping branches and also trellised plantations of third-size trees. This is the most historicised form of green wall realised with natural elements anchored on vertical building elements (Lambertini 2014; Bit 2012).

Synonyms

Vertical greening; climbing green walls; ground-based greening; vertical greening systems

Section B - Technical details

Implementation conditions

The proper design of a green façade requires compliance with a series of technical, environmental, botanical, managerial, and regulatory conditions that ensure its structural stability and long-term durability.

From a structural perspective, the wall must possess sufficient mechanical strength to support the combined weight of vegetation, substrate, and water, with particular attention to dynamic loads generated by wind and rainfall. In indirect systems, the use of steel cables or metal frameworks positioned 5–15 cm from the wall surface promotes ventilation and prevents moisture accumulation (ENEA 2024). The design must also guarantee safe and accessible maintenance pathways in accordance with building safety regulations.

Microclimatic conditions represent another decisive factor. The orientation of the building directly influences solar radiation exposure and consequently determines the most suitable plant species: south-facing façades favour species adapted to living in arid environments or in conditions of limited water availability, whereas north-facing walls require shade-tolerant plants (Chojnacka et al. 2024). Additional climatic variables - such as wind velocity, relative humidity, and seasonal temperature variation - affect both plant water requirements and irrigation frequency (Cuce et al. 2021).

From a regulatory standpoint, the installation of green façades must comply with local building rules and landscape conservation regulations, particularly within heritage-protected contexts (ENEA 2024).

Design features

A green façade is a composite system that integrates both architectural and biological components to ensure hydraulic efficiency, mechanical stability, and long-term vegetative vitality. Its main elements include the load-bearing structure, the vegetation support system, the growth substrate, and the irrigation and drainage systems.

The load-bearing structure may coincide with the building's external wall or consist of an independent substructure made of stainless steel or anodised aluminium, anchored by spacer brackets that create a ventilated air cavity. This configuration enhances transpiration, prevents moisture accumulation, and helps preserve the integrity of the façade cladding (ENEA 2024).

The vegetation support system sustains the growth of climbing or trailing plants, which may either adhere directly to the wall surface (direct façades) or develop on detached metallic frameworks (indirect façades). The latter configuration offers greater durability, improved air circulation, and easier maintenance (Cuce et al. 2021).

The growth substrate, the biological core of the system, consists of a lightweight, porous mixture of organic and inert materials such as coconut fibre, perlite, lapillus, and expanded clay. Its thickness ranges from 10 to 30 cm, depending on the vegetation type. The growth modules or containers, typically made of stainless steel or high-density polyethylene (HDPE), are equipped with drainage openings and replaceable anchoring systems (ENEA 2024).

Plant selection favours native or well-acclimatised species with non-invasive root systems: tolerant to drought and water scarcity plants for south-facing façades, shade-tolerant species for north-facing ones, and deciduous species for temperate climates, providing summer shading and winter solar permeability (ENEA 2024).

The irrigation systems generally employ drip micro-irrigation, managed by automatic control units equipped with temperature and humidity sensors. In more advanced configurations, the system integrates fertigation units and rainwater storage tanks, thereby promoting water sustainability (Knifka et al. 2023). The drainage layer, composed of geotextile filters and granular materials, prevents water stagnation and ensures root health and substrate aeration.

Maintenance

A scheduled maintenance strategy is fundamental to ensuring the long-term durability and vegetative performance of a green façade system. Routine maintenance activities should be performed on a quarterly basis, while technical inspections of the irrigation network and structural supports are recommended annually (ENEA 2024). These activities typically include periodic pruning, phytosanitary assessment, replacement of non-viable plants, and inspection of the irrigation infrastructure, accompanied by seasonal calibration of the watering system to optimise plant health and water distribution efficiency (ENEA 2024; Knifka et al. 2023).

From a sustainability perspective, the integration of substrate moisture sensors and rainwater harvesting and reuse systems is essential to minimise potable water consumption. In advanced applications, continuous monitoring through sensors measuring temperature, relative humidity and solar radiation, connected to a Building Management System (BMS), enables automated control of irrigation and maintenance operations. This digital management approach enhances operational efficiency, reduces water and energy demand, and ensures consistent performance monitoring of the façade over time (Knifka et al. 2023).

Section c - Societal Challenges

Biodiversity enhancement

Green façades, through the vertical integration of vegetation on building surfaces, play an increasingly recognised role in supporting urban biodiversity. By introducing living plant structures into built environments, they help increase the connectivity of natural areas, acting as ecological stepping stones between fragmented habitats. This is particularly valuable in dense urban settings where continuous green corridors are often limited.

The layered vegetation of green façades creates diverse microhabitats for a range of organisms, including insects, birds, and small invertebrates. As such, they contribute to an increase in habitat diversity, offering shelter, food sources, and nesting opportunities across varying vertical levels. Over time, these conditions support local species richness, promoting an increase in both native species and taxonomic groups (Francis and Lorimer 2011; Manso and Castro-Gomes 2015).

Climate Resilience

Green façades remove carbon through storage in vegetation and associated soil layers. Plants on green façades absorb atmospheric CO_2 during photosynthesis, while the substrate and plant biomass serve as carbon sinks, aiding in the long-term sequestration of carbon (Perini et al. 2011).

Green façades reduce greenhouse gas emissions indirectly by lowering building energy consumption. The vegetative layer provides insulation and shading, thereby reducing the need for air conditioning in summer and heating in winter (Puppim de Oliveira et al. 2024).

Green façades enhance microclimatic mitigation capacity in urban environments. By shading building surfaces, reducing heat absorption, and releasing moisture through evapotranspiration, they contribute to lower surface and air temperatures, helping to mitigate the urban heat island effect and improving thermal comfort at the pedestrian level (Ottelé et al. 2011).

Green façades contribute to the urban stormwater management by reducing the surface runoff. Vegetation integrated into building walls intercepts rainfall, retaining a portion of it on leaves and stems through canopy storage. A fraction of this intercepted water is then lost through evapotranspiration, while the remainder is slowed down, reducing the intensity and volume of water reaching the ground (Puppim de Oliveira et al. 2024). In systems where green façades include a growing medium or are combined with green roofs or permeable surfaces, their capacity to absorb and delay runoff is enhanced (Li and Babcock 2014). This reduction in peak flow contributes to lowering the risk of urban flooding, particularly during intense rain events. Green façades help to reduce the burden on traditional drainage systems, thus playing a valuable role in sustainable urban drainage strategies (Öztürk et al. 2024).

Health, Well-being and Air Quality

Green façades and green spaces have benefits for mental health and the reduction of chronic stress. Research conducted using virtual reality experiments has shown that exposure to vertical vegetation on building façades produces a greater stress-reducing effect compared to simple aesthetic interventions such as painting a wall (Chan et al. 2021). The integration of natural vertical elements into the urban environment can significantly contribute to people's psychological well-being.

Furthermore, studies on long-term exposure to residential green spaces have found that greater access to nature is associated with a lower risk of anxiety and depression (Engemann et al. 2019). The presence of urban green therefore plays a protective role for mental health, helping to reduce symptoms of common psychological disorders and enhance the overall well-being of the population.

Green wall

Section A - General Description

Fig. 8 – Green wall in the Sorgane neighborhood in Florence (Source: Hasanaj 2025).

Description

Green walls are controlled-growth living plant systems that grow on a vertical structure with above-ground vegetation, including ground cover plants, shrubs, grasses and herbs. They are complex systems involving planting of species that are integrated with technological and plant components, including the irrigation system that provides the water and mineral essential nutrients. Green walls mainly consist of four functional layers: structural support, growing substrate, operating and management system and plant structure (Lambertini 2014; Croce and Vettorato 2021).

The substrate of green walls can be organic or artificial (expanded resin, felt, perlite, mineral wool). The solution system is characterised by hydroponic cultivation and allow a wide variety of vegetation along the vertical surface (Perini 2013; Croce and Vettorato 2021).

Two methods exist for the application of the vegetation; plants can grow in lightweight felt layers without requiring a soil substrate (i.e. continuous green walls), or in panels constituted by specific supporting elements (i.e. modular green walls) (Manso and João Castro-Gomes 2015).

Synonyms

Living walls; vertical gardens; green walls systems; moss walls

Section B - Technical details

Implementation conditions

The implementation of a green wall requires the definition of structural, mechanical, and biological parameters to ensure stability, durability, and long-term sustainability. The supporting structure must be designed to withstand both permanent and variable loads resulting from the weight of the substrate, water, vegetation, and accidental actions. When saturated with water, such systems can reach loads of 150–250 kg/m^2, making it essential to verify the load-bearing capacity and assess compatibility with waterproofing and anchoring systems (ENEA 2024; FLL 2018; Manouchehri et al. 2024).

A ventilated cavity between the wall surface and the vegetated modules is recommended to prevent moisture accumulation and to promote natural convection, with positive effects on material durability and on the thermo-hygrometric performance of the building envelope (ENEA 2024; City of Hamburg 2018; State of Victoria 2014).

The solution should include automated irrigation and efficient drainage, with provisions for rainwater collection and reuse. The integration of moisture sensors and control systems reduces water consumption and optimises resource management (ENEA 2024; GIZ 2024; Ode Sang et al. 2022).

Plant species selection should be consistent with local microclimatic conditions, orientation, and water availability. The use of hardy, perennial species with non-invasive root systems is recommended, alongside a planned maintenance and replacement schedule (ENEA 2024; City of Hamburg 2018).

Life Cycle Assessment (LCA) analyses have demonstrated that the choice of materials, particularly the substrate and supporting structure, and water management strategies significantly influence the environmental impact of green walls. The use of low-energy-intensity components and water recirculation systems contributes to improving the overall environmental performance (Irga et al. 2023; Manouchehri et al. 2024).

Design features

From a construction standpoint, a green wall consists of a metal framework made of galvanised steel or aluminium, which provides mechanical stability and accommodates a ventilated cavity of at least 5 cm between the wall surface and the vegetated modules. The modular panels, manufactured from HDPE, technical felt, or recycled plastic materials, contain the substrate and plant species (ENEA 2024; GIZ 2024; City of Hamburg 2018).

The substrate serve as both anchoring and nutrient. Optimal mixtures combine organic and inorganic components (such as coconut fibre, perlite, and silica sand) to ensure physical stability, adequate drainage, and aeration (ENEA 2024; Manouchehri et al. 2024; FLL 2018).

The irrigation system, a key functional component of the green wall, must ensure uniform water distribution through drip or micro-spray systems. The water used should maintain optimal chemical conditions for nutrient absorption and to prevent physiological imbalances in plants. The integration of collection tanks and recirculation systems enables sustainable water management (ENEA 2024; Irga et al. 2023; GIZ 2024).

Floristic selection should follow both functional and ecological criteria: evergreen and perennial species ensure visual continuity and biological stability, while tropical understorey plants are suitable for indoor or shaded environments. Hardy species are more appropriate for sun-exposed locations (Ode Sang et al. 2022; City of Hamburg 2018).

Installation must comply with a quality control protocol including cleaning and waterproofing of the wall surface, static verification, fixing of the supporting structure with stainless steel anchors, assembly of the modules, and functional testing of the irrigation system. An acclimatisation phase of at least two weeks is recommended, characterised by intensive irrigation and monitoring of microclimatic parameters (ENEA 2024; State of Victoria 2014; GIZ 2024).

Maintenance

The maintenance of a green wall represents an essential phase in the system's life cycle and must be planned from the design stage. Effective management includes monitoring of hydrological and vegetative parameters, scheduled inspections of the structure and irrigation system, replacement of deteriorated plant species, and biomass management through pruning and controlled fertigation (ENEA 2024; GIZ 2024; Manouchehri et al. 2024).

Structural inspections, to be carried out at least biannually, should assess the integrity of metallic components, the stability of fixings, and the functionality of the ventilated cavity. Waterproofing and sealing systems must also be checked to prevent water infiltration (FLL 2018; City of Hamburg 2018). The irrigation system requires periodic cleaning of filters and nozzles, verification of flow rate, and water quality control. The efficiency of drainage and recirculation tanks is crucial to prevent waterlogging and root stress (ENEA 2024; Irga et al. 2023).

Vegetation monitoring should be conducted monthly, supported by environmental sensors. Quarterly pruning and annual replacement of 5–10% of the plants help maintain biological continuity and uniform coverage (State of Victoria 2014; City of Hamburg 2018). Automated fertigation with nutrient solutions should alternate fertilised and non-fertilised cycles to prevent salt accumulation (ENEA 2024; Irga et al. 2023).

Phytosanitary control should prioritise ecological approaches based on preventive monitoring and targeted biological treatments, avoiding broad-spectrum pesticides (Ode Sang et al. 2022). A scheduled maintenance plan with routine, semi-annual, and annual inspections ensures traceability of interventions and overall system efficiency (GIZ 2024). The service life of a well-maintained green wall is estimated at 20–25 years, with replacement of modules and major components every 8–10 years (ENEA 2024). Systematic maintenance preserves both the ecological functionality and the long-term durability of green infrastructure in the urban context.

Section C - Societal challenges

Biodiversity enhancement

Green walls contribute to an increase in habitat diversity within urban environments by offering new ecological niches for a wide range of organisms, including pollinating insects, birds, and small invertebrates. Thanks to the variety of plant species that can be cultivated on these vertical structures, there is an observable rise in local biodiversity, both in terms of flora and fauna. The integration of green walls into the urban landscape not only enhances aesthetics and air quality, but also supports the creation of microhabitats that sustain richer and more diverse biological communities, thereby contributing to the ecological resilience of urban ecosystems (Collins et al. 2017; Vannik et al. 2025).

Green walls can support biodiversity in cities at a landscape scale by acting as a "corridor" or "stepping stone" to facilitate movement and despersal (Angold et al. 2006). A well-connected network, managed at a landscape scale, will increase the stability of urban biodiversity in the face of increased disturbances and stochastic changes (Goddard et al. 2010).

Climate Resilience

Green walls play a significant role in enhancing climate resilience. Through the process of photosynthesis, the vegetation in green walls sequesters atmospheric carbon dioxide, contributing to direct carbon removal. Moreover, by providing natural insulation and shading, green walls can effectively reduce cooling energy consumption in various urban microclimates, thereby indirectly decreasing greenhouse gas emissions associated with energy production (Bakhtyari et al. 2024).

Additionally, green walls contribute to improved microclimatic conditions by moderating temperature extremes, increasing humidity and reducing wind speed around buildings. The optimal orientation of green walls can significantly reduce building surface temperatures, enhancing thermal comfort and reducing the urban heat island effect (Jayasooriya et al. 2025). The integration of green walls with renewable energy systems, such as photovoltaic panels, has been explored to enhance energy production.

The integration of green walls into buildings not only improves water quality but also contributes to sustainable water management practices. By treating greywater on-site, these systems decrease the load on municipal wastewater treatment facilities.

Green walls can support urban greywater recycling by using vegetation and lightweight growing layers to improve water quality before reuse. Recent studies show that systems with ornamental plants can be effective in treating greywater and can therefore be integrated into urban design strategies (Dal Ferro et al. 2021). Large-scale applications have also shown promising results in reducing unwanted substances and microorganisms, although the choice of the growing layer requires careful attention to avoid negative effects on water quality (Lakho et al. 2021).

Health, Well-being and Air Quality

Green walls contribute to improved air quality by filtering pollutants and particulate matter, thereby enhancing urban environmental conditions (Perini et al. 2017). Beyond their ecological benefits, green walls have been linked to positive mental health outcomes, including reduced chronic stress and anxiety. Exposure to natural elements and biophilic environments, such as vertical greenery, fosters psychological restoration and emotional well-being (Xiaoxue and Huang 2024; Fonseca et al. 2023; Gunn et al. 2022; Shao et al. 2024).

Visual interaction with green walls and natural views promotes a faster recovery from both physiological and psychological stress in older adults, reducing heart rate and perceived anxiety levels (Xiaoxue and Huang 2024).

Both indoor and outdoor green walls contribute to stress reduction, mood enhancement, and an improved perception of psychological comfort, aligning with the broader framework of biophilic design theory (Fonseca et al. 2023). In educational settings, the introduction of green walls in schools has been found to support students' emotional well-being and concentration (Gunn et al. 2022), whereas in workplace environments, living wall systems have been shown to reduce occupational stress and enhance environmental satisfaction (Shao et al. 2024). Exposure to vertical natural elements produces measurable psychological benefits, consistent with the notion that interaction with nature facilitates emotional restoration and the physiological regulation of stress (Bringslimark et al. 2009).

Planter green wall

Section A - General Description

Fig. 9 – Planter green roof in Fukuoka, Japan, designed by Emilio Ambasz (Source: Kenta Mabuchi 2013).

Description

Planter Green Walls represent a typology of indirect vertical greening systems characterised by the use of self-contained planting units - such as pots, planters, boxes, or prefabricated modules—that are not connected to the natural soil but are instead anchored, supported, or integrated into the building façade or an independent structural frame. Within these containers, plants develop in lightweight or engineered substrates, with their root systems confined to the modules and without direct contact with the wall surface (Perini and Rosasco 2013; Lambertini 2014; Bustami et al. 2018; Ottelé 2011).

These systems exhibit a modular design and high configurational flexibility, positioning them as an intermediate solution between conventional direct-rooting green façades and technologically advanced living wall systems (Bustami et al. 2018). Unlike traditional green façades, where vegetation grows from the ground and climbs vertically with the aid of support structures, planter-based systems are entirely independent of the soil and can be installed at any height along the façade, including roofs, parapets, balconies, or freestanding metal frameworks. This structural autonomy enables their application in both new developments and urban retrofit interventions, offering a versatile strategy for the greening and ecological regeneration of existing buildings (GIZ 2024).

Planter Green Walls frequently integrate automated irrigation and fertigation systems, together with rainwater harvesting and recirculation technologies, allowing precise management of water and nutrient resources. Such integrated systems enhance operational efficiency and contribute to the long-term sustainability and performance of vertical greening solutions (Lambertini 2014; Irga et al. 2023).

Synonyms

Hybrid green wall, planter-box-based façade, modular green wall system, indirect greening façade

Section B - Technical details

Implementation conditions

The implementation of a modular container-based vertical greening system follows a well-defined operational sequence. During the design phase, factors such as building orientation, microclimatic conditions, and structural characteristics are analysed in order to determine the optimal arrangement of modules and the most suitable plant species (ENEA 2024; Kraus et al. 2018). Although this solution is particularly suitable for integration into newly constructed buildings—allowing full exploitation of the benefits of an integrated design approach with purpose-built façade containers—it can also be effectively applied to existing structures.

In the latter case, the process includes the installation of a supporting framework composed of load-bearing elements. The subsequent installation of the container modules must ensure proper connection of the irrigation and drainage networks, verifying both water flow efficiency and the integrity of joints.

For both new and retrofit applications, plant installation may involve the use of pre-grown specimens or rooted cuttings, in order to minimise acclimatisation time and achieve an immediate visual and functional impact (Bit 2015; GIZ 2024).

Design features

From a construction perspective, Planter Green Walls can be categorised into two main typologies: terraces and planter boxes, or container-wall systems. Both configurations represent complex systems that integrate structural engineering, architecture, ecology, and landscape design.

The use of terraces or planter boxes as architectural elements enables the controlled growth of trees, shrubs, and herbaceous species within the building structure (Giacomello and Valagussa 2015; Bono et al. 2020). A notable example is the *Bosco Verticale* in Milan, where cantilevered reinforced concrete balconies—projecting up to 3.25 m—incorporate planters for vegetation (1.10 × 1.10 m deep for trees and 0.50 m deep for shrubs), allowing full canopy development (Bianchini n.d.). The multilayer stratigraphy includes a waterproof bituminous membrane, root barrier, drainage layer, geotextile filter, and a volcanic lapillus-based substrate. The drip irrigation system utilizes treated greywater and rainwater, regulated through climatic sensors and automated control (Baratta 2015). Plants are anchored with steel frames and tension cables engineered to withstand wind loads of up to 90 km/h (Giacomello and Valagussa 2015).

Container-wall systems, such as those implemented in the Physics Building of Humboldt University in Berlin-Adlershof, comprise a supporting structure, vegetated modules, and an integrated irrigation and drainage network (Köhler 2015; Oppla n.d.). The modular containers filled with technical substrates are either integrated into the building façade or assembled on independent frames that allow the cultivation of climbing, shrubby, or small-sized species, adapting to diverse architectural configurations and urban contexts.

The functional performance of these systems depends primarily on the correct dimensioning of the growing substrate, which must ensure an optimal balance between water retention capacity, aeration, and mechanical stability, and on the supporting structure, designed to withstand both static and dynamic loads arising from the saturated substrate and plant biomass. The system should be equipped with automated irrigation and fertigation technologies, incorporating sensors to monitor moisture and water supply in relation to climatic conditions. Plant selection must prioritise resilient species compatible with the façade's microclimate and orientation, while climbing plants require the integration of guide structures such as cables or grids (Köhler 2015; Kraus et al. 2018).

Maintenance

The maintenance of Planter Green Walls is a continuous and technically specialised process aimed at ensuring the physiological stability of the vegetation and the durability of the construction components.

A key factor in long-term performance is the efficiency of water supply, which must be achieved through drip irrigation systems, water-retention mechanisms within the containers, and the selection of plant species with low water requirements (Bono et al. 2020).

Routine maintenance includes the periodic calibration of the automated irrigation system, inspection of the fertigation network, and replacement of any deteriorated components. Annual or semi-annual pruning operations, performed by professionals specialised in arboriculture, are essential to control plant growth and to preserve both the safety and the aesthetic quality of the façade covering (Kraus et al. 2018).

