Augmented Nature-Based Solutions: A Possible Taxonomy of Technologies "in" and "for" Urban Greening Strategies

Israa Mahmoud, Eugenio Morello, Adriano Bisello, and Dionysia Kolokotsa

Abstract The conceptualization and application of nature-based solutions (NBS) in the practice of planning and projects on urban and architectural scales have reached a level of maturity in the last 10 years, thanks to a strong push from European policies and funding for European projects and evidence from scientific literature. However, a systemic insight into the role of technology in supporting the spread of NBS has not yet been developed. The role of technology is understood here as fundamental to the very core concept of NBS, i.e., engineering solutions that integrate technological aspects to effectively increase nature's potential. The authors, therefore, propose an investigation into the various opportunities offered by technology integrated "**into**" greenery and used "**for**" promoting greenery, based on the experience of two European Horizon 2020 projects, CLEVER Cities and VARCITIES, and from the application cases presented during the dedicated track at the SSPCR 2022 conference.

Keywords Nature-based solutions · Green technologies · Co-monitoring · Citizen science · Citizen participation · Internet of nature

I. Mahmoud (✉) · E. Morello
Laboratorio di Simulazione Urbana Fausto Curti, Department of Architecture and Urban Studies (DAStU), Politecnico di Milano, 20133 Milan, Italy
e-mail: israa.mahmoud@polimi.it

A. Bisello (✉)
Institute for Renewable Energy, Eurac Research, 39100 Bolzano/Bozen, Italy
e-mail: adriano.bisello@eurac.edu

D. Kolokotsa
Chemical and Environmental Engineering School, Technical University of Crete Kounoupidiana, 73100 Chania, Crete, Greece

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1 Introduction

The discipline of implementing Nature-Based Solutions (NBS) at architectural, urban planning, and landscape levels is supported by numerous experiences and several European projects and case studies (Bulkeley 2020; European Commission 2020). The concept of NBS is based on green or blue engineering solutions that replace more traditional gray solutions. The presence of technology in NBS is, therefore intrinsic and fundamental, no matter how low or high-tech this technology is (Andersson et al. 2022). Technology is directly embedded in NBS or applied as an essential component of all technological NBS generally. With NBS, nature is, in fact, "augmented" using technology to improve performance and increase the co-benefits of nature itself in the built environment.

Recent literature on NBS shows a strong interest in possible demonstrations and applications with a technologically embedded approach towards better solutions implementation (Tsekeri et al. 2022; Scheuer et al. 2022; Wellmann et al. 2022). Lately, technologies related to the possible integration of NBS into urban planning are coming to light towards execution scopes in order to increase the environmental performance and social impact of NBS.

However, a systemic insight into the role of technology in supporting the spread of NBS has not yet been conducted (Ahlborg et al. 2019). In this paper, a new proposed NBS taxonomy based on the technology-nature relationship is presented, supported by an extensive overview of the implementation of various technologies within case-study settings of NBS in urban greening strategies and European projects.

The proposed taxonomy is discussed from a twofold perspective: technology embedded "**in**" green, and technology "**for**" supporting the flourishing of green in the built environment, i.e., applied externally to NBS. In particular, the following explorations around technology in and for NBS are significant:

1. **Technology in Green**: Embedding technologies inside NBS aims at increasing its environmental performance and social impact; for instance, environmental sensors measuring the health of nature and linked environmental aspects in the surroundings; urban displays and communication interfaces for people to communicate relevant messages; sensors for co-monitoring campaigns as part of citizen science activities around urban greening activities.
2. **Technology for Green**: outside and beyond NBS per se, technologies can be applied to enhance the widespread presence and impact of NBS in the built environment; for instance, ICT can be used to engage citizens in co-producing (co-design, co-implementation activities) and taking care of green spaces (co-maintenance, co-monitoring activities), thus generating a stronger sense of belonging and social bond within communities, with emphasis on the inclusion of marginalized and vulnerable groups. Moreover, mapping technologies such as remote sensing and LiDAR applied to urban green, can support monitoring overall progress towards greener cities (Ahmed et al. 2019; Ramzan et al. 2021), contributing to assessing the global targets of the UN 2030 Agenda at the local scale (e.g., localizing SDGs in cities), see (Breuer et al. 2022; Mahmoud et al. 2022).

2 Context: European Projects and a Dedicated Conference Track

This paper originates from an investigation into several applications of NBS in real settings, where we looked explicitly for scientific methods and innovative products and services to enhance the potential of NBS in urban contexts while using technology. An initial literature review on the analysis of "Technology" and "Nature-based Solutions" was carried out in Scopus,[1] whereas 259 articles and scientific products have resulted more prominent since 2016, with a noticeable peak in the years 2021 and 2022.

In addition, our sampling was increased by the session at the Smart and Sustainable Planning for Cities and Regions Conference[2] (SSPCR 2022) held in July 2022, where the contributions and discussions offered "food for thought" for the content of this paper. The research questions are related to the main session topic on Augmented Nature-based solutions in urban planning and embedded technologies to improve NBS performance and foster social inclusion in urban greening strategies. In contrast, scientific contributions came from different countries, mainly: Italy, Spain, Austria, and Germany. Lastly, we relied on the ongoing application of two European Projects funded by the Horizon 2020 Programme to consolidate the proposed taxonomy, namely CLEVER Cities and VARCITIES, in which the authors are currently involved in.

The CLEVER Cities[3] project (June 2018–September 2023) aims to co-create, co-design, co-implement, and co-manage locally tailored NBS to deliver tangible social, environmental, and economic improvements for urban regeneration. It gathers 36 international partners and involves three front-runner cities (Hamburg, Germany, London, United Kingdom, and Milan, Italy) and six fellow cities (Madrid, Larissa, Belgrade, Malmo, Quito, Sfantu Gheorghe). CLEVER Cities applies a place-based approach, starting with key urban regeneration challenges and employs strong local partner clusters to foster sustainable and socially inclusive urban regeneration locally, in Europe, and globally. The CLEVER Cities project co-creates, co-designs, co-implements, and co-manages locally tailored NBS to deliver tangible social, environmental, and economic improvements for large-scale urban regeneration processes. Particular attention in the implementation of NBS within CLEVER Cities is given to shared governance mechanisms and collaborative pathways of co-creation aimed at advancing the cities' adaptation to a more bottom-up approach to urban planning (Borsboom-Van Beurden et al. 2023; Bradley et al. 2022; Mahmoud and Morello 2021).

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[1] https://www.scopus.com/results/results.uri?sort=plf-f&src=s&sid=197ad86419648a8651cca486de4deeeb&sot=a&sdt=a&sl=56&s=TITLE-ABS-KEY%28%22technology%22+AND+%22nature-based+solutions%22%29&origin=searchadvanced&editSaveSearch=&txGid=c1ef373d55fd60c8742f163143abbd87.

[2] https://www.sspcr.eurac.edu/session-augmented-nature-based-solutions-or-cities/.

[3] https://cordis.europa.eu/project/id/776604.

The VARCITIES project[4] (September 2020–February 2025) bridges the NBS approach traditionally characterized by low-tech solutions devoted to enhancing environmental quality with high-tech devices more familiar with the smart city approach to increase the health and well-being of citizens around Europe. It gathers 28 international partners and involves seven pilot cities (Castelfranco Veneto—Italy, Gzira—Malta, Skellefteå—Sweden, Novo Mesto—Slovenia, Dundalk—Ireland, Chania—Greece and Leuven—Belgium) willing to test and implement a series of innovative initiatives on urban green/public spaces. Digitally advanced NBS are therefore implemented through a co-design, co-creation, and co-implementation process, bearing in mind local stakeholders' social and cultural perspectives. Urban spaces are envisioned as people-centered areas that support creativity, inclusivity, health, and happiness for citizens.

3 Technology "in" Green and Technology "for" Green: The Proposal for a New Taxonomy for Augmented Nature-Based Solutions

Initial understanding of the technology "**in**" green urban strategies topic includes different types of sensors that could be used to measure the NBS health status or remote sensing methods to enhance ecosystem services delivery in people's everyday lives (Li and Nassauer 2021). Gudowsky and Peissl (2016, pp. 5–6) highlight the importance of technology in corresponding citizens' visions and social needs by using it as a support and catalyst for change in public engagement processes. In the meantime, Maes and Jacobs (2017, p. 123) call for the need to use NBS with low-technological impact to increase the social empowerment of local communities.