Continuous phytosanitary and nutritional monitoring allows the assessment of plant establishment, growth dynamics, and substrate balance, enabling the early detection of environmental stress factors (Bono et al. 2020). The service life of the system may exceed thirty years, provided that regular management of both vegetative and technical components is maintained, with careful attention to substrate quality, drainage efficiency, and compatibility between plant species, microclimatic conditions, and façade orientation (Kraus et al. 2018).

The long-term success of Planter Green Walls depends on an integrated maintenance strategy involving agronomic, engineering, and other expertise, ensuring water-use efficiency, ecological stability, and sustainable management of modular green façades (Köhler 2015).

Section C - Societal challenges

Biodiversity enhancement

The integration of planter green walls into building infrastructure has contributed to increasing habitat diversity in urban environments, providing vertical ecological niches that support a wider range of plant and animal species, and promoting functional biodiversity in highly anthropised settings (Francis and Lorimer 2011). Planter green walls contribute to increasing local diversity, in terms of species, through the creation of heterogeneous microhabitats along vertical surfaces. These provide varied environmental conditions - such as light, moisture, and substrate - that are capable of supporting a broader range of plant and invertebrate organisms, thereby enhancing ecological richness in densely built urban contexts (Ottelé et al. 2011). Finally, the integration of Nature-based Solutions, such as rain gardens, green roofs, and planter green walls, contributes to enhancing connectivity between scattered natural areas, facilitating the ecological flow of species, seeds, and resources, and promoting the resilience of fragmented urban ecosystems (Tzoulas et al. 2007).

Climate Resilience

Planter green walls contribute to the removal of atmospheric carbon through storage in plant biomass, enhancing carbon sequestration capacity in urban settings and mitigating the effects of climate change through photosynthesis and the accumulation of organic carbon in plant tissues (Reyhani et al. 2022). Planter green walls contribute to improving microclimatic mitigation in urban environments by reducing surface temperatures and the urban heat island effect, thanks to plant evapotranspiration and the shading of vertical surfaces (Perini and Rosasco 2013). This mitigation capacity is made possible by the vegetative structure, which modulates the local microclimate by increasing relative humidity and absorbing solar radiation, thereby creating cooler and more comfortable environmental conditions for the surrounding urban spaces (Ascione 2020).

Planter green walls play a significant role in urban stormwater management by mitigating surface runoff. By integrating vegetation into building containment structures, these systems capture rainfall not only from the leaves and stems, where part of the water is temporarily stored (canopy storage), but also in the containers that host the plants. Some of the water is lost through evapotranspiration, while the remaining water is released more slowly, reducing both the flow rate and the overall volume that reaches ground level (Puppim de Oliveira et al. 2024).

Planter green walls used in combination with green roofs or permeable surfaces increase their ability to retain and delay runoff (Li and Babcock 2014). This delay in peak flows contributes to reducing the risk of urban flooding, especially during heavy rainfall.

Health, Well-being and Air Quality

The presence of trees, shrubs, and other types of vegetation in planter green walls significantly improves air quality in urban environments. These plants, in green wall configurations, contribute to capture airborne pollutants such as particulate matter (PM), nitrogen dioxide (NO_2), and carbon dioxide (CO_2) (Viecco et al. 2021). Dense foliage and layered planting in these systems increase the surface area available for filtering contaminants, confirming the general effectiveness of green walls in filtering air (Paull et al. 2020) and making planter green walls an effective tool for enhancing environmental health in cities.

Incorporating natural vertical features into urban settings can play a crucial role in enhancing mental health. Additionally, research examining prolonged exposure to green spaces near homes indicates that increased contact with nature correlates with a reduced likelihood of experiencing anxiety and depression (Engemann et al. 2019).

Co-benefits and key design features of Nature-Based Solutions in the built environment

Nature-Based Solutions (NbS) integrated into buildings create new habitats for flora and fauna. The selection of plant species, substrate depth, and ecological connectivity are determining factors in their ecological effectiveness (Calviño et al. 2023). Studies have shown an increase in plant diversity in older green roofs (Nash et al. 2016) and a greater presence of pollinators associated with flowering species (Jacobs et al. 2023). Higher vegetation cover and structural complexity have been found to enhance arthropod richness (Calviño et al. 2023) and to support urban bird communities (Partridge and Clark 2018).

The implementation of green roofs and walls significantly contributes to the microclimatic regulation of buildings. Compared with conventional roofs, vegetated surfaces can reduce external surface temperatures by up to 35 °C (He et al. 2017) and internal temperatures by up to 20 °C, thereby improving indoor thermal comfort (Hao et al. 2022). Thermal inertia is increased, delaying heat-load peaks and reducing diurnal temperature fluctuations (Guttari et al. 2020). In temperate and cold climates, NbS also provide an insulating effect, maintaining higher indoor temperatures during winter (Juras 2022) and reducing thermal stresses on building materials (Tariku and Hagos 2022).

At the urban scale, building-integrated NbS generate wider environmental benefits by lowering ambient air temperatures by up to 6.4 °C in the airspace between vegetation and building façades (Juras 2022). The associated cooling effect contributes to mitigating the urban heat-island phenomenon (Almaaitah and Joksimovic 2022) and can enhance the efficiency of photovoltaic panels by reducing their surface temperature by more than 8 °C (Arenandan et al. 2022).

Energy performance improvements are also well documented: NbS applied to buildings can reduce cooling energy demand by up to 25 % during summer (Tan et al. 2020) and heating demand by up to 18 % in winter (Zheng 2021). A green roof can yield energy savings of approximately 11.53 kWh/m^2 per year (Cai et al. 2019), with CO_2 emission reductions of up to 27 tonnes per summer season for extensive large-scale installations (Jim and Peng 2012). Although the direct carbon-sequestration capacity of vegetated systems is relatively modest yet measurable, the indirect benefits derived from reduced energy consumption are substantially greater (Kandel et al. 2024).

Green roofs also improve stormwater management, reducing runoff volumes by up to seven-fold compared with conventional roofs (Perales-Momparler et al. 2017) and lowering flood peaks by 82–85 % in intensive systems (Almaaitah and Joksimovic 2022). They can retain up to 96 % of rainfall during light precipitation events (Abualfaraj et al. 2018), with runoff delays exceeding one hour (Tariku and Hagos 2022). Furthermore, they enhance water quality, with reductions of 79–97 % in suspended solids and significant decreases in nitrogen and phosphorus concentrations (Liu et al. 2021).

Beyond environmental outcomes, NbS integrated into buildings deliver notable social and economic benefits. Users report improved well-being and positive perceptions of green spaces (Mesimäki et al. 2019), alongside reductions in noise and enhanced thermal comfort. From an economic perspective, energy savings are substantial (Fleck et al. 2022), and edible living walls can provide up to 46 % of household food requirements (Nagle et al. 2017). Return-on-investment values as high as 660 % have been reported, albeit with relatively long payback periods (Pérez-Urrestarazu et al. 2017).

The effectiveness of NbS applied to buildings depends on a set of critical design parameters that directly influence system performance (Kandel et al. 2024).

A primary consideration concerns the selection of plant species and the quality of the root system, both of which are fundamental to vegetative resilience and to the chemical-physical stability of the substrate. Informed plant selection helps to reduce thermal fluctuations and structural stress, thereby enhancing building durability (Zhang et al. 2019).

Water management is another key factor. The efficiency of green roofs and walls is strongly dependent on substrate moisture rather than vegetation density (Bevilacqua et al. 2015). Well-designed irrigation systems and drainage layers help to maintain optimal moisture content, support plant growth, and improve thermal performance (Tan et al. 2017). Substrate depth contributes to maintaining lower root-zone temperatures (Benedito al. 2023), while the use of root barriers protects building structures from potential damage (Tariku and Hagos 2022).

Substrate design - encompassing depth, composition, and structure - forms the functional foundation of NbS. Greater substrate thickness increases the building's thermal capacity and inertia (Stella and Personne 2021), while the use of porous materials such as lightweight expanded clay aggregate (LECA) improves water retention, reduces overall weight, and enhances thermal efficiency (Tan et al. 2017). Substrate composition also affects filtration capacity, with more porous and heterogeneous mixtures demonstrating higher efficiency in nutrient and pollutant removal (Abualfaraj et al. 2018).

Vegetation design must be tailored to the climatic context. Parameters such as leaf area index (LAI), canopy density, and photosynthetic pathway significantly affect cooling performance and urban heat-island mitigation (Kandel et al. 2024). Moreover, species diversity broadens the range of ecosystem services provided (Olivieri et al. 2013).

Additional influencing factors include the distance between vegetation and the building façade—as observed in vertical greening systems - which affects insulation properties (Piro et al. 2018); as well as building height and surrounding urban context, which influence solar radiation exposure and habitat suitability for insects (Jacobs et al. 2023). Façade orientation also plays a key role: south-facing façades are particularly effective in reducing surface temperatures in temperate climates (Sendra-Arranz et al. 2020).

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Nature-based Solutions for urban forestry

Lorenzo Nofroni

Abstract: The chapter concerns the NbS grouped within the urban forestry (UF) approach defined as a strategic and flexible concept aimed at enhancing vegetation in open spaces within urban, suburban, and peri-urban areas. UF is not limited to woodlands but includes the entire vegetation network (street trees, parks, private gardens, infrastructure corridors) as an integrated system. The chapter analyzes six specific NbS that contribute to this strategy: afforestation, tree rows, vegetation cluster, tree plantation on paved surface, hedgerows and shrub strips, flower meadows. Each solution presents a brief description that concisely defines its characteristics and functionalities, a list of the most recurrent synonyms used in scientific and technical literature, a description of technical details with particular reference to Conditions (requirements, loads), specifications for Construction (built-up, layers, performance), and maintenance, and a section dedicated to Societal Challenges, organized into three categories: Biodiversity enhancement, Climate Resilience and Health, Well-being and Air Quality.

Keywords: Urban Forestry, Climate Change Adaptation, Open spaces, Climate Resilience, Green Infrastructure.

The contribution of urban forestry to urban biodiversity

Nature-based Solutions based on the establishment of vegetation in open spaces within urban, suburban, and peri-urban areas can be grouped inside an interpretive category for strategic and design actions referable to the concept of urban forestry. Indeed, the solutions presented in the remainder of the chapter contribute to the implementation of an urban strategy that, through the progressive enhancement of spaces hosting plant populations, aims to protect and strengthen the urban forest, understood as a peculiar wooded system integrated within the city. The result of a long definitional process, the urban forest is frequently considered a «flexible concept that includes tree-lined streets and groups of trees in urban parks, green belts between cities, and even woodlands far from the urban center […] it occupies that part of the urban ecosystem constituted by vegetation and its natural resources» (Moeller 1977). In this sense, it can be imagined as the totality of plant species within and around urban settlements and includes, for example, vegetation present in both public and private areas; vegetation in parks and gardens, as well as that existing in infrastructural corridors (Miller et al. 2015). Internationally, it is common to refer to urban forests as a network or system that includes woodlands, tree groups, street trees, and individual trees found in urban and peri-urban areas, in parks and gardens, and also in abandoned zones (Salbitano 2016). In the national context, the term appeared since the early 2000s to define «the entirety of vegetation within urban, suburban, and the city-country fringe» (Sanesi 2002), which includes «residual agricultural land, natural spaces, tree-lined areas, avenues, gardens and parks of historic villas, municipal villas, allotments, riparian areas, groves, forest areas, road and railway buffer zones, uncultivated lands, etc.» (Agrimi 2013).

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Urban forests are conceived as multifunctional systems that play an important role in the ecology of human habitats, as they cause variations in climate and economy, are recreational places for city dwellers, and simultaneously represent refuge areas for wild fauna (Jiri Lev 2017). In this sense, it is common to assign a structural role to the concept of urban forest within the context of green infrastructure (Tzoulas et al. 2007). Linked to the broad concept of urban forest is a process-oriented dimension due to the effects on urban environmental factors attributed to the presence of vegetation; this dimension particularly refers to the field of studies on ecosystem services, which investigate vegetation structures with the aim of estimating the value of this component in the production of services within the urban ecosystem (Taylor et al. 2013). In this sense, urban forests «provide a conceptual framework to organize a research program to maximize the benefits that forests can bring to the improvement of urban environments» (Moeller 1977); this objective is at the heart of a strategic approach, usually called urban forestry, aimed at the creation, care, and management of the vegetative component of urban systems. Actions related to urban forestry are considered NbS as they contribute to the pursuit of an adaptive and dynamic urban strategy intentionally inspired by the processes and functions of forest ecosystems to address the social, economic, and environmental challenges of cities in an integrated manner (Sanders and Mc Curdy 2021; Castellar et al. 2021). Furthermore, urban forestry actions entail multiple simultaneous benefits, for example, an urban woodland or a tree-lined avenue can simultaneously regulate the microclimate, contribute to stormwater management, improve air quality, provide wildlife habitats, and offer recreational opportunities. In the international NbS catalogs, actions related to urban forestry are part of numerous documents and data collections, including Unlab, Nature4Cities, ThinkNature, Urbangreenup, and NWRM. Urban forestry and related actions are crucial for biodiversity conservation in highly anthropized contexts (Hutt Taylor et al. 2024) due to three main key factors:

- Urban forestry actions constitute habitats for wild flora and fauna, offer refuge, food, and nesting sites for numerous species, particularly for avifauna, supporting rich and diversified communities.
- Urban forestry actions contribute to ecological connectivity, connect isolated habitat fragments, facilitating species movement, maintaining genetic diversity, and strengthening the resilience of the entire urban ecosystem
- Urban forestry actions makes the living community itself more resilient; for example, a system of open spaces in an urban context rich in arboreal and shrub species more easily overcomes stresses derived from diseases, pests, climate change, and pressures from human presence.

Within the context of the Italian National Recovery and Resilience Plan (PNRR), among the interventions related to safeguarding air quality and territorial biodiversity (Intervention Line 3), specifically Investment 3.1 for the «Protection and Valorization of Urban and Extra-urban Green Spaces», the objective has been set to create urban, peri-urban, and extra-urban woodlands in the broad areas of the 14 Metropolitan Cities. Consequently, the Urban and Extra-urban Forestry Plan has been drafted to strengthen and systematize indications, criteria, and requirements, in order to provide a unified and coherent national reference framework for designing forestry interventions. Other important reference documents for urban forestry actions include:

- the National Biodiversity Strategy 2030 (Mi.T.E. 2023), within which a section of strategic objectives is dedicated to urban biodiversity, with particular reference to Action B10.1 Promoting Urban Greening.

- The National Urban Green Strategy (M.A.T.T.M., Comitato del Verde Urbano 2018), which includes three chapters of the strategic framework dedicated to urban and peri-urban forests, and particularly in the transversal lines of intervention, mentions: «increasing tree and green area cover moving from m2 to ha»; «increasing the plant diversity of urban forests in line with the territorial potential»; «Incentivizing Green Infrastructure projects to reconnect urban and peri-urban green spaces»; «connecting green areas into integrated systems based on the 'demand' for ecosystem services»; «considering tree-lined avenues and tree rows as 'linear parks' useful for the ecological connection of urban and peri-urban forests»; «promoting a more equitable distribution of green areas among different parts of the city».
- The Guidelines for Urban Green Management and initial indications for sustainable planning (M.A.T.T.M., Comitato del Verde Urbano 2018), containing criteria for green space design.
- Ministerial Decree No. 63 of March 10, 2020, for the Minimum Environmental Criteria (CAM) for public green space management and the supply of green care product.

Afforestation

Section A - General description

Fig. 1 – Urban woodland in Natur-Park Südgelände, Berlin (Source: Wiki Common, Autor: Jacobo.ka, 2015 CC By 4.0).

Description

Afforestation is an extensive areal intervention aim to the creation of areas covered with trees, associated with shrub and herbaceous vegetation, with an extension of no less than 5,000 square metres, with a prevalence of tree species that at maturity exceed 5 m in height and with a forest tree cover at maturity greater than 10% (FAO 2020). This action contributes to the creation of multifunctional systems that play an important role in the ecology of human habitats because they determine changes in the climate and the economy, are recreational places for city dwellers and at the same time represent refuge areas for wildlife (Salbitano et al. 2016). In this sense, it is recurrent to assign this action a structural role in the context of green infrastructure (Tzoulas et al. 2007). The intervention may include the maintenance and preservation of existing vegetation, with particular attention to spontaneous trees and shrubs and/or those resulting from the recolonization of abandoned or underutilized areas. The action may include interventions aimed at the creation of surface water regimentation, drainage and retention systems, carried out with low-energy input materials and technologies; paths made with natural filtering materials; elements for geomorphological management derived from local culture and tradition – e.g. dry stone walls – or made with naturalistic engineering techniques. Such forest transformations of the territory can benefit from landscape and forest protection conforming to property rights that prevent or in any case minimise the possibility of building, also prevailing over town planning instruments at municipal level. Given the same area availability, it is preferable to implement the solution in a geometrically regular plot, whose perimeter to area ratio is no greater than 1/8 and average width no less than 20 metres. In relation to the open space system in which it is inserted, this solution can play different roles, e.g. it can take on a protective function – for other habitats –, a connective function – between habitats –, or a generative function – as a habitat.

Synonyms

Forest planting, Forest creation, Woodlands creation

Section B - Technical details

The integration of design solutions into specifically urban contexts requires meticulous planning and design, aimed at identifying specific site characteristics and intervention objectives. It is fundamental to analyze the climatic and edaphic – soil – context, water resource availability, the eco-region, and the – potential and present – vegetation series. Objectives must assess ecological criticalities and potentialities, defining co-benefits and environmental quality standards. The prevailing objective is proper environmental integration within the urban ecosystem, aiming for de-fragmentation and the enhancement of ecological infrastructures. The solution must be coherent with general – Landscape Plans, Hydro-geological Asset Plans, General Regulatory Plans – and specialized – Green Plans, PAESCs – territorial governance instruments.

Conditions: requirements and loads

In medium-density urban environments, the availability of open spaces may be limited, and the integration of the afforestation areas must be adapted to spatial and geometric conditions made complex by the presence of buildings, roads, utilities, and subsurface services. These elements, in addition to constituting physical constraints and stressors on the new environments, necessitate compliance with regulations and codes – e.g., maintaining required distances from roads or private properties –. For sourcing plant material, it is advisable and preferable to use species native to, or compatible with, the environmental context; alien species should be avoided, while the use of invasive exotic species is strictly prohibited. In the design – new development and/ or redevelopment – of areas accessible to the public for recreational, play, and social activities, and particularly those used by children, consideration must be given to the allergenic potential of the species to be introduced.

Construction: built-up, layers and performance

Based on implementation experience and the technical and scientific literature, six guiding principles can be identified.

- Minimization of energy and material inputs: achieved by using available resources and observing the site's vocations. This requires a detailed site survey: microclimate – considering the urban 'heat island' effect –, morphology, water runoff, infiltration, soil quality – pH, permeability –, pollutants, existing structures, and a botanical and phytosociological analysis of the vegetation – considering urban alterations and potential vegetation –.
- Correct site configuration: aimed at the effective management of water – surface, infiltration, groundwater – and soil fertility. Traditional methods – e.g., dry-stone walls – or naturalistic engineering techniques can be employed, favoring a minimal intervention approach. Infrastructures – roads, paths – must reduce or eliminate impermeability and integrate hydraulic solutions.
- Principles of systemic forestry 'Silvosystemics': to maximize biodiversity conservation and restoration. The intervention is aimed at constructing a complex biological

system capable of initiating autopoietic – self-regulating – processes and achieving dynamic stability, fostering the free evolution of the plant formation.

- Design of the cultivation unit: the initial vegetation cluster – arboreal, shrubby, herbaceous – must be low-impact, increasing biodiversity and structural diversification. Cultivation operations follow the population's needs rather than rigid schemes. The system must promote continuous natural regeneration. Techniques are suggested for a naturalistic, heterogeneous, and unstructured woodland, where the objective is to trigger the biological process rather than define a static form.
- Choice of the phytocoenosis – plant Community –: a crucial aspect based on studying potential and present vegetation. An incorrect choice leads to high maintenance costs and failure. Considerations must include: eco-compatibility – climate, soil, water –; characteristics of the floristic alliance; growth times and longevity – especially under urban stress –; light tolerance – heliophilous, sciophilous species –; adult habit – aiming for multi-level structures –; foliage persistence, flowering, and fruiting; resistance to pollutants and pathogens; and support for symbiotic mycoflora.
- Support for wildlife: fostered through multi-level, heterogeneous vegetation structures with variable densities to create diverse habitats. A rich floristic composition supports entomofauna – a trophic resource for insectivores – and avifauna – flowers, fruits –. Toxic species must be avoided, and variable terrain morphology – e.g., depressions for water stagnation – should be planned to create further habitats – e.g., for amphibians –.

Maintenance

A correct design approach enables the establishment of a complex vegetation formation capable of rapidly achieving a dynamic equilibrium with the environment, facilitated by its structure being open to self-variations. The management of such areas must aim to support the self-organization of the afforestation area, without directing it towards a predetermined structure. Monitoring and control constitute the essential elements for assessing the evolutionary processes. Silvicultural and utilization interventions are cautious, continuous, and localized, based on the needs of the various stands. At planting and for the subsequent years – a minimum of five –, particular attention must be paid to the water requirements of the newly established vegetation. Silvicultural care must be guaranteed to ensure the proper development of the flora, along with targeted interventions to reduce the impact of pathogens and phytoparasites. The management model can also be based on differentiation criteria for distinct zones and/or by levels of functionality/pressure related to anthropogenic use, applying more extensive and experimental maintenance in areas with low anthropogenic pressure. Experimental maintenance approaches can also be implemented to pursue objectives of public awareness and participation in the care and management of these places.