Meanwhile, understanding of the technology "**for**" green urban strategies topic incorporates all the technological support to enhance NBS functionality, durability, and diffusion (Dick et al. 2020). Among others, technologies for green include the use of digital platforms and efficient software to visualize, analyze, and integrate data for NBS deployment in urban planning, such as drones and GIS modeling and mapping methods (Rakha et al. 2021). For instance, recent developments in technology and integration into the human-built environment could help develop the redesign of certain NBS and green infrastructures while increasing their co-benefits and improving ecosystem services (O'Hogain and McCarton 2018). This broad concept is related to the diversity in scales of implemented NBS. Nonetheless, some scholars argue that even "low-tech" or "no-tech" green—also considered as traditional urban greening measures—would still need data elaboration, especially if it relates to vegetation performance against natural and water management capacities to enhance the possibility for urban planners, architects, and landscape designers to reclaim valuable urban spaces correctly (Snep et al. 2020).

[4] https://cordis.europa.eu/project/id/869505.

Based on this ideation, the resulting taxonomy for Augmented NBS with technologies "**in**" and "**for**" green is divided into two main subcategories: sensing with technologies and citizen engagement methods. Other technological aspects are also related to NBS, like structural technologies that sustain and support nature. However, in this taxonomy, we only focus on those technologies that help to give nature a voice and enhance it through sensors or collaboration with people.

On one side, sensing "**in**" green refers to all the technologies directly embedded in NBS to detect the health of natural elements or surrounding environmental aspects (e.g., air, water, soil). On the contrary, sensing "**for**" refers to all the technologies that are situated outside the NBS, hence remote sensing devices (mounted on drones, satellites to collect LiDAR, thermal data, and similar technology) to monitor the health of natural NBS performance.

On the other side, citizen engagement "**in**" green refers to technologies placed inside or around NBS that directly involve human activities in detecting, mapping, and assessing the direct social impact of people on nature or the environmental impact of nature on people. Detaching ourselves from NBS, the engagement of people "**for**" green, i.e., to promote urban nature, is undoubtedly very vast and can take place in a variety of ways: from low-cost technologies, such as participation models and protocols (from co-design and co-maintenance) of greenery, to more advanced technologies to facilitate collaboration in the creation of NBS (digital fabrication, applications and social media, wearable technologies, etc.).

A further category that structures the taxonomy refers to the phase in which the technologies are employed, i.e., in the planning, design, construction or monitoring and evaluation (M&E) of NBS. This categorization is important to understand the planning phase of technologies themselves and the duration of their use in relation to NBS. The last category refers to the low-tech or high-tech level of technology as considered its readiness level.

Table 1 summarizes the above-mentioned categories, enriched with references to tangible examples from research and practice to emphasize the importance of technology in different phases of urban planning.

Table 1 Taxonomy of Augmented NBS illustrating technologies "**in**" and "**for**" green with practical examples and throughout urban planning and management phases coupled with technology readiness level

Possible Taxonomy for NBS implementations and examples			Phases of urban planning and management			Technology readiness level	
Technology in Green		**Examples**	**Analysis**	**Co-design**	**M&E**	**High tech**	**Low tech**
Structural technology	3D printed hardware	CO-MIDA: [a] 3D vertical gardens hosting plants		x	x	x	
Sensing	Sensors to monitor water content and humidity	VARCITIES: humidity and air quality, water, and snow level	x	x	x	x	
	Sensors for weather micro-climate and noise	VARCITIES: monitored by static/bike mounted/rover mounted sensors	x		x	x	
	Sensors for measuring the production of biological photovoltaics	CO-MIDA: [a] Bio-Photovoltaic System producing energy from bacteria	x		x	x	
	Wearable for plants	(Li et al. 2021): monitoring of plant stresses via chemiresistive profiling of leaf volatiles	x		x	x	
Technology for Green		**Examples**	**Analysis**	**Co-design**	**M&E**	**High tech**	**Low tech**
Remote sensing	GIS and LiDAR	RENATURE, VARCITIES: mapping vegetation and vegetation health	x	x	x		
	Drones for ecosystem services	VARCITIES Green modelling and mapping	x		x	x	
	Platforms for digitalization	Nature Quant: [b] Nature Score	x		x	x	

(continued)

Table 1 (continued)

Possible Taxonomy for NBS implementations and examples			Phases of urban planning and management			Technology readiness level	
Technology in Green		**Examples**	**Analysis**	**Co-design**	**M&E**	**High tech**	**Low tech**
		VARCITIES: Health and Well-being online platform	x		x	x	
	Sensors embedded in urban furniture and digital displays	Participate Melbourne: [c] social spaces and benches	x		x	x	
		VARCITIES: interactive totem with touch screen and multiple services					
		VARCITIES: smart benches					
Citizen engagement	Mobile applications	VARCITIES: Planet App		x	x		x
	Augmented Reality, Virtual Reality	VARCITIES: Wearables	x	x		x	
	Protocols of (digital) citizen engagement	VARCITIES: Gamification	x	x	x	x	
		CLEVER Cities: DIPAS	x	x	x	x	
		CLEVER Cities: Co-mapping urban NBS contest	x		x	x	
		VARCITIES: NBS impact appreciation, SROI calculation	x	x	x	x	
	Social media and smart devices	Nature Quant: [d] Nature doses		x	x	x	
		I Naturalist [e]	x		x	x	

(continued)

Table 1 (continued)

Possible Taxonomy for NBS implementations and examples			Phases of urban planning and management			Technology readiness level	
Technology in Green		**Examples**	**Analysis**	**Co-design**	**M&E**	**High tech**	**Low tech**
	Biodiversity mapping	CLEVER Cities: butterfly co-mapping by citizens		x	x		x
		VARCITIES: Bird species mapping	x		x		x
	NBS impact	CLEVER Cities: Social monitoring protocols	x		x		x

Source The authors

Legend: x is applicable

[a] https://iaac.net/project/co-mida-en/

[b] https://www.naturequant.com/naturescore/

[c] https://participate.melbourne.vic.gov.au/emerging-tech-testbed/social-spaces

[d] https://www.naturequant.com/naturedose/

[e] https://www.inaturalist.org/

4 Case Study and Applications from Two European Projects: VARCITIES and CLEVER Cities

Based on the above-mentioned taxonomy, we can report some examples that use similar technologies to evaluate NBS performance while using technology "in" green and "for" green.

4.1 VARCITIES Project

For instance, within the VARCITIES project, almost all demos and several partners are engaged in testing and developing technologies to achieve multiple purposes related to NBS.

Concerning the technology "in" green, it is worth mentioning that some municipalities have shown interest in exploring this concept further, moving towards a phygital solution, where the digital advanced content is made available to citizens and visitors through a physical installation. The city of Castelfranco Veneto is discussing with the project partner Eurac for the possible implementation of a totem equipped with an LCD touchscreen and audio system to be placed nearby the demo site of the historical garden of Villa Revedin Bolasco. The totem would make the activity of the VARCITIES project recognizable to citizens. For example, the explanation of scientific experiments conducted by the University of Padova on perceived restorativeness and benefits associated with exposure to nature in a garden (Sella et al. 2023) or effects of the landscape related to physiological and environmental parameters (Pirotti et al. 2022) would be accessible to non-experts and thus contribute to sharing the main results with adults and children. It would also serve cyclists and provide a charging point for smartphones and e-bikes, encouraging sustainable tourism and access to digital services. Moreover, it would show data coming from the H&WB platform (described in the next paragraph), adjusted for a better user experience considering the different framework conditions (larger screen, open-air location, specificity of the site), integrated with local info on touristic amenities and activities, and possible additional services or gamification tools. Similar installations have been already tested in smart city projects, e.g., the Sinfonia project in Bolzano—IT, see Grilli et al. (2018), but so far have never been conceived to interact with NBS or activities.

All pilot cities in VARCITIES are going to equip the demo sites with a large variety of IoT sensors, including wearable ones, according to the specific aim of some scientific experiments or the intention to monitor and report local environmental characteristics or users' habits and performance. For example, in the historical garden of Villa Revedin Bolasco the University of Padova (department of Agroforestry) installed several sensors to monitor microclimate conditions in various places in the garden and equipped a small, unmanned vehicle (a so-called rover) operated either by remote control or by an integrated GNSS system to gather data on the microclimate condition related to specific places in the garden. They also used a multispectral camera or portable sensor for vegetation index estimation and terrestrial laser scanning of "healthy areas" for 3D point cloud generation and AR/VR. Some benches have been turned into "smart" ones able to record the number of users sitting there and provide data on the effectiveness of their positioning along pedestrian paths.