Section C - Societal challenges

Biodiversity enhancement

Afforestation is a crucial strategy for the restoration of forest ecosystem functions. Plant species diversity in afforested sites is dependent on previous land use, the proximity of natural vegetation, soil properties – e.g., texture, pH, and total nitrogen –, and plantation age. Afforested soils showed higher plant diversity and an improvement in edaphic parameters – soil organic carbon, nitrogen, and potassium – than arable cropped soils. Nevertheless, the conversion from treeless landscapes to forests can have negative impacts on organisms adapted to open habitats (Elmarsdóttir et al. 2008), in particular vascular plant diversity decreases – e.g., shade tolerant plant are favoured – but other functional groups are favoured – e.g., fungi and soil invertebrates –. Finally, considering that forest management and tree species affect all functional groups, it is crucial when planning afforestation to include strategies for biodiversity conservation by preserving endangered habitat and species. To that, urban and metropolitan afforestation projects showed the importance to work in multidisciplinary teams to ensure ecological, historical, spatial quality as well as social goals (Resemini et al. 2025).

Climate Resilience

Forests store and sequester carbon in the above ground vegetation and in the soil, providing climate change mitigation benefits (World Bank 2021; Doelman et al. 2020). Forests have a great potential to mitigate the urban heat island effect by shading building surfaces, deflecting radiation from the sun, and releasing moisture into the atmosphere. Shaded surfaces may be 11-25°C cooler than peak temperatures of unshaded materials. Evapotranspiration, alone or in combination with shading, can help reduce peak summer temperatures by 1–5°C (EPA n.d). Forests provide large carbon stocks owing to the high carbon content of the above and below ground biomass. Among terrestrial ecosystems and their habitats, forests have the highest carbon sequestration rates, reaching up to three times that of wetlands and agroecosystems (EEA 2026). Forests absorb and retain stormwater. Trees and soils of forested areas intercept precipitation and recycle the water through evapotranspiration, root water uptake, and infiltration (Gehrels et al. 2016). Mountain forests with deep soils can intercept and infiltrate rainwater, reducing flood hazards along canals and rivers downstream (Ozment et al. 2019). Forest soils have an ability to reduce atmospheric and aquatic pollutant sources. The beneficial effects of forests on air quality are well established (Beckett et al. 1998) and forests can also facilitate improvements in surface water and groundwater quality (NRMW). Forests play an important role in the hydrological cycle and its components, having a major influence on the amount of water flowing to groundwater, streams and other water bodies. Forests have a crucial impact on the amount of surface water as well as soil and groundwater (EEA 2015).

Health, Well-being and Air Quality

Urban forests make a positive contribution to the physical, mental, social, and economic wellbeing of societies (World Bank 2021; Bratman et al. 2019). Forests, rich in photosynthesising biomass, improve air quality by removing tropospheric ozone, a pollutant harmful to human and plant health (Calfapietra et al. 2016). Urban and peri-urban forests are able to absorb ozone through their leaf stomata, thus contributing to the improvement of air quality. Differences between tree species and environmental conditions influence the effectiveness of this process. It is important to promote the selection of species with high ozone uptake capacity to maximise the ecosystem benefits of green areas (Calfapietra et al. 2016). A nationwide assessment estimated that, in 2010, trees and forests in the US removed approximately 17.4 million tonnes of air pollutants, with human health benefits estimated at $6.8 billion. Although most of the pollution removal occurred in rural areas, the health effects were more significant in urban areas (Nowak et al. 2014).

Tree rows

Section A - General Description

Fig. 2 – A tree row with shrubs and herbaceous plants at Queen Elizabeth Olympic Park (London, UK), Piet Oudolf and Nigel Dunant, 2010 (Source: Wiki Common, Autor: DarkestElephant, 2014 CC By 3.0).

Description

Tree Rows are linear interventions aimed at establishing vegetated open space bands, incorporating trees, associated shrubs, and herbaceous vegetation. These rows must have a minimum length of 50 m and a minimum width of 1.5 m, with planting arranged in rows. They can be situated in either mostly unpaved areas like parks and gardens, or predominantly paved areas such as infrastructure surrounds, traffic islands, squares, and parking lots. This solution can be integrated with surface rainwater management and sustainable urban drainage systems. Depending on their context within the open space system, tree rows can serve a role in de-fragmentation and connection.

Synonyms

Street trees; Tree-lined Streets, Green Corridors, Boulevard

Section B - Technical details

The integration of design solutions into the context requires a meticulous planning and design phase. This phase is aimed at identifying the characteristics of the site –climatic, edaphic, water availability, eco-region, potential and present vegetation series – and the project objectives – assessment of ecological criticalities and potentialities, co-benefits, environmental and landscape quality goals –. The prevailing objective for designers is the correct environmental integration into the urban ecosystem, aiming for maximum effectiveness in terms of de-fragmentation, improvement, and enhancement of ecological infrastructures. The solution must be considered part of a broader strategy, requiring adequate planning of open spaces and coherence with general and specialized territorial governance instruments.

Conditions: requirements and loads

In high and medium-density urban environments, the availability of open spaces may be residual, and the integration of the tree row must be adapted to spatial and geometric conditions rendered complex by the presence of building structures, road configurations, and the presence of utilities and subsurface services. These elements, in addition to constituting physical constraints and pressure factors – stressors – on the new environments, necessitate compliance with regulations and codes, for example, maintaining required distances from roads or private properties. For the sourcing of plant material, it is advisable and preferable to use species native to, or compatible with, the environmental context; alien species are to be avoided, while the use of invasive exotic species is strictly prohibited.

Construction: built-up, layers and performance

Based on implementation experience and the technical and scientific literature, six guiding principles can be identified.

- Minimization of energy and material inputs: achievable through the careful use of available resources and observation of the site's vocations. This requires a detailed survey of the area, analyzing microclimatic conditions – including the urban 'heat island' effect –, morphology, slopes, water runoff, infiltration rates, soil quality – e.g., pH, permeability –, pollutants, built elements, and infrastructure. A botanical and phytosociological analysis of the vegetation is also fundamental, considering urban alterations and potential vegetation.
- Correct configurational setup: aimed at the effective management of water – surface runoff, infiltration – and the preservation or improvement of soil fertility. Sustainable Urban Drainage Systems (SUDS) and water-sensitive urban design methods can be used. A minimal approach, with low or zero matter and energy inputs, is preferable. It is also necessary to manage critical nodes related to utilities and subsurface services.
- Maximizing biodiversity: the design approach must be oriented towards ecologically effective choices. The planting – e.g., tree-shrub row – is framed as a solution for linear connection between habitats, strengthening the network of ecological infrastructures. It must possess sufficient complexity to foster autopoietic – self-regulating – processes and dynamic stability.
- Design of the cultivation unit: the plant population must be low-impact, conserving and increasing biodiversity. It must support heterogeneity and compositional diversification. The goal is an indefinite cultivation cycle open to self-variations, based on biological and ecological evaluations – longevity, evolutionary trends –. The choice of structure – even-aged, uneven-aged, hybrid – depends on the initial conditions and the plant alliances.
- Choice of the phytocoenosis – plant Community –: must be executed with care, studying potential and present vegetation. The project's success, functional effectiveness, and dynamic stability depend on this choice. An incorrect choice leads to failure and high maintenance costs. Aspects to consider include: eco-compatibility – climate, microclimate, soil acidity, moisture, porosity and water requirements –; floristic composition of the alliance, growth rates and longevity (considering urban stress); temperament regarding light (heliophilous, sciophilous); adult habit and dimensions – favoring multi-level structures –; leaf persistence, flowering, and fruiting characteristics; urban context – historical-cultural, landscape aspects

–; resistance to pollutants, pathogens, and synergies between species; support for symbiotic and saprophytic mycoflora.
- Protection of wildlife: the project must adopt solutions to protect fauna. Favorable aspects include: favoring multi-level vegetation structures; rich floristic composition – for co-benefits to soil organisms: bacteria, fungi, invertebrates –; species with flowers and fruits to create habitats rich in food and shelter for entomofauna; entomofauna serves as a trophic resource for insectivores – birds, mammals, reptiles –; fruits serve as a trophic resource – especially for birds –; avoiding species toxic to fauna.

Maintenance

A correct design approach allows the establishment of a complex vegetation formation capable of rapidly achieving a dynamic equilibrium with the environment, facilitated also by its structure being open to self-variations. The management of such areas must tend to support the self-organization of the tree-shrub row, without directing it toward a predetermined structure. Monitoring and control constitute the essential elements for the verification of evolutionary processes. Silvicultural and utilization interventions are cautious, continuous, and localized capillary, according to the needs of the various stands. At planting and for the subsequent years – a minimum of five –, particular attention must be paid to the water requirements of the newly established vegetation. Silvicultural care must be guaranteed to ensure the proper development of the flora, along with targeted interventions to reduce the impact of pathogens and phytoparasites. The management model can also be based on differentiation criteria for distinct zones and/or by levels of functionality/pressure related to anthropogenic use, applying more extensive and experimental maintenance in areas with low anthropogenic pressure.

Section C - Societal Challenges

Biodiversity enhancement

Tree rows can play a role in defragmentation and connection, and can also become an integral part of the habitat for birds and invertebrates. Tree rows soils showed higher plant diversity and an improvement in edaphic parameters –soil organic carbon, nitrogen, and potassium – than other types of soils.

Climate Resilience

Tree rows sequester carbon in aboveground vegetation and soil, providing climate change mitigation (World Bank 2021; Doelman et al. 2020) and microclimate regulation benefits by shading surfaces, diverting solar radiation, and releasing moisture into the atmosphere. Shaded surfaces can be 11-25 °C cooler than the peak temperature of unshaded materials. Evapotranspiration, alone or in combination with shading, can help reduce peak summer temperatures by 1-5 °C (EPA n.d.). Trees and soils intercept precipitation and recycle the water through evapotranspiration, root water uptake, and infiltration (Gehrels et al. 2016). Trees play an important role in the hydrological cycle and its components, having a major influence on the amount of water flowing to groundwater, streams and other water bodies (EEA 2015).

Health, Well-being and Air Quality

Tree rows as an urban forestry intervention make a positive contribution to the physical, mental, social, and economic wellbeing of societies (World Bank 2021; Bratman et al. 2019). Trees, rich in photosynthesising biomass, improve air quality by removing tropospheric ozone, a pollutant harmful to human and plants health (Calfapietra et al. 2016). Tree rows are able to absorb ozone through their leaf stomata, thus contributing to the improvement of air quality.

Vegetation clusters

Section A - General Description

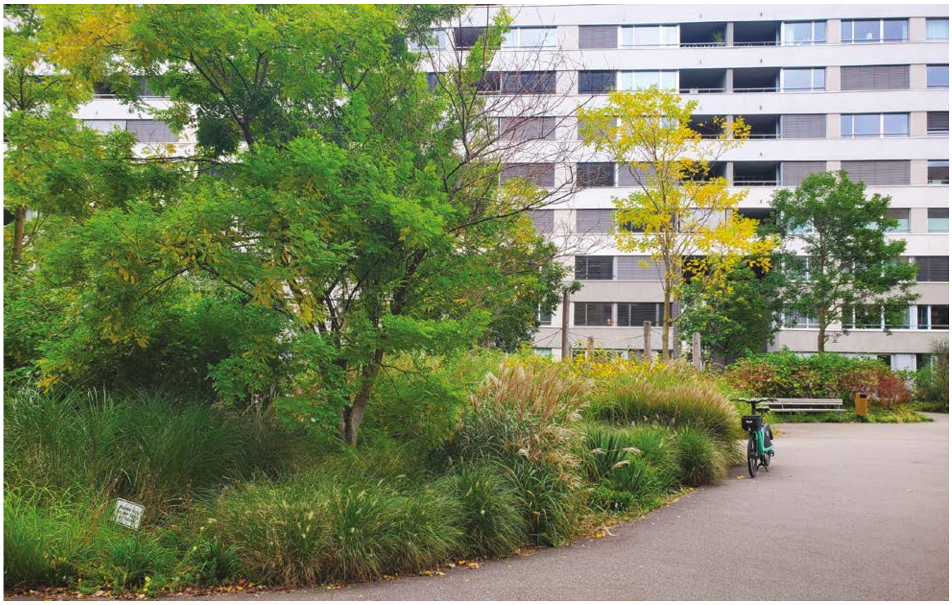

Fig. 3 – One of the vegetation clusters designed by Vulkan Landschaftsarchitektur for the Maaghof-Park in Zurich, 1999 (Source: Lorenzo Nofroni).

Description

Vegetation clusters are small-scale, localized interventions aimed at promoting the spread of complex vegetation structures, including tree, shrub, and herbaceous layers. These interventions can be implemented in urban green spaces such as gardens, parks, building grounds, and areas surrounding squares and infrastructure. They can be used to replicate mini and micro forests in urban settings (Eisenberg et al. 2022). In some urban contexts, like abandoned areas undergoing natural rewilding, vegetation clusters can be formed around spontaneously established groups of trees and shrubs, often made up of pioneer and ruderal species undergoing free, dynamic evolution (Eisenberg et al. 2022). This solution can also be combined with surface stormwater management and sustainable urban drainage systems. Depending on the open space system in which it is integrated, it can play a supporting role in strengthening ecological networks, helping to reduce habitat fragmentation and promote habitat reconnection.

Synonyms

Group of trees; Micro forest, Vegetation Patch, Plant Clump

Section B - Technical details

The incorporation of design interventions into the surrounding context mandates a meticulous planning and design phase. This foundational stage is focused on identifying the site's specific characteristics, including climatic, edaphic, and hydrological conditions, as well as the eco-region and both potential and extant vegetation series. Concurrently, this phase defines the project objectives, encompassing the evaluation of ecological criticalities and potentialities, the assessment of co-benefits, and the establishment of environmental and landscape quality goals. The objective for practitioners is achieving correct environmental assimilation into the urban ecosystem. This integration strives for maximum effectiveness in terms of ecological de-fragmentation, and the improvement and enhancement of green infrastructures. Any solution must be viewed as an integral part of a broader strategic framework, necessitating suitable planning of open spaces and ensuring coherence with general and specialized territorial governance instruments.

Conditions: requirements and loads

The integration of vegetation cluster must be adapted to complex spatial and geometric constraints imposed by built structures, road configurations, and the presence of subterranean utilities and services. These factors not only constitute physical limitations and exert stress on the new environments but also mandate strict adherence to regulations and codes, such as maintaining prescribed distances from roadways or private property. Regarding the procurement of plant material, the use of species that are native to, or at least compatible with, the local environmental context is strongly advisable and preferred. Alien species should be avoided, and the use of invasive exotic species is strictly forbidden.

Construction: built-up, layers and performance

Based on practical implementation experience and the techno-scientific literature, six guiding principles can be delineated:

- Minimization of energy and material inputs: this is achievable through the judicious use of available resources and by observing the site's natural vocations. This necessitates a detailed survey of the area, analyzing microclimatic conditions – including the urban 'heat island' phenomenon –, morphology, slopes, water runoff patterns, infiltration rates, soil quality – e.g., pH, permeability –, existing pollutants, built elements, and infrastructure. A thorough botanical and phytosociological analysis of the vegetation, considering urban alterations and potential vegetation dynamics, is also fundamental.
- Correct configurational setup: This principle aims for the effective management of water – both surface runoff and infiltration– and the preservation or enhancement of soil fertility. Methodologies such as Sustainable Urban Drainage Systems (SUDS) and water-sensitive urban design may be employed. A minimal-impact approach, characterized by low or zero inputs of matter and energy, is preferred. It is also imperative to manage critical junctures related to utilities and subterranean services.
- Maximizing biodiversity: the design methodology must be oriented toward choices that are ecologically effective. The planting is conceived as a solution for linear connectivity between habitats, thereby reinforcing the network of ecological infrastructures. It must possess adequate complexity to foster autopoietic – self-regulating – processes and achieve dynamic stability.
- Design of the cultivation unit: the plant population selected must have a low environmental impact, while conserving and augmenting biodiversity. It must support heterogeneity and diversification in both structure and composition. The objective is an indefinite cultivation cycle that remains open to self-variation, predicated on biological and ecological assessments – e.g., longevity, evolutionary trends –. The selection of the structure – e.g., even-aged, uneven-aged, hybrid– is contingent upon the initial site conditions and the identified plant alliances.

- Choice of the phytocoenosis – plant community –: this selection must be executed with extreme care, involving the study of both potential and extant vegetation. The project's ultimate success, functional effectiveness, and dynamic stability are dependent on this choice. An erroneous selection will invariably lead to failure and substantial long-term maintenance costs. Factors requiring consideration include: eco-compatibility – relative to climate, microclimate, soil acidity, moisture, porosity, and hydrological requirements –; the floristic composition of the alliance, growth rates, and longevity – especially considering urban stressors –; temperament concerning light exposure – heliophilous vs. sciophilous –; adult habit and dimensions – favoring multi-level structures –; characteristics of leaf persistence, flowering, and fruiting; the specific urban context – including historical-cultural and landscape aspects –; resistance to pollutants and pathogens, and inter-species synergies; and support for symbiotic and saprophytic mycoflora.
- Protection of wildlife: the project must incorporate solutions designed to protect fauna. Favorable aspects include: favoring multi-level vegetation structures; implementing a rich floristic composition – which provides co-benefits to soil organisms like bacteria, fungi, and invertebrates –; selecting species with flowers and fruits to create habitats rich in food and shelter for entomofauna. This entomofauna, in turn, serves as a trophic resource for insectivores – e.g., birds, mammals, reptiles –. The fruits also serve as a crucial trophic resource, especially for avifauna. Finally, species known to be toxic to wildlife must be avoided.

Maintenance

A correct design approach facilitates the establishment of a complex vegetation formation. This formation is capable of rapidly achieving a dynamic equilibrium with the environment, a process aided by its structure being open to self-variation. The management of such areas must be oriented toward supporting the self-organization of the vegetation clusters, rather than directing it toward a predetermined structure. Monitoring and control represent the essential elements for verifying evolutionary processes. Silvicultural and utilization interventions should be cautious, continuous, and highly localized capillary, tailored to the specific needs of various stands. Both at planting and during the subsequent years – a minimum of five –, particular attention must be devoted to the water requirements of the newly established vegetation. Continuous silvicultural care must be guaranteed to ensure the proper development of the flora, alongside targeted interventions to mitigate the impact of pathogens and phytoparasites. The management model can also be predicated on differentiation criteria, distinguishing between distinct zones and/or by levels of functionality and anthropogenic pressure. This allows for the application of more extensive and experimental maintenance strategies in areas subject to low anthropogenic pressure.

Section C - Societal Challenges

Biodiversity enhancement

Vegetation clusters can be used to replicate mini and micro forests in urban settings (Eisenberg et al. 2022), play a role in defragmentation and connection, and can also become an integral part of the habitat for birds and invertebrates.

Climate Resilience

Vegetation clusters sequester carbon in aboveground vegetation and soil, providing climate change mitigation (World Bank 2021; Doelman et al. 2020) and microclimate regulation benefits by shading surfaces, diverting solar radiation, and releasing moisture into the atmosphere. Shaded surfaces can be 11-25 °C cooler than the peak temperature of unshaded materials. Evapotranspiration, alone or in combination with shading, can help reduce peak summer temperatures by 1-5 °C (EPA n.d.). Thanks to their permanent vegetation intercept precipitation and recycle the water through evapotranspiration, root water uptake, and infiltration (Gehrels et al. 2016). Trees play an important role in the hydrological cycle and its components, having a major influence on the amount of water flowing to groundwater, streams and other water bodies (EEA 2015).

Health, Well-being and Air Quality

Vegetation clusters are tree planting interventions with an important role in covering, shading, and protecting underlying surfaces. They contribute to making a positive effect on the physical, mental, social, and economic wellbeing of societies (World Bank 2021; Bratman et al. 2019).

Tree plantations on paved surfaces

Section A - General Description

Fig. 4 – The tree-lined urban staircase designed by Kiefer and Koster with Freiraum Landschaftsarchitekten for Pfingstweid Park in Zurich, 2015 (Source: Lorenzo Nofroni).

Description

Tree plantations on paved surfaces are tree planting interventions to be implemented in predominantly paved areas with intense anthropogenic use such as squares, playgrounds, outdoor sports areas, picnic areas, and seating areas. Tree plantations can have an important role in covering, shading, and protecting underlying surfaces. This is an option for designing shaded paved urban areas that can offer advantages in terms of rainwater management and sustainable urban drainage, climate resilience, and mitigation of urban heat stress (Eisenberg et al. 2022). Tree plantations on paved surfaces represent a solution for introducing arboreal vegetation in spaces where, due to surface functionality and accessibility, it is not possible to introduce linear tree rows and vegetation clusters. Their use can perform a subsidiary function and enhance the ecological network, contributing to the de-fragmentation and reconnection of the system. Planting density, species, and diversification of forms and behaviors are to be established according to environmental conditions – phyto- and pedo-climatic – and human presence and related usage and management methods. Preference should be given to trees with expanded canopies, plantations diverse in species and varieties, and with adaptability to critical soil, water, and pollutant conditions.

Synonyms

Mixed plantations for recreation; Regular plantations; Tree canopy for shaded pavement surfaces

Section B - Technical details

The integration of solutions within the context requires a meticulous planning and design phase to identify site-specific characteristics – climatic, edaphic, water availability, eco-region, potential and present vegetation series–. Project objectives must be defined, including ecological assessments – criticalities, potentialities, opportunities, threats –, co-benefits, environmental and landscape quality goals. The prevailing objective is the correct environmental integration into the urban ecosystem, maximizing efficiency in de-fragmentation, improvement, and enhancement of ecological infrastructures. The solution must be considered part of a broader strategy, requiring adequate planning of open spaces and coherence with general – e.g., Territorial Address Plans, Landscape Plans, Hydro-geological Plans, General Regulatory Plans – and specialized – e.g., Green Plans, PAESC – territorial governance instruments.