Within the research and development activities granted by the project, the partner Sensedge is providing some demos with an advanced version of its "Senstick", a LoRaWAN sensor designed to generate reliable and quality data in harsh indoor and outdoor environments. The Senstick already includes sensors' functionalities such as environmental parameters (air temperature, relative humidity, and pressure), solid parameters (temperature, moisture). In VARCITIES, further evolution of the Senstick will support researchers and public administrations to understand and monitor thermal comfort in cities better. Another industrial partner Cyclopolis in Greece is developing and testing an innovative sensor to be mounted on any bicycle and able to monitor the air quality during movement from one location to another and relate it to the vehicle's position. Measured parameters include Particulate Matter (PM) sized 1, 2.5, and 10 μm, as well as temperature and humidity, while a GPS tracks the location.

Finally, in the demo case of Gzira, Malta which consists of greening and the social improvement of small public spaces along today's busy streets, a citizen science campaign is taking place that involves residents in measuring and reporting air quality and wind using low-cost sensors.

Regarding the second macro category of this framework technology “for” green; a so-called Health and Well-being (H&WB) platform is going to be designed and implemented by IES. The H&WB platform will be a visualization and management tool, a nature-focused digital twin to show KPIs and live and collected data in suitable and engaging ways to different STKs through specific dashboards. It will be developed using previous experience and iPIM and iCIM cloud-based tools provided by the project partner IES. 3D models of each pilot city will be accessible on the internet. The aim is to provide the final information to be published on the platform that is understandable and engaging for everyone by maximizing interaction and usability.

The project partner DEKKA is also developing an augmented reality platform to further engage citizens by placing digital elements in physical demo spaces and enhancing the visitor experience. Visitors can use it in combination with holovision glasses and enter an innovative and rewarding user experience.

Again, in the Castelfranco Veneto pilot scheme, additional wearable sensors have also been used by volunteers involved in physiological experiments designed by the Neural science department at the University of Padova to monitor and track the changes in the brain activity of visitors and relate them to various positions in the garden, microclimate parameters and aesthetic characteristics (eye-tracker glasses and portable electroencephalogram). Moreover, some smartphones with GPS and accelerometers are available to vulnerable visitors that are also equipped with a special app designed to provide real-time information on their position in the garden and request assistance on request or automatically in the event of tripping.

Alongside the development of scientific studies, EURAC engaged citizens and stakeholders in some remote and in-person evaluation activities related to the perception of societal value delivered by the foreseen execution of such innovative initiatives: social return on investment calculation in the Castelfranco Veneto choice experiment and willingness to pay elicitation in Gzira.

4.2 CLEVER Cities Project

CLEVER Cities, on the other hand, is an EU-funded project that did not rely so much on the technological components in its initial phase of co-creation planning and setting up of an urban innovation partnership (see Mahmoud and Morello 2021). Nonetheless, the co-design and co-monitoring phases have made extensive use of technological devices to enhance green spaces to focus on citizen engagement and co-monitoring processes, in particular e-participation techniques boosted by the COVID-19 pandemic.

Technology “**in**” green was mainly carried out during the environmental monitoring phases of the project lifetime started in 2021 in two living labs in Milan (Mahmoud and Morello 2023). Technological aspects were employed in order to help the co-monitoring of NBS environmental performance starting in 2022. In one of the urban living labs in Milan—IT, the so-called CLEVER Action Lab 1 aimed at diffusing green roofs and walls city wide, sensors in a two-story green wall of a public transport company ATM-owned depot building (via Giambellino 121) were used to monitor pollutants detection on leaves (ongoing) as well as for irrigation control of plants through the irrigation system. In another example in Milan, the CLEVER Action Lab 3, a public space adjacent to the new Tibaldi-Bocconi train station thermal camera drone flights helped to map the land surface temperature of the site prior to and after greening interventions implementation.