Conditions: requirements and loads

In high and medium-density urban areas, residual open space availability complicates the integration of tree-shrub elements due to spatial constraints from buildings, road configurations, and sub-services. These factors impose physical limits and stressors, requiring adherence to regulations – e.g., distances from roads/property –. For plant material sourcing, native or compatible species are preferable; alien species are to be avoided, and invasive exotics are prohibited. In public recreational areas, especially those used by children, the allergenic potential of species must be considered to avoid exacerbating allergies and asthma.

Construction: built-up, layers and performance

Based on implementation experience and the technical and scientific literature, six guiding principles can be identified.

- Minimization of energy and material inputs: achieved through judicious use of available resources and observation of site vocations. This requires a detailed site survey, noting microclimatic conditions – including the 'heat island' effect –, morphology, slopes, depressed areas, surface water runoff, infiltration rates, soil typology and quality – e.g., depth to rock, porosity, permeability, pH –, pollutants, built elements, infrastructure, and existing flora – analyzed botanically and phytosociologically – and fauna. Urban contexts necessitate analyzing potential vegetation due to significant alterations.
- Correct configurational setup: the design must ensure effective management of surface runoff and infiltration, alongside the preservation or improvement of soil fertility. Sustainable Urban Drainage (SUDS) and Water-Sensitive Urban Design (WSUD) methods are applicable, though a minimal intervention approach with low or zero inputs is preferable. Critical nodes involving utilities and sub-services must be correctly addressed.
- Maximizing biodiversity: the design approach must prioritize ecologically effective choices to conserve, restore, and enhance biodiversity. Small-area tree-shrub plantings can function as an "archipelago" of vegetated spaces, aiding habitat de-fragmentation and re-connection within the urban ecosystem. This reinforces the primary and subsidiary ecological infrastructure network, designed with sufficient complexity to trigger autopoietic – self-regulating – processes toward dynamic stability.
- Design of the cultivation unit: the initial planting must be low-impact, conserving and increasing biodiversity. It should favor heterogeneity and structural/compositional diversification for an indefinite cultivation cycle open to self-variation, based on biological and ecological evaluations – species longevity, system evolutionary

trends –. The structure – e.g., even-aged, uneven-aged, hybrid – depends on initial conditions and chosen plant alliances.

- Choice of the phytocoenosis – plant community –: this selection must be executed with extreme care, involving the study of both potential and extant vegetation. The project's ultimate success, functional effectiveness, and dynamic stability are depends on this choice. An erroneous selection will invariably lead to failure and substantial long-term maintenance costs. Factors requiring consideration include: eco-compatibility – relative to climate, microclimate, soil acidity, moisture, porosity, and hydrological requirements –; the floristic composition of the alliance, growth rates, and longevity – especially considering urban stressors –; temperament concerning light exposure – heliophilous vs. sciophilous –; adult habit and dimensions – favoring multi-level structures –; characteristics of leaf persistence, flowering, and fruiting; the specific urban context – including historical-cultural and landscape aspects –; resistance to pollutants and pathogens, and inter-species synergies; and support for symbiotic and saprophytic mycoflora.
- Protection of wildlife: the project must incorporate solutions designed to protect fauna. Favorable aspects include: favoring multi-level vegetation structures; implementing a rich floristic composition – which provides co-benefits to soil organisms like bacteria, fungi, and invertebrates –; selecting species with flowers and fruits to create habitats rich in food and shelter for entomofauna. This entomofauna, in turn, serves as a trophic resource for insectivores – e.g., birds, mammals, reptiles –. The fruits also serve as a crucial trophic resource, especially for avifauna. Finally, species known to be toxic to wildlife must be avoided.

Maintenance

A correct design initiates a complex vegetation formation capable of rapidly achieving dynamic equilibrium, aided by a structure open to self-variation. Management should support the system's self-organization rather than imposing a prefixed structure. Monitoring and control are essential to verify evolutionary processes. Silvicultural interventions must be cautious, continuous, and capillary, responding to stand needs. Post-planting (minimum five years), critical attention must be paid to the water needs of new vegetation. Cultural care is necessary for proper flora development and to mitigate pathogens/phytoparasites. Management models can be differentiated by zones or levels of anthropogenic pressure, applying more extensive/experimental maintenance in low-pressure areas. Experimental approaches can also foster public awareness and participation.

Section C - Societal challenges

Biodiversity enhancement

Tree plantations on paved surfaces is an option for designing shaded paved urban areas that can offer advantages in terms of rainwater management and sustainable urban drainage, climate resilience, and mitigation of urban heat stress (Eisenberg et al. 2022). They represent a solution for introducing arboreal vegetation in spaces where, due to surface functionality and accessibility, it is not possible to introduce linear tree rows and vegetation clusters. Their use can perform a subsidiary function and enhance the ecological network, contributing to the de-fragmentation and reconnection of the system.

Climate Resilience

Tree plantations on paved surfaces store and sequester carbon in the above ground vegetation and in the soil, providing climate change mitigation benefits (World Bank 2021; Doelman et al. 2020). Tree plantations can have an important role in covering, shading, and protecting underlying surfaces. Evapotranspiration, alone or in combination with shading, can help reduce peak summer temperatures by 1–5°C (EPA n.d). Among terrestrial ecosystems and their habitats, Paved Surfaces can contribute to the carbon sequestration rates (EEA 2022). Thanks to their permanent vegetation, tree plantations on paved surfaces offer favorable conditions for effective water infiltration and slowing surface flow. They thus promote natural water retention. Along slopes, they can reduce soil erosion by intercepting and slowing surface water runoff (Catalogue of NWRM 2013).

Health, Well-being and Air Quality

Tree plantations on paved surfaces are tree planting interventions to be implemented in predominantly paved areas with intense anthropogenic use such as squares, playgrounds, outdoor sports areas, picnic areas, and seating areas. Tree plantations can have an important role in covering, shading, and protecting underlying surfaces. They contribute to make positive effect on the physical, mental, social, and economic well-being of societies (World Bank 2021; Bratman et al. 2019).

Hedgerows and shrubs strips

Section A - General Description

Fig. 5 – A flowering and shrubby strip designed by Michel Desvigne for the Parc de Saône within Lyon Confluence, 2010 (Source: Wiki Common, Autor: Guilhem Vellut, 2017 CC By 2.0).

Description

Hedgerows and shrubs strips are predominantly linear areas characterized by vegetation cover. Their specific vegetation configuration is determined by environmental conditions – phyto and pedo-climatic –, competitive or cooperative interactions with other plant and animal species, human presence, and associated usage and management methods. These strips can range from alliances consisting solely of herbaceous species to highly structured associations of herbaceous, shrubby, and arboreal species. Hedgerows and shrubs strips are typically located at the margins of watercourses – known as riparian strips –, woodlands – clearing shrublands –, grasslands, and cultivated areas – field hedges –. They are also found in parks, public gardens, and adjacent to transport infrastructure – hedges and shrub strips –. They differ from tree lines primarily because they are composed mainly of herbaceous and shrubby species, with arboreal species being more sporadic. Beyond serving as habitats for various species, including plants, animals – vertebrates and invertebrates –, fungi, and bacteria hedgerows and shrubs strips can play a significant connectivity role. Where they form linear systems and nearly continuous networks, they are utilized by certain species for movement between different areas. Strips featuring species that produce berries, fruits, and nectar are important foraging sites, particularly for insects and birds. In rural contexts, hedgerows and shrubs strips are typically used for controlling livestock, delimiting boundaries, or providing shelter. In urban areas, they can constitute boundary hedges or function as separation and protection strips for other vegetation structures. Thanks to their permanent vegetation, hedgerows and shrubs strips offer favorable conditions for effective water infiltration and slowing surface flow. They thus promote natural water retention. Along slopes, they can reduce soil erosion by intercepting and slowing surface water runoff (Catalogue of NWRM 2013).

Synonyms

Street hedgerows, buffer shrubs strips, green fences, roads verges.

Section B - Technical details

The integration of solutions within the context requires a meticulous planning and design phase to identify site-specific characteristics – climatic, edaphic, water availability, eco-region, potential and present vegetation series –. Project objectives must be defined, including ecological assessments – criticalities, potentialities, opportunities, threats –, co-benefits, environmental and landscape quality goals. The prevailing objective is the correct environmental integration into the urban ecosystem, maximizing efficiency in de-fragmentation, improvement, and enhancement of ecological infrastructures. The solution must be considered part of a broader strategy, requiring adequate planning of open spaces and coherence with general – e.g., Territorial Address Plans, Landscape Plans, Hydro-geological Plans, General Regulatory Plans – and specialized – e.g., Green Plans, PAESC – territorial governance instruments.

Conditions: requirements and loads

In high and medium-density urban areas, residual open space availability complicates the integration of tree-shrub elements due to spatial constraints from buildings, road configurations, and sub-services. These factors impose physical limits and stressors, requiring adherence to regulations – e.g., distances from roads or property –. For plant material sourcing, native or compatible species are preferable; alien species are to be avoided, and invasive exotics are prohibited. In public recreational areas, especially those used by children, the allergenic potential of species must be considered to avoid exacerbating allergies and asthma.

Construction: built-up, layers and performance

Based on implementation experience and the technical and scientific literature, six guiding principles can be identified.

- Minimization of energy and material Inputs: this principle is achievable through the prudent utilization of available resources and a sensitive observation of the site's natural vocations. It mandates a detailed survey of the intervention area. This analysis must encompass microclimatic conditions – including the urban 'heat island' phenomenon –, morphology, slope gradients, water runoff patterns, and infiltration rates. Furthermore, a thorough assessment of soil quality – e.g., pH, permeability, porosity –, the presence of pollutants, and existing built elements or infrastructure is required. A foundational component is the botanical and phytosociological analysis of extant vegetation, considering potential vegetation series and an understanding of urban alterations.
- Correct configurational setup: the design must establish a configuration aimed at the effective management of water dynamics, including both surface runoff and infiltration, while simultaneously preserving or enhancing soil fertility. Methodologies such as Sustainable Urban Drainage Systems (SUDS) and water-sensitive urban design (WSUD) can be employed. However, a minimal intervention approach, characterized by low or zero inputs of matter and energy, is preferable. It is

also imperative to correctly manage critical nodes and potential conflicts related to the presence of utilities and subsurface services.

- Maximizing biodiversity: the design methodology must be oriented toward ecologically effective choices to conserve, restore, and enhance biodiversity. The planting – e.g., a tree-shrub row or patch – should be framed as a solution for linear connectivity or as part of a 'vegetated archipelago'. This strengthens the network of ecological infrastructures by fostering habitat de-fragmentation and re-connection within the urban ecosystem. The system must possess sufficient complexity to foster autopoietic – self-regulating – processes, thereby achieving long-term dynamic stability.
- Design of the cultivation unit: the initial plant population, or cultivation unit, must be designed for low environmental impact, focusing on conserving and increasing systemic biodiversity. It must support heterogeneity and diversification in both structure and composition. The objective is an indefinite cultivation cycle that remains open to self-variations, predicated on biological and ecological evaluations such as species longevity and the system's evolutionary trends. The choice of structure – e.g., even-aged, uneven-aged, regular, or hybrid – is contingent upon the initial site conditions and the selected plant alliances.
- Choice of the phytocoenosis – plant community –: this selection must be executed with extreme care, involving the study of both potential and extant vegetation. The project's ultimate success, functional effectiveness, and dynamic stability are dependent on this choice. An erroneous selection will invariably lead to failure and substantial long-term maintenance costs. Key aspects to consider include: eco-compatibility with climatic, microclimatic, and edaphic conditions – acidity, moisture, porosity – and water requirements; the specific floristic composition of the alliance; growth rates and longevity, especially considering urban stressors; species' light temperament – heliophilous vs. sciophilous –; adult habit and dimensions, favoring multi-level structures; phenological characteristics – leaf persistence, flowering, fruiting –; the urban context – historical-cultural, landscape –; resistance to pollutants and pathogens; inter-species synergies; and support for symbiotic and/or saprophytic mycoflora.
- Protection of wildlife: the project must adopt solutions specifically designed to protect and support fauna. Favorable aspects include: implementing a rich floristic composition, which provides co-benefits to soil organisms – bacteria, fungi, invertebrates –; and selecting species with flowers and fruits to create habitats rich in food and shelter for entomofauna. This entomofauna, in turn, serves as a critical trophic resource for insectivores – e.g., birds, mammals, reptiles –. Furthermore, fruits – berries, drupes, etc.– provide a trophic resource for numerous species, especially avifauna. Species known to be toxic to wildlife must be avoided.

Maintenance

A correct design approach facilitates the establishment of a complex vegetation formation. This formation is capable of rapidly achieving a dynamic equilibrium with the environment, a process aided by its structure being open to self-variation. The management of such areas must be oriented toward supporting the self-organization of the hedgerows and shrubs strips, rather than directing it toward a predetermined structure. Monitoring and control represent the essential elements for verifying evolutionary processes. Silvicultural and utilization interventions should be cautious, continuous, and highly localized capillary, tailored to the specific needs of various stands. Both at planting and during the subsequent years – a minimum of five –, particular attention must be devoted to the water requirements of the newly established vegetation. The management model can also be predicated on differentiation criteria, distinguishing between distinct zones and/or by levels of functionality and anthropogenic pressure. This allows for the application of more extensive and experimental maintenance strategies in areas subject to low anthropogenic pressure.

Section C - Societal challenges

Biodiversity enhancement

Where hedgerow and shrubs strip form linear systems and nearly continuous networks, they are utilized by certain species for movement between different areas. Strips featuring species that produce berries, fruits, and nectar are important foraging sites, particularly for insects and birds. In rural contexts, hedgerows and shrubs strips are typically used for controlling livestock, delimiting boundaries, or providing shelter. In urban areas, they can constitute boundary hedges or function as separation and protection strips for other vegetation structures. Thanks to their permanent vegetation, hedgerows and shrubs strips offer favorable conditions for effective water infiltration and slowing surface flow. They thus promote natural water retention. Along slopes, they can reduce soil erosion by intercepting and slowing surface water runoff (Catalogue of NWRM 2013).

Climate Resilience

Hedgerow and shrub strip store and sequester carbon in the above ground vegetation and in the soil, providing climate change mitigation benefits (World Bank 2021; Doelman et al. 2020). Evapotranspiration, alone or in combination with shading, can help reduce peak summer temperatures by 1-5°C (EPA n.d). Among terrestrial ecosystems and their habitats, Hedgerow and shrub strip can contribute to the carbon sequestration rates (EEA 2022). Thanks to their permanent vegetation, hedgerows and shrubs strips offer favorable conditions for effective water infiltration and slowing surface flow. They thus promote natural water retention. Along slopes, they can reduce soil erosion by intercepting and slowing surface water runoff (Catalogue of NWRM 2013).

Health, Well-being and Air Quality

Hedgerows and shrubs strips as an urban forestry intervention contribute to make positive effect to the physical, mental, social, and economic wellbeing of societies (World Bank 2021; Bratman et al. 2019).

Flower meadows

Section A - General Description

Fig. 6 – One of the flower meadows designed by Nigel Dunnett for the Tower of London superbloom 2022 (Source: Wiki Common, Autor: amandabhslater, 2022 CC By 2.0).

Description

Flower meadows are habitat characterized by the dominance of annual and/or perennial herbaceous species, favored by low-intensity anthropogenic management, related usage patterns, environmental conditions – phyto and pedo-climatic – and the interactions with other plant species – trees and shrubs –, animals, fungi, and bacteria. Flower meadows can take various shapes and sizes: from small patches or strips in areas adjacent to buildings and infrastructure, to large meadow extensions in parks or grazing meadows in urban rural areas. They are distinguished from high-intensity anthropogenically managed grass lawns – seeding, mowing, irrigation, fertilization – by a greater diversity of plant, animal, bacterial, and fungal species and a different human approach to use and management, which allows herbaceous populations to complete their entire life cycle, accommodate other spontaneous herbaceous species, and change over time and with the seasons. Given that flower meadows are characterized by plant species that have evolved zoogamous pollination strategies through coevolutionary processes with pollinating insects (Adams 2005), this type of habitat, in addition to representing a great opportunity to increase plant diversity in urban areas (Chollet. et. al. 2018), has high potential for the protection of animal biodiversity, as the very survival of a flowering meadow depends on the presence of a wide range of invertebrates – pollinators and their predators – for which it simultaneously represents a habitat and an ecological corridor (Klaus 2013). Two types of urban flowering meadows can be distinguished: those with a prevalence of annual herbaceous plants or those with a prevalence of perennial herbaceous plants. The first type is characterized by the presence of species that complete their life cycle in one year or one season; therefore, they develop and change very rapidly with short cyclical phases. The second type is characterized by the presence of perennial species whose life cycle is multi-year. These meadows take two to three years to establish because perennial grasses have a deep root system and spend much of their energy in the first year on root growth, in the second on root system expansion, and in the third on above-ground establishment. Numerous experiments on the formation and management of urban flowering meadows have shown that the creation and/or maintenance of a mosaic of diversified types of flowering meadows: varying in height – controlled through the number of mows –; in species richness in the initial seed mix; and in the alternation between annual and perennial species, improves biodiversity – plant, animal, fungal, and bacterial – over an annual cycle, to a greater extent than creating habitats with only one type of meadow (Norton et. al. 2019).

Synonyms

Wildflower Meadow, Perennial Meadow, Wildflower Field

Section B - Technical details

The integration of solutions within the context requires a meticulous planning and design phase to identify site-specific characteristics – climatic, edaphic, water availability, eco-region, potential and present vegetation series –. Project objectives must be defined, including ecological assessments – criticalities, potentialities, opportunities, threats –, co-benefits, and environmental/landscape quality goals. The prevailing objective is the correct environmental integration into the urban ecosystem, maximizing efficiency in de-fragmentation, improvement, and enhancement of ecological infrastructures. The solution must be considered part of a broader strategy, requiring adequate planning of open spaces and coherence with general – e.g., Territorial Address Plans, Landscape Plans, Hydro-geological Plans, General Regulatory Plans – and specialized – e.g., Green Plans, PAESC – territorial governance instruments.

Conditions: requirements and loads

In high and medium-density urban areas, residual open space availability complicates the integration of tree-shrub elements due to spatial constraints from buildings, road configurations, and sub-services. These factors impose physical limits and stressors, requiring adherence to regulations. For plant material sourcing, native or compatible species are preferable; alien species are to be avoided, and invasive exotics are prohibited. If a survey determines the site already contains a degree of wildflower diversity and old meadow grasses – and no pernicious weeds –, this diversity should be retained.

Construction: built-up, layers and performance

Based on implementation experience and the technical and scientific literature, six guiding principles can be identified.

- Minimization of energy and material Inputs: this principle is achievable through the prudent utilization of available resources and a sensitive observation of the site's natural vocations. It mandates a detailed survey of the intervention area. The ideal site for a species-rich meadow, which minimizes long-term management inputs, is one with low soil fertility. High nutrient levels, particularly available phosphorus, tend to promote the growth of vigorous grasses and pernicious weeds – like nettles, thistles, and docks –. These undesirable plants outcompete the desired wildflowers for nutrients and water. A preliminary soil test is recommended to establish baseline levels of available Nitrogen (N), Phosphorous (P), Potassium (K), and soil pH. On sites with very high fertility, it may be necessary to remove the topsoil to reduce nutrient loads, though this requires expert assessment to determine the correct depth. In long-term management, it is essential to remove all cut material – cuttings – from the site after mowing. This prevents the cuttings from smothering the sward and, critically, stops nutrients from being returned to the soil, thus maintaining the desired low-fertility state.

- Correct configurational setup: a successful setup begins with a comprehensive site survey that must assess existing vegetation, hydrology, and all site conditions. The primary goal when creating a meadow from scratch is to produce a firm, weed-free tilth through soil cultivation. This setup phase is critical for removing competition. Pernicious weeds must be addressed. A typical ground preparation sequence for fertile sites involves: shallow cultivation – e.g., rotovator – followed by rolling to consolidate the ground, harrowing or treating regrowth, and finally, using a power harrow to create a fine surface tilth. A final spray may be required before sowing.
- Maximizing biodiversity: starts with assessing current assets. A site survey may reveal existing diversity, as wildflowers might be present in the seed bank. If a survey determines the site already contains a degree of wildflower diversity and old meadow grasses – and no pernicious weeds –, this diversity should be retained. Biodiversity can be enhanced by introducing new seeds: this is done by using a harrow or disc to expose at least 30% bare earth and then broadcasting a 100% wildflower seed mix. To ensure the new introductions are appropriate, it is vital to use native provenance seed sourced from reputable suppliers adhering to the Flora Locale Code of Conduct. Furthermore, if the site is in or near an environmentally sensitive area – such as a designated site for nature conservation –, seed must not be introduced from outside the local area. Long-term biodiversity is ensured through monitoring; botanical surveys should be conducted at fixed points for at least the first 5 years to assess vegetation establishment, species abundance, and flowering potential.
- Design of the cultivation unit: the optimal timing for sowing seed is late summer or early autumn. This timing avoids high soil temperatures and exposes the seeds to cold, moist winter temperatures, which can help break the dormancy of some species. Spring sowing – March/April – is also suitable, particularly for areas of land that are prone to winter flooding. During application, the seed must be mixed regularly to ensure even species distribution and surface broadcast. Recommended sowing rates are 5g/m2 for 80:20 grass/wildflower mixes or 1.0 g/m2 for pure wildflower mixes. After sowing, the seed bed must be firmed; this is achieved using a Cambridge Roller or by using cattle to tread the seed in. Alternatively, for small areas – under one hectare – or for specific species, plug plants can be used. Small plugs should be planted at a density of 20 plants per sqm, arranged in clusters of 4 to 5 plants per species.
- Choice of the Phytocoenosis – plant community –: it is important that the correct plant species are selected which are adapted to the local site conditions and resemble the semi-natural plant communities of the local area. Species must be matched to the site's soil type (pH), fertility, hydrology, and topography. A commonly recommended seed mix is an 80:20 grass-to-wildflower ratio. However, this mix must not include vigorous grasses, as these will compete with the wildflowers for resources. If vigorous grasses are identified as a problem on the site, the introduction of the annual plant Yellow Rattle – *Rhinanthus minor* – can be highly effective. This plant is parasitic on the roots of grasses and is effective at reducing their vigour.

- Protection of wildlife: management protocols are essential for protecting the floral community, which in turn supports wildlife. The first year of establishment is critical for controlling weeds and reducing competition from grasses. In Year 1, the sward should be kept short – cut to 5cm –, cutting roughly every two months or when the sward reaches 15cm. Critically, cutting must stop during June, July, and August; this allows any establishing wildflowers to set seed. A final cut is made in September/October. For future maintenance of a summer flowering meadow, the first cut (5cm) should take place in March/April. The main second cut – 5cm – should occur after the flowering season, during September/October. This "hay cut" timing allows plants to complete their life cycle. For cornfield annuals, the management differs: the site must be harrowed – in Autumn or Spring – to regenerate the annuals. Where persistent weeds are a problem, they should be spot-treated with a broad-spectrum herbicide or dug out.

Maintenance

A correct design approach facilitates the establishment of a flower meadow formation capable of rapidly achieving a dynamic equilibrium with the environment, a process aided by its structure being open to self-variation. Monitoring and control represent the essential elements for verifying evolutionary processes. Botanical surveys should be conducted by a suitably qualified person at fixed points within the meadow for at least the first 5 years. These surveys must assess vegetation establishment, species abundance, sward height, vegetation cover, and flowering potential. The management model can also be predicated on differentiation criteria, distinguishing between distinct zones and/or by levels of functionality and anthropogenic pressure.

In the first year of management, particular attention must be paid to control weeds and reduce competition from grasses. For spring-seeded meadows, the first cut – to 5cm – should be in May. For autumn-seeded meadows, the first cut – 5cm – is March/April. The sward should be cut every 2 months, or when it reaches approximately 15 cm. Cutting must cease from June to August to permit wildflowers to set seed. A final cut is required in September/October. It is critical to remove all cuttings to prevent smothering the sward. For future maintenance – perennial meadows – first cut – to 5cm – should be performed in March/April. The second, primary cut – 5cm – must occur at the end of the flowering season, during September/October. All cuttings must be removed. Additional cuts may be necessary in autumn to remove untidy growth if the growing season is extended.

Section C - Societal challenges

Biodiversity enhancement

Flower meadows, spontaneous or sawn-on-purpose provide habitat and connectivity increasing diversity at many levels. Flower meadows create continuity between rural and urban areas, increasing the diversity of plant species and invertebrates (Bretzel et al 2016), represent a fundamental strategy and an often-overlooked opportunity to enhance and sustain biodiversity in urban environments. These spaces, when properly managed, counteract the ecological sterility of traditional short-mown grasslands, which dominate urban greening initiatives but offer scarce ecological value. The primary importance of FM lies in their capacity to transform low-biodiversity green areas into complex and vital habitats. This management shift permits a variety of wildflower species to complete their life cycle -flowering and setting seed- which is impossible in grasslands subjected to continuous cutting. This increase in plant diversity triggers a positive cascading effect on the entire ecosystem. Flower meadows provide essential food resources – nectar, pollen, seeds – and shelter for a wide range of wildlife, particularly pollinators – such as bees and butterflies –, birds, and other small fauna that struggle to survive in the built environment. Finally, this biodiversity is not an end in itself: it contributes to the general stability of the meadow ecosystem and enhances the resilience of the urban environment.

Climate Resilience

Flower meadows contribute to carbon storage through rich herbaceous biomass (Wang et al. 2021), carbon accumulation in topsoil (Kortleve and Mogollón 2023), and higher net primary productivity. Plant diversity and low-intensity management further enhance this effect (Thölix et al. 2025). Flower meadows reduce surface runoff thanks to vegetation cover, which intercepts rainfall, and more porous soil due to root systems. Studies show a 20-50% reduction in runoff compared to conventional lawns (Lin et al. 2020) and better infiltration than cultivated fields (Zimmermann et al. 2006). Root biodiversity improves soil structure (Bardgett et al. 2014), enhancing water retention. Flower meadows improve water quality by reducing erosion, retaining nutrients – e.g., nitrates and phosphates –, and filtering pollutants. Roots stabilize the soil and increase nutrient uptake (Zhang et al. 2010; Tilman et al. 2002). Meadow buffer strips reduce nitrates by up to 80% and phosphates by up to 90% (Hefting et al. 2005). Additionally, requiring fewer fertilizers, they lower contamination risk (Tzoulas et al. 2007).

Health, Well-being and Air Quality

Flower meadows increase physical activity by making green spaces more attractive and inviting (Pretty et al. 2005; Norton et al. 2019). Their biodiversity and aesthetics encourage walking and outdoor recreation, especially in urban areas (Giles-Corti et al. 2005; Hoyle 2016). Exposure to natural settings also improves mood, indirectly boosting motivation to move (Barton et al. 2010). Meadows thus support healthier, more active lifestyles. Flower meadows improve mental health and reduce chronic stress by providing restorative natural environments that lower cortisol and anxiety (Ulrich et al. 1991). Their biodiversity enhances wellbeing through sensory stimulation (Fuller et al. 2007). Urban meadows encourage social interaction and physical activity, benefiting mental health (Hoyle 2016). Reduced mowing increases natural aesthetics, promoting relaxation (Chollet et al. 2018). Natural sounds in meadows further decrease stress responses (Alvarsson et al. 2010).

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Nature-based Solutions for water management

Costanza Carbonari, Giulio Hasanaj

Abstract: Within the approach “working with nature”, Nature-based Solutions (NbS) for water management collect the set of actions, items and management measures aiming at reducing water-related risks, namely flooding, water scarcity and poor water quality, as well as preserving and restoring river ecosystems and creating new wet ecosystems. The more important ecosystem services provided by Nature-based Solutions for water management are definitely regulating ecosystem services such as flood mitigation, water purification and climate resilience, but also provisioning, supporting and cultural services are delivered, examples of which are, respectively, water availability, nutrient cycle support, aesthetic and recreational services. Nature-based Solutions for water management include both NbS pertaining to the riverscape, i.e. having a functional connection to the river and located in open spaces contiguous to the river, and NbS for sustainable urban drainage, which generally are not functionally connected nor contiguous to surface water bodies. Riverscape NbS include interventions for fluvial flood mitigation, riverbank erosion control and reduction of pollutant inputs into streams. NbS for sustainable urban drainage are those natural water retention and infiltration measures aiming at reducing pluvial flooding, increasing water storage and improving water quality.

Keywords: Natural water retention measures, Riverscape, Wetlands, Sustainable Urban Drainage System.

NbS for water management can at once enhance ecosystem services and ecological functioning

Nature-based Solutions (NbS) for water management are actions to protect, sustainably manage, and restore natural and modified ecosystems specifically addressing the challenge of improving water quantity and quality in an adaptive way, simultaneously benefiting people and nature (International Union for the Conservation of Nature 2016, European Commission and Tom Wild 2020). With regard to water quantity, we refer to the variability of water resources with resulting impacts on people and the anthropic and natural environment. In other words, this is the risk related both to excess water quantity resulting in floods and to water scarcity with possible droughts (United Nations 2018). Such hydrological-hydraulic variability includes both natural variability due to seasonal fluctuations in precipitation and the resulting river flows, and variability caused by anthropogenic factors such as climate change and land use change, which are responsible for exacerbating the frequency and intensity of extreme events. With regard to water quality, we refer to pollution and degradation of aquatic ecosystems losing their natural ability of purification. Water pollution is mainly due to agricultural and urban land use resulting in contaminants flows to water bodies, which thus receive nutrients, chemicals, heavy metals and even pathogens. Pollutants reach water bodies vehiculated by the water phase of runoff but also by the solid phase consisting of sediments and solid waste. It is important to emphasize that water availability -particularly scarcity- and water quality are closely linked. For example, improving water quality enables its reuse. Another example: changes in precipitation and streamflow, which reduce water quantity, directly lead to a decline

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in water quality (due to higher concentrations of pollutants); the resulting lower water quality levels turn out to be a form of scarcity themselves, as the water can no longer be directly used for many productive purposes (United Nations 2018).

NbS mitigating such water risks, and NbS in general, also aim at reversing environmental degradation and biodiversity loss (International Union for the Conservation of Nature 2020), hence, together with improving water management, they have to achieve a certain degree of ecological restoration, also specifically addressed and required by national and European regulation (European Commission 2022, European Parliament and Council of the European Union 2000, Ministero dell'Ambiente e della Sicurezza Energetica n.d.). Actually, biodiversity enhancement is both an NbS' goal in itself and a way to improve ecosystem functioning and services, by making ecosystems more resilient.

NbS for water management can also be labelled Natural Water Retention Measures, NWRM, these being a wide set of actions and land use types for the protection and enhancement of water retention capacity of aquifers, soil, and ecosystems with a view to improving their status. NWRM have the potential to provide multiple benefits, including the reduction of risk of floods and droughts, water quality improvement, groundwater recharge and habitat improvement (Burek et al. 2012, European Commission 2014, European Commission et al. 2015). NWRM are many and multifaceted, so various and numerous that are usually sorted per sector: hydro-morphology, urban, forest, agriculture; for a complete catalogue the reader is referred to the guide by European Commission et al. (2015).

The current contribution addresses some of the Nature-based Solutions part of the urban and hydro-morphology sectors, in particular those related to water storage and wetlands and those more directly related to surface water bodies. In the present contribution we therefore analyse

1. NbS pertaining to the riverscape, namely those NbS having a functional connection to the river and implemented in open spaces contiguous and associated to the river (Carbonari and Solari 2025); given the capillary presence of the hydrographic network on the territory, riverscape NbS can stand in urban, peri-urban and rural settings;
2. Sustainable Drainage Systems, SuDS, which are Nature-based Solutions for the regulation of the urban water cycle and are not functionally connected to rivers (Li et al. 2023).

Riverscape Nature-based Solutions

In the past -and still today in contexts where traditional urban water management planning prevails- hydraulic risk from fluvial flooding is mitigated primarily through grey infrastructure, meaning conventional structures based solely on engineering approaches. According to these approaches, flood risk is reduced, for example, by protecting urban centers with levees, diverting peak flood volumes through spillway channels to prevent critical water levels, or temporarily storing such volumes in reservoirs. These structural works can be implemented purely as grey infrastructure, but when they are part of an integrated approach that includes ecological solutions and nature-based engineering, they become components of Nature-based Solutions for flood risk mitigation and for regulating hydrological and hydraulic variability (Frantzeskaki et al. 2019). In fact, within the context of flood risk mitigation, the combined "Green + Grey infrastructure" approach is increasingly common due to its effectiveness, and NbS represent the pathway to integrating conventional engineering structures with ecological solutions. The NbS described in this section represent Natural Water Retention Measures for which it is also possible to simulate the reduction of flood peaks based on the size of the catchment and the magnitude of the flood event (Burek et al. 2012). The measures here described can, not only attenuate floods, but also store water to contrast water scarcity and increase the riverscape capacity to retain water and mitigate low flows during dry weather. Finally, riverscape NbS can significantly improve water quality through phytoremediation and vegetation filtering of runoff with its pollutant load, and through stream bed and banks' substrate reactivation with resulting enhanced microbial processes.

With regard to ecological restoration of riverscape Nature-based Solutions, biodiversity improvement for these interventions present a great potential since ecotones across aquatic and terrestrial ecosystems have a great habitat heterogeneity which is a primary support to biological diversity (Rosenzweig 1995, Chester and Robson 2013). Furthermore, rivers and channels are ecological corridors connecting different landscapes with different degrees of natural capital: for instance, the good status of ecological corridors between urban environments and more natural ecosystems represent the way urban systems can benefit from outskirt greenery.

Sustainable Drainage Systems

Grey infrastructure interventions (traditional engineering works lacking ecological solutions) aimed at retaining urban surface runoff, facilitating its infiltration into the soil, and potentially enabling water reuse, have long been practiced. These interventions seek to rebalance the altered urban hydrological cycle by increasing soil permeability and mitigating the problem of inadequate sewer networks. Examples of grey infrastructure with these objectives include drainage solutions such as permeable pavements and storage solutions like cisterns, as well as interventions to eliminate Inflow and Infiltration and to separate stormwater from wastewater. However, it has been shown that the most effective water retention in urban catchments is achieved by combining traditional storage and drainage systems with Sustainable Drainage Systems, specific NbS consisting of environmentally sustainable urban drainage solutions (Pampaloni 2022). Notably, "sponge cities" are urban plans based on the integration of grey infrastructure and SuDS for the management of stormwater flooding, effectively absorbing and reusing rainwater (Li et al. 2023).

The ecosystem services provided by SuDS go beyond mitigating the risk of pluvial flooding: the collection and reuse of rainwater help to alleviate drought and water scarcity; the vegetation in SuDS further restores the altered urban hydrological cycle by promoting infiltration and evapotranspiration; the vegetation in wetlands created through many SuDS allows for phytoremediation and microbial decomposition of organic carbon and phosphorus and nitrogen compounds. Indeed, special attention should be given to the capacity of SuDS to improve water quality by removing nutrients (carbon, phosphorus, and nitrogen) as well as solid particulates such as fine dust present in the atmosphere and on road surfaces. These pollutants, carried by rainwater, are intercepted by the wetlands of SuDS and purified and broken down by the plant and bacterial communities of the wetland ecosystem; SuDS thus serve as effective "traps" for nutrients and particulates (Tsatsou et al. 2023). An extensive network of SuDS can significantly reduce the flow of nutrients into surface water bodies, thereby alleviating eutrophication issues in inland waters -common in heavily urbanized areas. Ultimately, these nutrient traps help reduce the degradation of aquatic ecosystems in surface water bodies, since these bodies receive water from SuDS after it has undergone a genuine purification process.

With regard to ecological restoration, SuDS can have a relevant potential in supporting biodiversity because they represent wetlands providing significant habitats' structural heterogeneity, both abiotic and biotic. This heterogeneity is further enhanced by the fact that wetlands have ecotones across aquatic and terrestrial ecosystems (Rosenzweig 1995, Monberg et al. 2018).

Flood mitigation basins

Section A – General Description

Fig. 1 – Flood mitigation basin of the Secchia River with integrated implementation of vegetation. Basin in Rubiera, Reggio Emilia, Italy.

Description

Flood-mitigation basins are among those structural measures aiming at the mitigation of fluvial flood risk. They are reservoirs designed to temporarily store flood volumes upstream of the section of interest (the section of the watercourse where areas to be protected from river flood risk are located) and release them more slowly than they appear in the natural flood wave (Figure 1). Flood mitigation basins are differentiated in "more artificial" basins labelled flood expansion tanks and "partially natural" reservoirs: expansion tanks are areas enclosed by levees (representing the perimeter of the basins themselves), while "partially natural" reservoirs are established in areas along the watercourse that, due to their natural morphological characteristics, can store significant volumes of water. In particular, areas for the implementation of "partially natural" flood-mitigation basins are selected between the river and riverine plains and meet the principle of geomorphological and hydrodynamic consistency between the area itself and the watercourse. An example that effectively illustrates this concept is the attenuation areas created in the abandoned meanders of rivers (Burek et al. 2012, Rijke et al. 2012). The use of natural depressions to store flood volumes allows a reduced implementation of artificial levees. In general, all types of flood mitigation basins, unlike traditional, grey structures based solely on engineering approaches, can represent valuable NbS if implemented according to ecological approaches. Indeed, artificial reservoirs for flood risk prevention can be designed as multipurpose basins to fulfil the community's needs for potable water, energy, irrigation, and basins' optimal siting according to all these goals can be achieved through participatory multi-criteria decision-making (Masi et al. 2024); vegetation can be included in the basin according to an integrated design; ecological flooding can be easily supplied (Schmitt et al. 2009) as well as river ecological flows. Afforestation and the assurance of providing basins' ecological flooding and rivers' ecological flows can effectively support wetland ecosystems established by the artificial basin and the protection of the riverine ecosystem. Finally, a typical ecological design of flood-mitigation basins provides for permanent waterbodies with increased, temporary water storage during flood attenuation (Gerner et al. 2018).

Synonyms

Flood restoration; flood retention basins.

Section B – Technical details

A flood-mitigation basin is primarily a hydraulic structure that requires specific hydraulic design and planning. In the Italian framework, the design of the attenuation basin is the responsibility of the Consorzio di Bonifica (in agreement with the Region and the Municipality), as it is part of the extraordinary maintenance activities on the hydrographic network. The flood mitigation basin is generally a large-scale structure so that the reservoir can significantly reduce hydraulic risk. However, the primary criterion regarding the dimensions of the structure is the geomorphology and topography of the landscape. Two types of flood-mitigations basins exist: in-line reservoirs, in which flood water enters the basin along the watercourse and for which it is necessary a dam within the watercourse and transversal to the flow direction; and side-channel reservoirs in which flood water enters the basin through a lateral spillway on the watercourse or a lateral diversion channel. Moreover, the retention area must be equipped with several engineering works such as:

- Spillway: This is the intake structure that allows the diversion of flows arriving at the basin during flood retention. It is usually made up of a fixed structure (with a straight-lined spillway crest) which may or may not be equipped by gates.
- Bottom outlet: equipped by a gate to be open when the flow in the riverbed drops below the maximum acceptable level downstream.
- Descent ramp: For access by maintenance or repair vehicles.
- Safety overflow or emergency spillway.
- Perimeter embankments/levees: For containment (not necessary if it is possible to use exclusively the natural depression of the landscape).

In addition to the construction of works for the hydraulic functioning of the basin, the design and placement of vegetation must also be planned (in agreement with hydraulic designers to avoid loss of functionality of hydraulic structures).

Section C – Societal Challenges

Biodiversity enhancement

Increased connectivity of natural areas

Flood-mitigation basins definitely increase the connectivity of natural areas being "partially natural" reservoirs as they are established in areas along the watercourse that, due to their natural morphological characteristics, can store significant volumes of water. Such zones, selected between the river and riverine plains, meet the principle of geomorphological and hydrodynamic consistency between the area itself and the watercourse. The use of natural depressions to store flood volumes allows a reduced implementation of artificial levees (thus more natural basins with respect to expansion tanks). However, also attenuation basins enclosed by artificial embankments are directly connected to the river, thus they definitely improve the connectivity of natural areas reconnecting the river to a reclaimed part of floodplain.

Increased diversity of habitats

An ecological design of flood-mitigation basins usually provides for permanent waterbodies whit increased, temporary water storage during flood attenuation, therefore such basins represent valuable Nature-based Solutions for the recovery and improvement of wetland, riparian and aquatic ecosystems in riverine environment (Burek et al. 2012, Gerner et al. 2018). Indeed, permanent water bodies with varying water level offer a variety of habitats mainly located in the transitional zone between the aquatic and terrestrial domain. Moreover, vegetation can be included in the basin according to an integrated design, and ecological flooding (i.e. planned flooding also for relatively small and frequent floods) can be easily supplied (Schmitt et al. 2009); both measures can effectively support wetland ecosystems established by the artificial basin.

Water management

Increased surface water storage and/or groundwater recharge

Flood mitigation basins definitely increase surface water storage being permanent or temporary surface water bodies whose main objective is the temporary storage of excess flood volumes, and secondarily directly stores rain water. In case of permanent water bodies (with increased temporary water storage during flood attenuation), and in case of basins releasing flood volumes to water course after long detention time, groundwater recharge is also enhanced (European Commission 2014).

Climate resilience

Improved microclimatic mitigation capacity

Flood-mitigation basins are among those structural measures aiming at the mitigation of fluvial flood risk. They are reservoirs designed to temporarily store flood volumes upstream of the section of the watercourse where areas to be protected from river flood risk are located and release them more slowly than they appear in the natural flood wave. These basins are therefore primarily built to reduce area adversely impacted by the natural disaster consisting in fluvial flooding, this natural phenomenon being often exacerbated by extreme events due to climate change. Flood mitigation basins ultimately mitigate at the local scale hazardous flood events made more severe by climate change.

Removed carbon via storage in vegetation, soil biogenic reefs

Flood mitigation basins with an integrated ecological design including vegetation implementation remove carbon through vegetation storage. Plants capture and store atmospheric carbon dioxide as well as organic carbon compounds contained both in water and soil. In particular, those flood mitigation basins designed as permanent water bodies (with increased water volume during flood events) better act as carbon sink through an effective carbon stock in sediments: organic matter from dead organisms and washed-in plant material sinks to the bottom and becomes buried in the sediment layer (Gerner et al. 2018). Organic carbon becomes trapped in the sediment, preventing the carbon from being released back into the atmosphere as a gas. Over long periods, the basins conceived as permanent water bodies can accumulate vast amounts of carbon in their sediments, acting as a long-term carbon reservoir.

Health, well-being and air quality

Improved mental health and reduced chronic stress

Flood mitigation basins enhance the recreational and aesthetic value of public spaces by providing visually appealing landscapes, offering opportunities for recreational activities, and contributing to a more pleasant landscape. They can be implemented integrating forestation along the basin shore line or in general where it is possible (i.e. avoiding interferences with hydraulic substructure of the artificial basin such as flow intake and spillover) and they can be integrated into parks and other recreational areas, adding to the overall quality of life for residents. The enhanced visual appeal of such basins stems from the presence of the water body, preferably permanent. A good implementation should include complex shorelines, featuring diverse emergent plants and presenting a naturalistic design. When integrated in public places on extensive areas, artificial basins support various recreational activities such as walking, birdwatching, picnicking, and even fishing in some cases. This provides opportunities for people to connect with nature and enjoy outdoor activities (Rijke et al. 2012, European Commission 2014).

River banks and terraces connectivity restoration

Section A – General Description

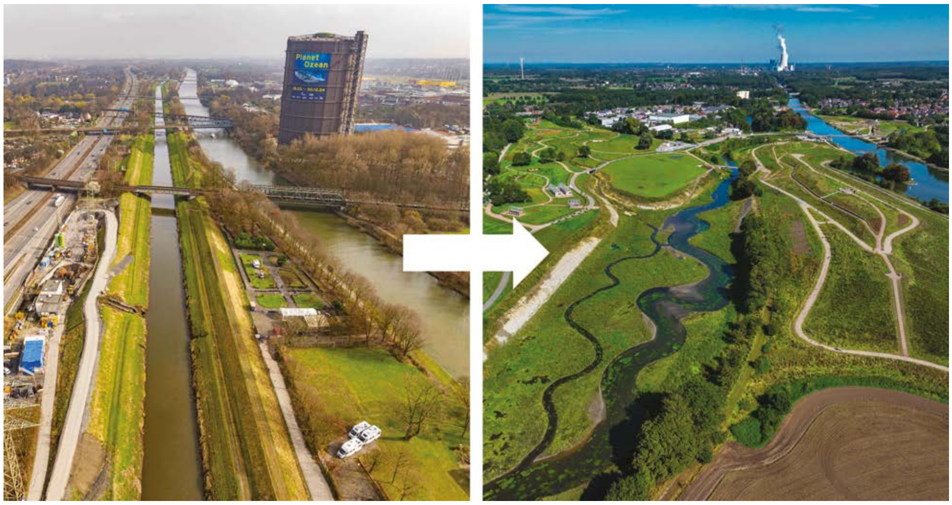

Fig. 2 – River banks and terraces connectivity restoration. Comparison between unrestored (left) and restored (right) channel's reach in the Emscher catchment in Oberhausen (left) and in Castrop-Rauxel (right), North Rhine-Westphalia, Germany. The restored reach presents restored natural sinuosity and secondary channels, larger channel sections, floodplain reconnection, presence of vegetation. Photo source: Emschergenossenchaft and Lippeverband; photo credit: Andreas Fritsche (left picture), Rupert Oberhäuser (right picture).

Description

The restoration of river banks and terraces connectivity is the recovery of the lateral connectivity between the main river channel and its banks and terraces (Figure 2), namely those landforms consisting in elongated bench-like landforms parallel and above the river channel and below the outer floodplain and representing riparian reservoirs (they mitigate flood waves by temporarily stocking flood volumes). River terraces sensu stricto are the natural landforms formed by erosion and deposition cycles and representing a former level of the floodplain, while here we intend terraces sensu lato, namely also including artificial riparian reservoirs consisting in flat-floored berms limited by levees or earthen embankments. In other words, here we address the connectivity recovery between the main active channel and river banks intended in a broad sense, namely including also the band of floodplain between the active channel and the embankments (O'Briain et al. 2024). Essential interventions in this field are the depaving and concrete removal in channelized streams (Gerner at al. 2018) allowing stream self-purification (denitrification and dephosphatation), plant colonization and habitat availability. In general, river-bank connectivity restoration aims at reshaping very channelized streams providing more natural sections and reaches, thus enabling biogeomorphological functions, among which flow patterns diversification and lateral sediment morphodynamics are of paramount importance for riparian environmental quality (del Tánago and de Jalón 2006).

Synonyms

Lateral connectivity restoration

Section B – Technical details

River banks and terraces connectivity restoration consists of morphological lateral connectivity restoration that first of all aims at reshaping very channelized streams providing wider and more natural cross-sections and reaches. Banks and terraces connectivity restoration can also include depaving and concrete removal, interventions that together with section reshaping need careful siting consideration for space requirements and infrastructure constraints. Indeed, much of the land along riverbanks and terraces has been converted for agriculture, infrastructure, and urban development. Securing land or collaborating with landowners to set back levees and reconnect floodplains can be politically and financially challenging. In particular, restoration efforts in urban areas is often more expensive due to higher land values and development density. Projects can also face public opposition if they are perceived to reduce flood protection, limit access, or conflict with development plans.

Moreover, river connectivity restoration is effective if interventions are undertaken at large spatial scales since river connectivity is affected by catchment-wide problems; in other words, issues upstream or in the wider catchment can undermine local restoration efforts. For instance, pollutants, altered water flow, and excessive sediment loads from sources like agriculture or urban runoff can re-degrade a restored area. Another typical example of connectivity restoration failure is the case of reaches widening with possible sediment replenishment in order to restore lateral sediment morphodynamics, an effect that can not persist in the long term if the watercourse faces upstream issues of disrupted natural sediment supply (i.e. dams and other barriers blockage of sediment downstream with resulting sediment starvation and possible erosion processes). Finally, river banks and terraces connectivity restoration being mainly morphological restoration involving significant changes in the channel cross-sections should be coupled with riparian vegetation recovery, in a perspective of a more complete and effective river renaturation.

Section C – Societal challenges

Biodiversity enhancement

Increased connectivity of natural areas

The restoration of river banks, terraces and possibly adjacent flood plain connectivity is the recovery of the lateral connectivity between the main river channel and the flood plain, namely the part of the alluvial plain adjacent to the river and naturally subject to flooding. This Nature-based Solution is therefore the par excellence measure allowing increased connectivity of natural areas of different domains (aquatic and terrestrial).

Increased diversity of habitats

It is of paramount importance that the river has a diversified flow patterns in a wider bed connected to riparian systems and possibly might flood some parts of the adjacent plain thus enabling an exchange of sediments and conditions for temporary wet areas and resulting hygrophilous vegetation allowing an overall increase in habitat diversity. Restored riverine ecosystems present a rich habitats' structural heterogeneity which is acknowledged to be a prerequisite for biological diversity.

Water management

Increased surface water storage and/or groundwater recharge

The restoration of river banks, terraces and possibly flood plain connectivity is the recovery of the lateral connectivity between the main river channel and the flood plain, namely some parts of the floodplain side channels, abandoned terraces and meanders are restored in water and sediment fluxes above all during floods. This produces wider streams and temporary flooded areas, therefore a gain in surface water storage, such that flood plain restoration is actually a measure for flood management (Rijke et al. 2012). Flooded areas such as reconnected river terraces return water volumes to the main channel slowly after peak flow, allowing for an improved groundwater recharge.

Improved water quality

During flood events volumes detention outside of the main active channel, as it is the case of restored riparian systems in which river terraces delay peak flow, water purification takes place through carbon, nitrogen and phosphorous accumulation in soil (Noe and Hupp 2005), provided permeable surfaces (i.e. also vertical connectivity restoration). Water purification through nutrient retention is enhanced if vegetation restoration is present, as an integral part of the project design and implementation or as a result of ecological succession. In certain cases, phytoremediation can even remove and/or retain other pollutants such as metals and plastics.

Climate resilience

Removed carbon via storage in vegetation, soil biogenic reefs; Improved microclimatic mitigation capacity

River banks, terraces and possibly floodplain connectivity restoration improves soil functions and composition thanks to temporary flooding of some parts of the plain contiguous to the stream, this enabling an exchange of sediments and conditions for temporary wet areas, as well as organic carbon storage in soil (Noe and Hupp 2005). Afforestation, as an integral part of the project design and implementation or as a result of ecological succession, also contributes to carbon storage. Living plants store atmospheric CO^2 and soil organic C in their biomass. Moreover, carbon stock is also provided by the buffer vegetation on river banks, terraces and restored floodplain areas which intercept the runoff and the related transported material, thus preventing the erosion-induced transport of C to reach the water body (Gerner at al. 2018).

River depaving and daylighting

Section A – General Description

Fig. 3 – Channel depaving. Comparison between paved channel with concrete banks and restored reach of the Borbecker Mühlenbach river in Essen, North Rhine-Westphalia, Germany. Photo source: Emschergenossenchaft and Lippeverband; photo credit Klaus Baumers.

Description

River depaving and daylighting are the two main measures to adopt in extremely artificial streams, the objective of such measures being the recovery of vertical and lateral connectivity. Depaving is the concrete bed removal in channelized streams (Gerner et al. 2018), it addresses not only strictly the streambed, but also embankments, since usually paved streams present also impermeable, fixed banks at least in their lowermost part (Figure 3). The impermeable shell removal not only allows vertical and lateral connectivity restoration, but also aims at reshaping very channelized streams providing more natural sections and reaches, thus enabling biogeomorphological functions. River daylighting and restoration of culverted rivers consists in removing streams from buried conditions and bring them to the surface in order to improve their ecological status (Wantzen et al. 2022). It is worth noting that culverted streams almost always present also impermeable bed pavement, so that restoration interventions of buried streams should include both daylighting and depaving. Deculverting allows the recovery of i) light and consequent processes based on primary production, ii) lateral connectivity to riparian zone and consequent ecological processes, iii) biologically active surfaces and consequent stream self-purification (Wantzen et al. 2022). Ecologically designed deculverting projects must include the improvement of aquatic and marginal habitats by recreating floodplains and replanting banks (Wild et al. 2011). A particularly important effect of deculverting is the improvement of longitudinal mobility and habitat availability of aquatic fauna (Baho et al. 2021). Further ecosystem services provided by river daylighting are flood mitigation and community revitalization (Wantzen et al. 2022, Wild et al. 2011).

Synonyms

Stream deculverting; Stream reopening; Impervious streambed removal.

Section B – Technical details

Paved and culverted streams are located in urban areas with an extremely high degree of human-made structures and infrastructures, therefore any potential depaving and daylighting project needs siting considerations accounting for space requirements and infrastructures intersections. Actually, extremely dense urban areas may be highly constrained by existing buildings, roadways and buried utilities lines for a sufficient space to build out a restored channel. In case of depaving interventions only, which presents less constraints with respect to deculverting, buried infrastructures like energy pipelines, sewage systems and water supply systems are quite common. In deculverting projects even major difficulties are encountered since, in addition to hidden utility lines underneath the stream bed, also structures and infrastructures covering the channel are present. Although, built infrastructures can always be moved, the associated costs can be prohibitive, especially in urban areas with very high land values. For this reason, daylighting projects are often integrated into broader economic revitalization effort that can capitalize on the new environmental benefits provided by the restored stream. Moreover, successful projects require ample width to allow for a natural flow path and gentle, stable slopes, which will almost always require a significantly wider area than the area occupied by a buried stream.

In addition to siting consideration, maintenance considerations must be accounted for, being usually burdensome. Indeed, depaving and deculverting interventions require significant monitoring and maintenance in the first few years to ensure that the channel and bank are stable and the vegetation is established. However, after the setting-up and the consolidation of stable conditions of bed, banks and vegetation an open stream will require far less ongoing maintenance than a culvert or other grey infrastructure.

Section C – Societal Challenges

Biodiversity enhancement

Increased connectivity of natural areas; Increased diversity of habitats

River daylighting and restoration of culverted rivers consists in removing streams from buried conditions and bringing them to the surface in order to improve their ecological status; in case of depaving the ecological improvement consists in restored vertical connectivity. This allows the recovery of i) light and consequent processes based on primary production, ii) lateral connectivity to riparian zone and consequent ecological processes, iii) biologically active surfaces and consequent stream self-purification (Wantzen et al. 2022). Ecologically designed deculverting and depaving interventions must include the improvement of aquatic and marginal habitats by recreating floodplains and replanting banks (Wild et al. 2011). A particularly important effect of deculverting and depaving is the improvement of longitudinal mobility and habitat availability of aquatic fauna (Baho et al. 2021).

Increased local diversity (species and/or taxonomic groups)

River depaving and above all daylighting are the river restoration measures that best increase local diversity in terms of both species richness and functional diversity. Indeed, this biodiversity enhancement is rapid and certain more than in other river restoration interventions, since the starting point of culverted and paved streams is the most ecologically degraded with respect to the great majority of streams in other unrestored conditions, being actually culverted and paved streams almost ecologically dead. By allowing sunlight to reach the stream, the growth of plants and algae that form the base of the food web is enabled. This new food source, along with the improved physical habitat from creating an open channel, leads to the colonization of more species, including invertebrates and vertebrates.

Water management

Increased surface water storage and/or groundwater recharge

Removing streams from buried conditions and bringing them to the surface definitely increases the surface collecting rain water: the impermeable cover is removed and the restored water body directly receives rain water and run off. Deculverting allows the recovery of i) light and consequent processes based on primary production, ii) lateral connectivity to riparian zone and consequent ecological processes, iii) biologically active surfaces and consequent stream self-purification (Wantzen et al. 2022). Stream depaving restores vertical connectivity between the stream, surface sediment layer and subsurface: the sealed, impervious stream bed is replaced by permeable, filtrating material, therefore a vertical water flow between the stream and groundwater is recovered. Since culverted streams almost always present also impermeable bed pavement, restoration interventions of buried streams should include both daylighting and depaving, thus an improvement river-groundwater exchange.

Improved water quality

The hydro-morphological and biological processes provided by deculverting and depaving drastically improve water quality because the daylighted, desealed, restored and revegetated stream guarantees the ecosystem service of nutrient regulation; this condition has to be compared to the ecologically dead zone with no stream self-purification represented by the buried and/or sealed configuration.

Climate resilience

Removed carbon via storage in vegetation, soil biogenic reefs

River depaving restores the vertical connectivity of the stream, both improving soil functions thanks to impermeable surface removal and to re-establishment of vegetation (Gerner et al. 2018). Permeable substrate on river bed allows a better aeration and infiltration as well as organic carbon storage. Living plants store atmospheric CO_2 and soil organic C in their biomass. River daylighting allows the recovery of light and consequent processes based on primary production: daylighting allows photosynthetic carbon fixation (Wantzen et al. 2022).

Riparian vegetation restoration

Section A – General Description

Fig. 4 – Riparian vegetation restoration. Comparison between unrestored and restored reach of the Marsh Creek in Oakley, California. The restored reach presents a gradient of different hydrophilic macrophytes from the in-channel zones to the terrestrial ones. Photo courtesy Restoration Design Group, Inc., Berkeley, California.

Description

Riparian forestry restoration (Figure 4) is a key measure for water security and quality as well as for climate adaptation (O'Briain et al. 2024). Riparian vegetation indeed enables several biogeomorphological functions such as shading the river channel and thus lowering water temperature, providing the detritus food chain for aquatic community, increasing spatial heterogeneity and thus habitat availability and biodiversity (Naiman and Decamps 1997, Pringle 2003), retaining excess nutrients dissolved in water (Gerner at al. 2018), protecting the water body by acting as a trapping buffer zone with respect to pollutants coming from the flood-plain. Riparian vegetation restoration is a key measure in river renaturation because it significantly improves river-bank connectivity from an ecological perspective (Pringle 2003). Indeed, riparian zones are valuable ecotones with a rich gradient of vegetation species having a variety of different characteristics, behaviours and ecological roles as we move from aquatic/in channel settings to terrestrial ones.

Synonyms

Riparian vegetation recovery; Tree and shrubs belts/strips along rivers.

Section B – Technical details

Riparian vegetation restoration can be safely implemented without increasing the hydraulic risk, and indeed new planning and ordinary maintenance of the hydrographic network can and must present a vegetation maintenance approach taking into account both hydraulic requirements and the ecological aspects of riparian and aquatic ecosystems. Riparian vegetation restoration can be implemented in river reaches with unchanged channel geometry, namely with "constant cross-section" or "quasi-constant cross-section"; in this case interventions concern only vegetation management changes and innovations. However, in a perspective of a more complete and effective river renaturation, riparian vegetation recovery can be coupled with morphological restoration involving significant changes in the channel cross-sections and possibly the adjacent floodplain.

The removal of in-channel and riparian vegetation is carried out because vegetation can have negative effects from a hydraulic perspective. Vegetation increases hydraulic roughness, which leads to reduced flow velocity, higher water levels, and an increased risk of flooding during high-flow events. Furthermore, the reduction in flow velocity promotes sediment deposition, which results in a reduced effective channel cross-section and, consequently, a further increase in flood risk. In addition to the primary issue of increased roughness, tree and shrub vegetation is also removed because, if carried by the current during flood events, it can increase the risk of blockages in narrow sections. Finally, vegetation removal is also carried out to ensure adequate visibility and access for monitoring and maintaining hydraulic structures.

However, in-channel vegetation in natural watercourses, and even in artificial channels, plays a fundamental role in shaping the chemical, physical, and biological conditions of habitats for numerous bacterial and animal species. It also helps maintain the ecological corridor function of the watercourse, ultimately contributing to biodiversity conservation. Moreover, vegetation plays an important role in bank stabilization and supports both phytoremediation and the self-purification capacity of the watercourse, particularly by mitigating pollution from nutrients such as nitrogen, phosphorus, and organic carbon. In addition to all these regulatory ecosystem services, the presence of vegetation along a watercourse enhances its aesthetic quality and potential recreational value.

Traditional vegetation management, adopted by the majority Italian river authorities among others, is featured by a complete mowing of both banks and the channel bed leading to a complete (or, at best, substantial) loss of the ecological and self-purification functions of the channel. It also causes resuspension of accumulated sediments, destabilization of the banks, and increased water temperature, resulting in decreased dissolved oxygen levels. This has led some river authorities and managers to develop and adopt a type of vegetation maintenance that better preserves the ecological and environmental functionality of canals. In practice, this approach is known as "gentle maintenance" (ANBI VENETO 2020, Consorzio di Bonifica Acque Risorgive n.d.), which involves less frequent cutting and different methods and timing compared to traditional management, with the aim of: i) always ensuring the hydraulic functionality of the channel; ii) maintaining good ecological functionality; iii) preserving ecosystem regulatory services.

This type of vegetation maintenance can be applied in channel sections where the design flood discharge, even for high return periods, is safely contained with an adequate hydraulic freeboard. In contrast, in sections where such flood discharges are not fully contained or only just pass through without a minimum safety freeboard, complete vegetation removal is required. In other words, depending on the actual flood conveyance capacity, it is appropriate to apply either traditional or gentle vegetation maintenance in a site-specific and case-specific manner, based on flood flow behaviour, determined through hydraulic simulations, of the relevant watercourse sections.

Section C – Societal challenges

Biodiversity enhancement

Increased connectivity of natural areas; Increased diversity of habitats

Riparian forestry restoration is a key measure for increasing connectivity of natural areas as well as habitats availability and diversity. Riparian zones represents ecotones between the terrestrial and aquatic domains, in other words transitional areas between different ecosystems (Naiman and Decamps 1997). Riparian vegetation recovery increases spatial heterogeneity and thus habitat availability and biodiversity, and also dead vegetation has an important ecological role providing both different ecological niches and the detritus food chain for aquatic community.

Increased local diversity (species and/or taxonomic groups)

Riparian forestry restoration should be designed envisaging the use of a great variety of plants, which is actually supported by the varying water levels and flows and different degrees of hydrophilic conditions. The increase of local biodiversity in terms of both species richness and functional diversity is provided both by the use of new plants starting from the implementation of the recovery intervention and by the ecologically succession that takes place in restored riparian zones (Carbonari and Solari 2025).

Water management

Increased surface water storage and/or groundwater recharge

Riparian vegetation restoration improves water quality due to plants' role in nutrient regulation and water course shading. Indeed, plants absorb excess nitrogen and phosphorous compounds and reduce total organic carbon dissolved in water. Plants shade on the water course enables lower water temperature and resultant higher dissolved oxygen. Plants also enhance water infiltration and evapotranspiration, therefore overall contribute in water cycle regulation (Gerner et al. 2018, O'Briain et al. 2024).

Climate resilience

Removed carbon via storage in vegetation, soil biogenic reefs

Riparian forestry restoration envisages extensive setting of a variety of plants which store in their biomass atmospheric carbon dioxide and carbon component of soil organic matter. Furthermore carbon stock is also provided by the buffer vegetation on the river bank which intercept the runoff and the related transported material, thus preventing the erosion-induced transport of C to reach the water body (Gerner et al. 2018, Naiman and Decamps 1997). Moreover, a vegetated permeable surface favours carbon stock in the soil itself, which acts as a sink in the carbon cycle.

Health, well-being and air quality

Improved air quality

Riparian forestry restoration plays a fundamental role in improving air quality both through carbon sequestration and absorbing and degrading airborne pollutants. In addition to CO_2 sequestration, plants can remove further carbon compounds called volatile carbon compounds (VOCs). Other gaseous pollutants (different from carbon compounds) removed by vegetation are sulphur dioxide and nitrogen oxides, and also particulate matter. It's crucial to remember that riparian zones are vital ecotones characterized by a natural resilience since riparian plants are adapted to geomorphic and hydrologic perturbations and tolerate great seasonal and annual variability of environmental conditions (Naiman and Decamps 1997). Therefore riparian vegetation is more resilient to climate change effects with respect to vegetation in adjacent upland habitats; thus ultimately also ecosystems services, including air quality enhancement, provided by riparian vegetation are robust.

Constructed wetlands

Section A – General Description

Fig. 5 – Phytoremediation in a Constructed Wetland (CW). CW for the treatment of grey water through gravel bed filtering and phytoremediation using *Cyperus papyrus*; Florianopolis, Brazil. Photo credit: Heike Hoffmann.

Description

Constructed Wetlands (CWs) are engineered systems that mimic the functions of natural wetlands to treat various types of contaminated water. They enhance water quality through a combination of physical, chemical, and biological processes, ultimately purifying used water before it is either discharged into natural surface water bodies or used to recharge aquifers (Hsu et al. 2011). CWs are effective for treating municipal and agricultural wastewater and are commonly employed as a cost-effective alternative to conventional tertiary treatment systems. They are also used for managing Combined Sewer Overflows (Rizzo et al. 2020) and domestic Grey Waters, as reported in Figure 5 (Boano et al. 2020). Constructed Wetlands can reduce organic matter, nutrients, suspended solids, and landfill leachate from polluted waters. Based on the flow path, CWs are categorized into surface-flow and subsurface-flow systems, both of which utilize plants for phytoremediation (Rizzo et al. 2020). In subsurface-flow CWs, the wastewater flows through a porous medium, which plays a key role in physically filtering contaminants and supporting the growth and interaction of bacteria and plant roots, thereby enhancing pollutant removal.

Synonyms

Engineered reedbeds; Treatment wetlands; Wetlands for tertiary treatment of effluent.

Section B – Technical Details

Constructed Wetlands are valuable and multipurpose Nature-based Solutions whose field of application however needs to be carefully delimited. Actually, CWs presents several limitations and in many cases can not replace conventional waste water treatment plants (WWTPs), as well as other NbS can not completely perform the function of large engineering facilities designed to respond to particular societal challenges, as it is the case of systems of SuDS in "sponge cities" that can not reduce flood risk as much as large flood mitigation basins (Li et al. 2023). In such contexts, the combined "Green + Grey infrastructure" approach turns out to be particularly effective, more than NbS alone. In particular, Constructed Wetlands cannot substitute large wastewater treatment plants because of their performance limitations, lack of standardized design, and sensitivity to varying conditions. Two main limitations are intrinsic of CWs compared to WWTPs such that CWs can not match WWTPs performances: i) CWs do not offer the consistent, high-level treatment of WWTPs in case of constant, high amount of pollutant load per day (i.e very large equivalent inhabitants) because CWs are less effective than WWTPs in primary and secondary treatment; ii) on equal pollutant load, CWs require direct land area larger than a traditional plant, thus presenting an overall lower "land use efficiency" (at least for large scales and large equivalent inhabitants).

Constructed Wetlands are therefore suitable as a cost-effective alternative to tertiary treatment, namely they can be used as a "polishing" step after primary and secondary treatment in conventional plants in order to remove residual contaminants; they are also implemented in case of used water without high pollutant load as it is for grey water (Boano et al. 2020), as well as in case of water quality improvement for non-potable uses such as irrigation. CWs are also suitable for storm water management and Combined Sewer Overflows' treatment (Rizzo et al. 2020), in this case providing large areas in order to buffer rapid discharge events releasing large volumes and considerable pollutants loads (i.e. much lower water quality comparable to mechanically treated domestic waste water). Overall, Constructed Wetlands implementation is recommended in small, decentralized systems, being cost-effective and sustainable solutions for small communities and scattered applications where traditional plants are not feasible.

Section C – Societal Challenges

Biodiversity enhancement

Increased connectivity of natural areas

Constructed wetlands with emergent vegetation support a variety of plants, which in turn provides diverse habitats for other organisms. Indeed, wet ecosystems, with the typical transitional zone between aquatic and terrestrial domains, present a rich habitat heterogeneity, which in turn provides a variety of niches for different species and ultimately enhances biodiversity. Constructed Wetlands create diverse habitats through their shallow depths, generally large surface areas, and complex, irregular shorelines, supporting a wide range of plants, invertebrates, and animals. Furthermore, the water purification capabilities of wetlands can lead to healthier ecosystems with a better regulation of nutrient cycles (Boano et al. 2020; Hsu et al. 2011).

Increased diversity of habitats

The design and implementation of constructed wetlands include the planting of numerous and various plants with specific roles of phytodepuration, therefore the plants themselves represent an increase of local diversity in terms of species and taxonomic groups. Furthermore, the new habitats provided by constructed wetlands supply food and shelter for numerous invertebrates, which in turn support higher trophic levels like amphibians, birds, fishes, and mammals, leading to a greater abundance of species than might be found in the surrounding landscape.

Water management

Increased surface water storage and/or groundwater recharge

A constructed wetland consists of a properly designed basin that contains water, a substrate of water-saturated sediments, plants and microbial communities. This shallow water basin intercepts rainfall and surface runoff, and, because of the large surface area of the water and its shallow depth, the system interacts strongly with the atmosphere through rainfall: the basin receives the rainfall directly on the water surface, and the runoff of a larger surface drained by the basin (both pervious and impervious cover). This shallow water basin therefore stores relevant water quantities (Hsu et al. 2011).

Improved water quality

Constructed wetlands are basins characterized by slow flows and shallow water depths which provide prolonged contact times between the water and the surfaces within the wetland (i.e. water-saturated sediments with biofilm, plants roots with biofilm) enabling gas/water interchanges and microorganisms activity of transforming a wide variety of substances including pollutants. Phytoremediation by plant also contributes to water quality improvement (Hsu et al. 2011). Plants purify water through denitrification, dephosphation and the removal of organic carbon compounds including various human-made pollutants such as industrial chemicals and pharmaceuticals, which make domestic waste- and grey-water rich in total organic carbon (Boano et al. 2020).

Climate resilience

Removed carbon via storage in vegetation, soil biogenic reefs

Constructed wetlands plays a role in carbon sequestration, which is the process of capturing and storing atmospheric carbon dioxide (CO_2) because the design of constructed wetlands includes the use of emergent aquatic plants. Plants absorb CO_2 during photosynthesis and convert it into biomass (photosynthetic carbon fixation). In addition to CO_2 sequestration, plants used in constructed wetlands can remove further carbon compounds contained in polluted waters for the treatment of which constructed wetlands are designed (Boano et al. 2020). Indeed, domestic waste- and grey-water have high values of total organic carbon (TOC) which includes various human-made pollutants such as industrial chemicals and pharmaceuticals. Furthermore, also the substrate of gravel and sand that form the bottom layer of constructed wetlands effectively store carbon organic matter from dead organisms and washed-in plant material sinks to the bottom and becomes buried in the sediment.

Health, well-being and air quality

Improved air quality

Constructed wetlands include numerous and various plants mainly used for water purification, however they also ensure phytoremediation processes improving air quality both through carbon sequestration and absorbing and degrading airborne pollutants. In addition to CO_2 sequestration, plants used in constructed wetlands can remove further carbon compounds called volatile carbon compounds (VOCs). Other gaseous pollutants (different from carbon compounds) removed by vegetation are sulphur dioxide and nitrogen oxides. Plants absorb gaseous pollutants, which are then metabolized or broken downs in less harmful substances (phytodegradation) and in some cases can be released back into the atmosphere in less harmful form (phytovolatilization). In addition to gaseous pollutants reduction, plants also remove particulate matter.

Bioswales

Section A – General Description

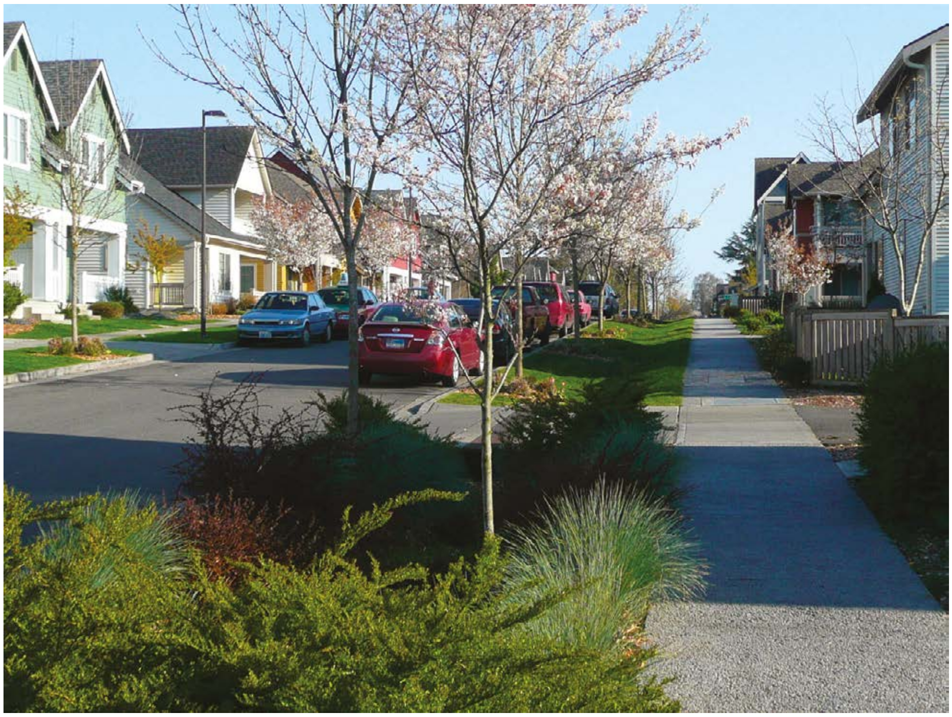

Fig. 6 – Bioswales for treating stormwater runoff from street in Seattle (Source: Architectsea 2011).

Description

Bioswales (also referred to as swales) are open, vegetated, broad and shallow channels specifically engineered to convey, treat, and, in many cases, attenuate surface runoff generated during rainfall events (World Bank 2021). As key components of Sustainable Drainage Systems (SuDS), bioswales integrate hydraulic conveyance, water quality treatment and ecological functions, thereby contributing to sustainable stormwater management in urban environments.

Characterised by gentle longitudinal gradients and continuous vegetated surfaces, bioswales reduce surface runoff velocities and mitigate flood risk during intense precipitation (Blanc et al. 2012; Atkins 2010; Woods-Ballard et al. 2015). They may operate as alternatives to conventional underground drainage systems, offering additional benefits through pollutant removal and the moderation of urban hydrological responses (Blanc et al. 2012).

Recognised as NbS, bioswales constitute shallow, vegetated depressions designed to intercept, infiltrate, divert and treat stormwater, thereby enhancing both hydrological and ecological performance within urban landscapes (Eisenberg and Polcher 2019). Their geometry promotes flow retardation, erosion reduction and temporary water storage, helping to regulate peak discharges (Woods-Ballard et al. 2015; World Bank 2021).

Water quality improvements are achieved through sedimentation, filtration and biological assimilation. As stormwater passes through vegetation and substrate layers, sediments, nutrients and particulate pollutants are progressively retained or degraded, resulting in measurable improvements in downstream water quality (World Bank 2021; Kazemi et al. 2011). The vegetative cover - typically composed of herbaceous species

- facilitates sediment trapping, evapotranspiration and infiltration, and contributes to soil ecological function and urban microclimate regulation (World Bank 2021).

Bioswales may be differentiated according to function within SuDS (World Bank 2021):

- standard conveyance bioswale, primarily designed to transport runoff to subsequent treatment facilities.
- enhanced dry bioswale, incorporating a prepared filter media and a subsurface underdrain to improve treatment and prevent waterlogging.
- wet bioswale, engineered to maintain permanently moist or marshy conditions at the base, supporting extended treatment processes for stormwater.

Synonyms

Swales; Green swales; Grassed swales; Vegetated filter strips; Stripswale.

Section B – Technical Details

Implementation conditions

Effective implementation requires a detailed assessment of environmental, topographical and design conditions to ensure hydraulic, treatment and urban landscape performance (NWRM s.d.; Woods-Ballard et al. 2015). Bioswales are most suitable for sites with sufficient space to accommodate shallow, wide channels; their spatial requirements exceed those of conventional piped drainage systems, making installation challenging in high-density urban areas (Woods-Ballard et al. 2015; Eisenberg et al. 2022).

They are commonly employed to manage runoff from roads, parking areas and other impervious surfaces, and are frequently located along road margins or integrated into parking facilities (NWRM s.d.; Woods-Ballard et al. 2015). Bioswales typically function as an early-stage SuDS component, receiving inflows from adjacent catchments.

Slope conditions strongly influence hydraulic performance. Recommended longitudinal slopes range from 0.3% to 1%, ensuring low flow velocities, reduced erosion risk and effective infiltration (NWRM s.d.; Woods-Ballard et al. 2015). Where natural slopes exceed 2%, check dams may be installed to create a stepped profile, enhancing retention time and infiltration capacity (Woods-Ballard et al. 2015). Conversely, extremely flat sites may experience poor drainage and require careful grading to avoid prolonged water stagnation (NWRM s.d.).

Design features

For optimal hydraulic efficiency and operational safety, bioswales should adhere to established geometric criteria (Woods-Ballard et al. 2007). Cross-sections are typically trapezoidal or parabolic, with side slopes between 1:3 and 1:4 and a maximum depth of approximately 60 cm to maintain safe and controlled flow conditions. Longitudinal slopes must remain shallow to promote flow attenuation, and the channel base is generally designed with a width of 0.5–2 m.

These configurations ensure low flow velocities, increased wetted perimeter, enhanced infiltration processes and improved safety for users and the surrounding environment (Woods-Ballard et al. 2007).

Soil permeability, groundwater level and the risk of groundwater contamination must be carefully evaluated. Bioswale type selection depends on soil infiltration capacity, with infiltration generally considered feasible when the soil exhibits a hydraulic conductivity ≥ 10^{-6} m/s. Where infiltration is not possible or appropriate, an impermeable geomembrane may be installed to prevent undesirable percolation (Woods-Ballard et al. 2015).

If infiltration is intended, groundwater should lie at least one metre below the base of the bioswale or associated infiltration device (NWRM s.d.). Sites with shallow groundwater may support wet bioswales, though infiltration should be limited or avoided (Woods-Ballard et al. 2015). In contaminated sites, infiltration must be preceded by environmental risk assessment to prevent pollutant mobilisation towards groundwater (Woods-Ballard et al. 2015; NWRM s.d.).

Soil compaction must be strictly avoided, as it significantly reduces infiltration capacity (Eisenberg et al. 2022). Excavation should be carried out from the sides to avoid loading the channel base. Bioswales should not receive runoff until vegetation is fully established and nearby construction activities are completed, preventing sediment pollution and functional degradation (Woods-Ballard et al. 2015).

Maintenance

Long-term performance depends largely on vegetation quality and regular maintenance. Dense herbaceous vegetation is essential to retard flow, facilitate sediment capture and enhance pollutant removal (Woods-Ballard et al. 2015). Bioswales should be located in areas receiving adequate sunlight to promote vigorous plant growth.

Species selection must consider local climatic conditions, soil characteristics, light availability and rainfall regimes. Vegetation should tolerate periodic inundation and be robust enough to remain functional during extreme weather events (Woods-Ballard et al. 2015; NWRM s.d.).

Maintenance programmes must ensure access for inspection, sediment removal, channel cleaning and periodic mowing. Regular maintenance is essential to preserve hydraulic, treatment and aesthetic performance (Woods-Ballard et al. 2015; Eisenberg et al. 2022).

Section C – Societal Challenges

Biodiversity enhancement

Bioswales provide multifunctional green spaces capable of substantially enhancing biodiversity, depending on vegetation type and spatial distribution (NWRM s.d.). When trees or hedgerows are present, bioswales form high-quality habitats and ecological linkages supporting wildlife movement in urban areas (Warner 2022). Native vegetation ensures resilient cover and suitable habitat for local fauna (Woods-Ballard et al. 2015). Integrated within wider green networks, bioswales contribute to ecological corridors that sustain terrestrial biodiversity (NWRM s.d.). Wildflower mixes and diverse planting schemes further support insects, invertebrates and birds (Woods-Ballard et al. 2015).

Climate Resilience and Water management

Through evapotranspiration, bioswales lower ambient temperatures, mitigating urban heat island effects and contributing to climate change adaptation. Vegetation also sequesters carbon in biomass and soil (Bowler et al. 2010). Bioswales effectively reduce runoff rates, particularly from impervious urban surfaces, and can decrease flood risk during short, intense rainfall events (Zölch et al. 2017). When combined with other Nature-based Solutions, they contribute to reducing peak river flows in small catchments (NWRM s.d.).

Health, well-being and air quality

By improving access to green and blue public spaces, bioswales support public health and well-being. They remove pollutants such as hydrocarbons, nitrogen compounds and heavy metals (NWRM s.d.), while infiltration stabilises soils and reduces subsidence risk (World Bank 2021). Their integration into streetscapes enhances the quality of public spaces and can foster recreation and informal social interactions (Kim and Song 2019). Public participation in design and maintenance can strengthen community cohesion, while combined traffic-calming measures contribute to safer and more liveable urban environments (World Bank 2021).

Vegetated permeable surfaces

Section A – General Description

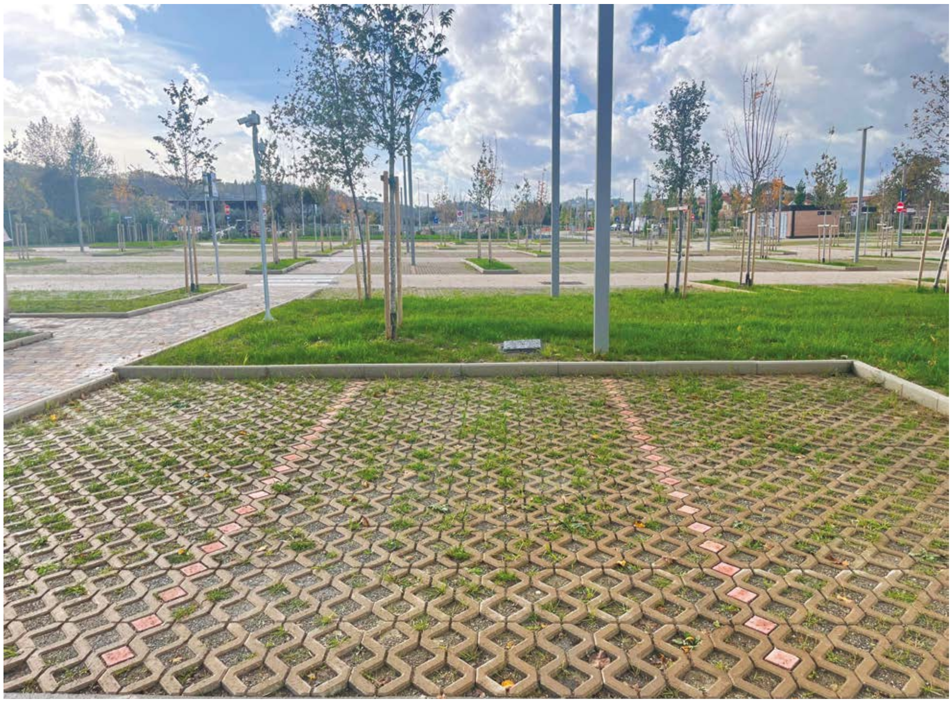

Fig. 7 – Example of vegetated permeable pavements in a parking lot in Florence, Italy (Source: Hasanaj 2025).

Description

Vegetated permeable pavements represent a specific type of filtering surface belonging to the broader group of pervious pavements, designed for the sustainable management of stormwater and the enhancement of urban resilience (World Bank 2021). These solutions are designed to allow rainwater infiltration through the surface and its subsequent percolation into the underlying soil, thereby contributing to the reduction of surface runoff and the improvement of water quality (Musco et al. 2018).

The structure of vegetated permeable pavements generally consists of prefabricated modular elements, such as concrete grass grids or reinforced plastic gratings, which contain voids that facilitate water infiltration and support vegetation growth (Woods-Ballard et al. 2015).

The vegetative component, integrated within the surface layer, enhances infiltration, absorption, and evaporative cooling capacity, while improving the ecological quality and microclimatic conditions of urban environments (Musco et al. 2018; Bono et al. 2020).

Vegetated permeable pavements are mainly applied in low-traffic areas, such as car parks, residential driveways, cycle paths, and pedestrian zones. To ensure long-term performance, design considerations must include adequate sunlight exposure and vegetation resistance to mechanical stress, since insufficient light, repetitive wheel loading, and heat radiation can impair grass growth and solution functionality (Woods-Ballard et al. 2015).

Synonyms

Vegetated permeable pavements; vegetated grid paves

Section B – Technical Details

Implementation conditions

The implementation of vegetated permeable pavements depends on the application context, environmental constraints, and site conditions, with reference to traffic intensity and soil characteristics. These systems are particularly effective in contexts characterised by moderate structural loads and are designed as alternatives to traditional impermeable surfaces, without requiring additional space for their installation. They can be integrated both into new urban developments and into projects involving the regeneration or replacement of existing pavements (Bono et al. 2020).

For proper design, it is essential to analyse the geological and hydrological characteristics of the native soil, with particular attention to permeability (Bono et al. 2020). Specifically, in clayey soils, a sub-surface drainage system (underdrain) is required to allow runoff to the stormwater network. In sandy soils, by contrast, the infiltration capacity is generally sufficient (Iwaszuk et al. 2019).

Vegetated permeable pavements are also suitable for flat terrain, provided that the surface layer is appropriately configured to ensure efficient capture and conveyance of stormwater (Bono et al. 2020; Woods-Ballard et al. 2015). Recommended installation conditions include a slope of less than 5%, and the absence of sensitive elements such as wells within 30 m, foundations within 3 m, or groundwater tables less than 1,2 m below the laying surface. Installation is also discouraged in the proximity of potentially contaminating sources such as fuel stations (Iwaszuk et al. 2019).

In areas subject to groundwater contamination risk or slope instability, it is possible to waterproof the pavement base layer to enable the retention and controlled treatment of stormwater before discharge to designated drainage points (Bono et al. 2020).

In car parks with high daytime usage, vegetation growth may be limited by reduced sunlight and heat radiated from parked vehicles. In such cases, it is advisable to replace the vegetated infill with gravel or inert aggregates to ensure surface stability and permeability (Bono et al. 2020; Musco et al. 2018).

Design features

The design of vegetated permeable pavements must combine hydraulic functionality, structural capacity, and ecological value. From a construction perspective, the solution is composed of the following functional layers: i) surface layer, consisting of modular elements made of concrete, reinforced plastic, or natural materials, designed with voids or cavities that facilitate water infiltration and allow vegetation to establish within the pavement structure; ii) base layer of gravel, which serves a dual function: providing structural support and acting as a temporary reservoir for infiltrated rainwater (its thickness varies according to the expected loads and the site's hydraulic requirements); iii) sub-base or natural soil, which promotes percolation and infiltration of water into the subsoil (in low-permeability soils, drainage pipes may be installed to channel water towards the stormwater network and prevent stagnation); iv) an optional geotextile filter layer may be placed between the gravel base and the underlying soil, serving to prevent the migration of fine particles and reduce the risk of clogging, thereby ensuring the long-term efficiency of the system (Woods-Ballard et al. 2015).

In grass-grid or resin-reinforced systems, the surface layer provides limited structural contribution; therefore, the thickness of the sub-base must be determined according to road pavement design criteria, based on the expected loads (Woods-Ballard et al. 2015; Bono et al. 2020).

The design must include an estimation of the volume of stormwater that the pavement will need to absorb. Considering the gradual reduction in permeability over time due to pore clogging, it is recommended to apply a long-term permeability reduction factor (Bono et al. 2020).

Permeable pavements can also drain water from adjacent impermeable surfaces, such as roofs or other paved areas; however, to avoid premature clogging, it is advisable to maintain a maximum ratio of 2:1 between drained impermeable surface and permeable surface. To ensure the hydraulic safety of the system, integration with an overflow or emergency drainage system is also recommended (Bono et al. 2020).

Maintenance

Regular and preventive maintenance is essential to ensure the durability, hydraulic functionality, and ecological performance of vegetated permeable pavements.

The surfaces should undergo periodic inspections to ensure they are free from sediments, debris, and waste, and to verify that the system allows effective drainage between successive rainfall events (Bono et al. 2020; Woods-Ballard et al. 2015).

Periodic vacuuming and brushing operations must be scheduled to remove fine sediments and restore infiltration capacity. Such maintenance is generally recommended every three to four years (Bono et al. 2020).

Surface clogging may occur due to the accumulation of sediments carried by runoff or vehicle loads, leading to a gradual reduction in infiltration capacity (Bono et al. 2020). It is therefore crucial to implement preventive measures and sediment source control strategies to preserve the system's hydraulic performance over time.

Planned and continuous maintenance helps extend the service life of the pavement and ensures its effectiveness as a green urban solution, contributing to the hydraulic and climatic resilience of the urban environment.

Section C – Societal Challenges

Biodiversity enhancement

Vegetated pervious pavements offer an ecologically valuable alternative to conventional impermeable urban infrastructure. As Bonthoux et al. (2019) demonstrate in their study of street-level biodiversity in Blois, France, street margins and pavement cracks, when allowed to support spontaneous vegetation, become unexpected hotspots of plant diversity. Over 300 plant species, including many natives, were recorded across just 48 kilometres of urban streets, representing approximately 20% of the region's flora. These findings underline the ecological potential of pervious pavements that allow for plant colonisation, particularly in low-maintenance or peripheral urban zones. By shifting urban management practices - such as reducing herbicide use and incorporating design elements that support spontaneous greening - vegetated pavements can actively promote biodiversity, enhance ecological connectivity, and encourage a more resilient and environmentally integrated cityscape.

Climate Resilience and Water management

The adoption of vegetated permeable pavements, integrated into broader green infrastructure strategies, represents an effective solution for mitigating urban flood risk. By enhancing the absorption of stormwater and limiting surface runoff, these solutions strengthen urban resilience and reduce the impacts of extreme events on communities. A study conducted in Humboldt Park, Chicago, demonstrated that the combined use of bioswales and permeable pavements led to a 61% reduction in total stormwater runoff, decreasing pressure on sewer networks and lowering the number of people exposed to flood-related damage (Zachary Bean et al. 2007).

Permeable pavements allow rainfall to infiltrate into the soil, helping to moderate peak flows through temporary storage within the underlying layers and subsequent controlled release. This capacity, confirmed by full-scale urban experiments, makes such surfaces a technically reliable component of sustainable urban drainage systems, with additional positive effects on groundwater recharge (Marchioni and Becciu 2015; Bono et al. 2020; Woods-Ballard et al. 2015).

Beyond hydraulic management, high-permeability pavements offer further environmental benefits. Vegetated surfaces and filtering layers improve the quality of stormwater runoff by trapping suspended solids and heavy metals, while the use of permeable materials and grassed grids contributes to lowering surface temperatures, enhancing urban cooling, and mitigating the urban heat island effect (Musco et al. 2018).

Health, well-being and air quality

Vegetated permeable pavements can play an important role in enhancing public health and overall well-being within urban environments. By increasing the presence of green and blue elements in cities, these systems help create more pleasant, restorative, and thermally comfortable spaces. The combination of permeable materials and vegetation not only supports natural rainwater infiltration - reducing runoff and contributing to groundwater recharge (Fletcher et al. 2015) - but also improves local microclimatic conditions, helping to lower surface temperatures and mitigate heat stress, a factor closely linked to human health.

Incorporating vegetated permeable pavements into urban design enriches biodiversity and strengthens ecological quality, providing residents with greater exposure to natural elements known to reduce stress, enhance psychological well-being, and encourage outdoor physical activity. By expanding interconnected networks of green and blue spaces, these pavements ultimately contribute to healthier, more resilient, and more livable urban environments (Gill et al. 2007).

Vegetated permeable pavements have been shown to enhance pro-environmental behaviour among urban residents by increasing awareness and engagement with sustainable water management practices. These pavements not only provide tangible environmental benefits, such as reducing stormwater runoff and improving urban greenery, but also serve as visible demonstrations of eco-friendly infrastructure, thereby fostering a stronger environmental ethic in local communities (Sanicola, 2018).

Furthermore, when integrated within green infrastructure networks and accompanied by educational initiatives, permeable pavements can encourage citizens to adopt more sustainable habits, including water conservation and support for urban biodiversity (Zhou et al. 2018). Such interventions contribute to building a culture of environmental stewardship essential for urban sustainability and resilience.

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Research result and open perspective

Roberto Bologna, Anna Lambertini, Luca Solari

The NbS paradigm

Reinterpreting the role, presence, and meaning of nature in cities constitutes, today more than ever, an essential research topic for those involved in architectural, landscape, and urban planning and design. This book aimed to explore it by connecting different disciplinary perspectives and approaches.

The concepts of «urban biodiversity» and Nature-based Solutions were placed at the center of an interdisciplinary exchange of ideas, critical reflections and research applications, collected in the first two sections of the volume. Furthermore, the Nature-based Solutions paradigm guided the creation of the probably most innovative part of the research, which aimed to set 'a toolbox' useful for local authorities and described in the third section.

As it is demonstrated by an increasingly substantial scientific literature, Nature-based Solutions (NbS) in fact are considered internationally as key strategic actions for implementing environmental governance processes that address, at the local level and particularly in urbanized territories, the challenge of ecological transition.

However, the urban and architectural redevelopment project is a complex issue that must take into account the multiplicity of aspects that a public administration must manage to guarantee the population the protection of rights, widespread well-being and the quality of the delivered services.

The application of naturalization projects of urban areas, therefore, must deal with issues relating to urban mobility, technological network infrastructures, existing and newly built plant systems precisely with a view to the green energy transition, the provision of cultural and social services, the citizens housing, the workplaces, the usability of green spaces and areas and everything that, in short, constitutes the essence of an urban settlement.

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Urban green structures are crucial landscape elements for the promotion and conservation of biodiversity in ever-growing urban areas. To achieve this objective, it is necessary to act through balanced planning and integrated adaptive management of open spaces, which reflects the development of a green matrix of multipurpose habitats.

This consideration suggests evaluating interventions on the natural component of urban elements (NbS) within a framework of objectives that a municipality must plan based on specific needs and priorities identified in such a way that divergences in effects or ineffectiveness of the interventions are not created.

When proposing the inclusion of NbS in an urban context, it will therefore be necessary to evaluate not only their effectiveness in terms of landscape and energy-environmental sustainability, with a view to mitigating the urban heat islands, controlling and reducing the effects of climate change, but also their compatibility and coherence, both on an economic and functional level, with the overall programme of interventions that the municipality is required to develop.

Some issues in particular are deemed relevant to make these interventions feasible and operational:

- develop site-specific and place-based projects and processes, which take into account the environmental and ecological local conditions, but also the different historical and cultural characteristics, specific heritage values, and peculiar socio-symbolic dimensions;
- dialogue with municipal administrations to develop suitable tools for the management of new urban districts from an LCA and LCCA perspective closely connected to the circular economy and the possibility of rational, thermodynamic exploitation of renewable energy;
- detect and interpret the needs of users and administrators to develop urban regeneration projects based on a systemic approach aimed at creating sustainable, pleasant, inclusive and safe multifunctional public open spaces;
- build predictive scenarios, through the use of dedicated software, according to a Multi Hazard Risk Assessment criterion, which takes into account the specific environmental and energy parameters of each individual intervention.

Urban Nature: Interpreting, Measuring, Managing

Main findings of the research are related to a variety of aspects related to both theoretical, methodological and instrumental approaches for urban regeneration through nature.

Regarding the theoretical framework, the research highlights that, since the 19th century, urbanisation has drastically altered ecological balances, creating cities that consume and fragment natural habitats. This has led to biodiversity loss, climate vulnerability, and degraded living conditions, prompting a transformation in urban planning. Integrating nature into cities is now essential to restore ecological functions and support human well-being and resilience.

Early visions, such as Ebenezer Howard's Garden City model or as the Boston Park System conceived by F.L. Olmsted, proposed parks, green belts, and self-contained neighbourhoods where natural processes and settlement could coexist. Today, internationally, in many urban areas the scarcity of green spaces intensifies the impacts of climate change and accelerates the decline of biodiversity.

NbS have thus become crucial, offering a holistic approach to urban regeneration by protecting, restoring, and creating ecosystems. Often implemented as hybrid solutions, NbS contribute to climate regulation, air purification, water management, and mental well-being.

In this context, Landscape architecture can play a pivotal role in favor of ecological transition, as demonstrated by a broad and heterogeneous international scenery of plans, projects, and interventions recognized as promising good practices.

Landscape architecture interprets cities as living systems, in which the well-planned and managed collection of diverse open spaces –including public and private, permeable and impermeable, historic or recently built, well-maintained and abandoned ones-forms an essential network for biodiversity. These spaces host ecological processes beyond human functions.

Starting from a reworking of the NbS paradigm, the concept of Landscape-Based Solutions is launched, which invites us to move from a mere 'green' paradigm towards systemic networks of open spaces that operate at multiple scales and time intervals, integrating ecological, historical, aesthetic and socio-symbolic dimensions.

This perspective aligns with the *UNESCO 2011 Recommendation on Historic Urban Landscape* (HUL) and the *European Landscape Convention*, which advocate for integrating natural and cultural values in planning.

In addition to that, historic gardens and archaeological sites (such as Florence's Oltrarno system with the Boboli and Bardini Gardens), illustrate how heritage spaces can function as ecological corridors while revealing the history of urban landscapes. Dynamic conservation in these contexts requires interdisciplinary strategies that combine archival research, climatic data, and active biodiversity management to address challenges like plant pathogens and climate change.

Urban biodiversity is thus a multi-layered concept embracing genetic, species, and ecosystem diversity. Contrary to stereotypes, cities can become biodiversity hotspots if properly planned. Urban forests, green roofs, wetlands, and spontaneous vegetation patches contribute to ecological connectivity and resilience, particularly when they feature diverse species and structures. Vacant or unmanaged spaces may serve as wildlife refuges, though they require monitoring to prevent invasive species.

NbS can also represent a powerful tool to address water security challenges (such as water availability, flood risk, water quality aspects) also considering climate change which is typically increasing extreme events in both floods and droughts worldwide. NbS can thus constitute a significant evolution toward comprehensive, adaptive, and sustainable responses to the growing complexity of global water challenges.

However, substantial challenges remain, including fragmented responsibilities and difficulty in implementing integrated, measurable, and effective actions. Despite the comprehensive European and national regulatory frameworks, including the *EU Biodiversity Strategy 2030* and the *Nature Restoration Law*, Italian local policies remain fragmented and largely declaratory. Urban plans often lack operational tools, monitoring indicators, and coherent integration of biodiversity as a central infrastructure. The text calls for stronger alignment between global, European, and local policies, with more robust planning, monitoring, and civic engagement to fully embed urban biodiversity within the ecological transition.

Another useful interpretative key provided in the framework of research to critically reread the NbS paradigm, proposes an evolution of it in terms of Nature and Culture-based Solutions (NCbS), to put together ecological, social, and cultural dimensions.

This shift from a purely technocratic notion of ecological transition towards ecological conversion reflects a deeper commitment to care, reciprocity, and co-evolution between humans and nature. NCbS extend beyond technical interventions, embedding themselves within the cultural and ethical fabric of cities, to create ecosystems of shared responsibility and stewardship. The implementation of NCbS requires governance systems that are collaborative, adaptive, and multi-level. Co-production among public institutions, private stakeholders, civic organisations, and local communities facilitates the creation of eco-cultural commons and fosters long-term community engagement. Iterative processes of monitoring, feedback, and learning ensure that urban interventions remain responsive to changing environmental and social conditions. Hybrid governance structures help overcome administrative silos and enhance urban resilience, while integrated planning embeds NCBS into city structures through green-blue networks, systemic visions, and ecological standards. Complementary regulatory and financial tools, such as fiscal incentives, green bonds, and Payments for Ecosystem Services, expand the feasibility of these approaches.

Participatory instruments, including citizen science, collaboration pacts, and community monitoring, sustain ecological citizenship and moral responsibility across generations. In this context, Landscape planning and Urban design play a critical role in translating these principles into practice. Every landscape project functions as a methodical sequence, shaping a transformation process that expresses spatial, ecological, perceptual, and semantic relationships. Contemporary planning focuses on reconnecting fragmented urban spaces, enhancing biodiversity, and re-establishing connective ecological tissues. The Green and Blue Infrastructure model exemplifies this trend, providing an integrated framework for designing and managing urbanised territories in ways that advance thermal comfort, resource efficiency, and climate adaptation.

Innovative methodologies, such as thermodynamics-informed urban analysis, support the quantification of energy-environmental sustainability. By integrating applied physics, high-resolution climate modelling, and detailed vegetation characterisation, urban designers can identify priority areas for intervention, assess trade-offs, and optimise the benefits of NCbS. This scientific approach demonstrates that urban greenery reduces air enthalpy, mitigates the heat island effect, and lowers cooling energy demands, contributing directly to citizens' health and well-being.

The urgency of adopting such strategies is underscored by the environmental crises confronting cities: climate change, biodiversity loss, and resource depletion. Urban areas, which consume the majority of global energy and resources, face a moral imperative to transition from extractive, linear models of development towards regenerative and circular urbanism. Circular urban regeneration aligns ecological, spatial, and social dimensions to create adaptive, self-sustaining systems. Practices such as adaptive reuse, material recovery from the "urban mine," and flexible design enable cities to evolve while reducing emissions and preserving ecological value. Case studies such as Emscher Park, Lyon Confluence, and Berlin's North-South Green Corridor illustrate the diversity of approaches to integrating biodiversity, resilience, and human well-being. These examples reveal that no single model is universally applicable; effective solutions require transdisciplinary collaboration, context-sensitive strategies, and active community engagement.

Public Engagement (PE) emerges as a central pillar in the success of NCBS. Co-creation, co-governance, and participatory tools reconnect citizens with their urban ecosystems, bridging the gap between policy, research, and lived experience. Initiatives such as Florence's "Code4Risk" embody this ethos, linking climate adaptation and disaster risk reduction with urban liveability through workshops, installations, and serious games. Urban Living Labs provide further platforms for collaborative experimentation, where moral and material citizenship are nurtured in the pursuit of sustainable transformation.

Tools to apply

The application tools of the research (Part 3) includes the NbS CataTool, specifically developed within National Biodiversity Future Center (NBFC), as a digital Decision Support System (DSS) designed to promote the adoption of NbS in the Mediterranean context. Integrating scientific research, innovation, and practical applications, it serves as a cornerstone for biodiversity-focused sustainable development and aligns with European strategies like the *Nature Restoration Regulation*. The CataTool offers three core functionalities that bridge knowledge and practice. First, the NbS Selection Tool guides users through a four-step process: defining the type of intervention (protect, restore, or create), selecting the domain (urban, terrestrial, or marine), identifying the implementation area, and choosing societal challenges to address. Second, the Learning Tool enables free exploration of a structured NbS taxonomy, fostering education, co-design, and citizen participation. Third, the Case Study Finder provides a georeferenced database of over 100 national examples, each accompanied by synthetic cards, detailed sheets, and monitoring data, offering decision-makers evidence-based insights for restoration and resilience initiatives. The CataTool's integration of ecological data, evaluation scores for 12 global societal challenges, and practical guidance makes it a unique resource for urban planners, environmental managers, and policymakers. By mainstreaming NbS, it accelerates ecological transition and supports sustainable territorial governance.

Furthermore, the research illustrates that NbS address a spectrum of urban and environmental challenges, from heat islands to water scarcity. In cities, building-integrated solutions like extensive green roofs (EGRs) provide ecological, climatic, and social benefits. EGRs are lightweight, low-cost systems with shallow substrates supporting mosses, sedums, and stress-tolerant plants. They deliver thermal and acoustic insulation, mitigate stormwater runoff, reduce urban heat islands, and support biodiversity. Their maintenance requires only periodic inspections, weed control, and occasional irrigation during droughts. When combined with renewable energy systems, such as photovoltaic panels, EGRs enhance energy efficiency and climate resilience, while also improving visual comfort and human wellbeing. Beyond buildings, urban forestry and vegetation-based NbS strengthen ecological connectivity and urban resilience; large-scale afforestation projects create multifunctional forest ecosystems in urban and peri-urban areas, offering carbon sequestration, stormwater regulation, and recreational opportunities; tree rows and hedgerows mitigate habitat fragmentation, provide corridors for wildlife, and enhance microclimatic regulation; vegetation clusters and flower meadows foster biodiversity, enrich soil health, and deliver aesthetic and psychological benefits to urban communities. These small- and large-scale interventions together form living infrastructure that integrates nature into the urban fabric.

Water management represents another critical domain for NbS. Climate change and human pressures exacerbate both water quantity and water quality challenges: floods, droughts, and pollution increasingly threaten ecosystems and human settlements. NbS address these through Natural Water Retention Measures (NWRM) and hydrological interventions that restore ecosystem functionality while providing societal co-benefits. Riverscape NbS enhance flood and drought resilience by storing water, attenuating peak flows, and improving riverine biodiversity. They create heterogeneous ecotones that connect urban, peri-urban, and rural landscapes, reinforcing ecological corridors. Complementary to these, Sustainable Drainage Systems (SuDS) manage urban runoff by fostering infiltration, storage, and reuse, contributing to the "sponge city" model. Vegetated wetlands within SuDS trap pollutants, reduce nutrient loads, and provide rich habitats for aquatic life. Together, riverscape NbS and SuDS demonstrate how integrating green and grey infrastructure can simultaneously protect water resources and restore ecological functionality.

Towards a transdisciplinary research project

Transdisciplinarity can be understood as a collaborative, participatory, and interactive approach that aims to understand and comprehend complex problems and find ways to address critical issues. The transdisciplinary approach requires the involvement of academic and non-academic actors.

A transdisciplinary research project therefore implies that different stakeholders – scholars, practitioners, public administrations, citizens etc. - collaboratively co-produce knowledge to address a challenge.

Starting from these premises, the contributions collected in this volume and briefly recalled in this closing chapter, open to subsequent explorations in a more strongly transdisciplinary perspective.

And this even considering that the 'nature' of the concepts of Urban Biodiversity and Nature-based Solutions is markedly transgressive of the disciplinary and sectoral limits.

From this perspective, among the possible developments that the 'Nature and City' research project could have, the following stand out:

- Development of a common working glossary, to reposition key concepts, research words, and neologisms in order to create new knowledge through creative cross-fertilization between different approaches and specialized languages;
- Activation of Urban Nature Living Labs in collaboration with public administrations and local authorities, aimed at applying the NbS catalogue tools to specific urban redevelopment plans and projects involving citizens;
- Implementation of new Landscape-Approach in the contents of the cata-tools;
- Development of Natural/Cultural-based Solutions and Landscape-based Solutions catalogs considering a qualitative-quantitative approach to the NbS device;
- Integration of further skills and competences for reading and evaluating the potential benefits of NbS in relation to economic, ecological-qualitative, and socio-health aspects.

These are just some of the possible open trajectories to explore: thus moving - with 'natural inclination' - from the early stages reached towards a closer collaboration between research and practice on NBS as a process of crossing disciplinary boundaries.

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