Meanwhile, technology "**for**" green was extensively used throughout the co-designing phase of the project. For instance, in the three living labs in Milan, the use of e-participation in all co-creation phases was widely used through digital meetings, interactive digital boards, and interface repositories. In addition, digital boards and online surveys supported co-monitoring activities and guaranteed continuity and willingness to participate in the co-creation process (Mahmoud and Morello 2018). Specifically, technology was used for data collection as well as in a repository hub to monitor and evaluate the social impact of NBS on local communities using online questionnaires distributed via QR codes and newsletters (Mahmoud et al. 2021).

Another example is the DIPAS *Digitales Partizipation system*, an e-participation and decision-making support system was implemented in the municipality of Hamburg, Germany (Arlati et al. 2021). Moreover, in Milan, a digital archive was collaboratively built thanks to a public call launched by the municipality in 2022 to award the best green roof and green wall solutions. "*Premia il tuo verde*" (translated: Reward your Green) became an online collaborative mapping experience that helped the city to detect the best practices of green roofs and walls around the city.

5 Discussion and Conclusions

In this paper, we propose a taxonomy to organize and frame how NBS improve their environmental performance and social impact through technology. We, therefore, introduced the concept of "Augmented NBS" to highlight technological support in and around green measures. This technological support can take the form directly on NBS or externally to it. Research projects' experiments and products on the market already show a rich variety of solutions, mostly adopting high-tech solutions as reported in Table 1 as well. An overview of these augmented NBS opens up a series of theoretical, ethical, and practical reflections on the use of technology in nature, thus posing new challenges in the triangulation of the relationship between human, nature, and technology.

"Tech-assisted NBS" or "smart green infrastructure" is becoming trend in a growing market that focuses on combining green and high-tech solutions, and the ambition towards the combined use of natural elements and innovative technological solutions challenges cities to rethink their governance structures and practices, calling for integrated approaches and the mobilization of competencies and skills across institutional sectors (Bisello et al. 2022). Numerous examples are already on the market for outdoor and indoor NBS and products. Embedding sensors in green infrastructure, according to the concept of Internet of Nature (IoN) proposed by

Galle (2019), is adding a layer of complexity to the materialization of the digital world or, on the contrary, to the digitalization of living systems. For instance, there are many examples of capillary and widespread applications of sensors in forests (Internet of Trees, IoTr), to monitor the spread of fires, drought, and the health of trees. Hence, "technological prostheses" applied to green solutions allow us to take care of nature with greater attention and effectiveness. Technology, therefore, supports the diffusion of NBS, often criticized for their maintenance costs, given that they are living and constantly evolving solutions, unlike corresponding gray solutions. Robots for the automated maintenance of vertical and horizontal green surfaces and systems to monitor the water and humidity content of plants and soil using sensors or thermal imaging cameras are already widely used examples that testify to the mature hybridization between technology and nature. However, all this smartness is not regulated and there are no shared protocols for the collection and transmission of data collected from the plant world. This aspect opens up a debate linked to the ethical aspects of exploiting nature and to the rights of nature itself in terms of protection and treatment of data produced through the IoN. Going further, nature can enhance the production of energy, opening up important and promising perspectives for research and development. Energy production through nature like bio-photovoltaic modules is the latest frontier of technology integrated with living organisms. Again, ethical questions are even more relevant in this case.

On the other hand, we have citizens and their willingness to protect and enhance nature, especially in urban areas. In this relationship to nature mediated by technology, awareness about nature's needs and impact is increased. Co-Diverse technologies can be deployed to facilitate participation and e-participation around nature and NBS. A closer and deeper human-nature relationship is enabled through digital (ubiquitous and connected) technology, which gives nature a voice and makes its needs visible to all. Digital technologies support improvements to this relationship in many ways, mainly increasing awareness of nature, shared governance, and democracy around nature and a sense of belonging and caring for nature. Firstly, Augmented Reality and Virtual Reality tools mounted on mobile or wearable devices help to make the invisible visible, represent nature and NBS in the current state or anticipate future urban greening scenarios and support monitoring, evaluation, and decision-making as part of design and co-design activities. Secondly, digital applications are excellent tools for building loyalty and establishing a caring relationship with nature by monitoring its health and state of conservation. In some cases, apps even initiate a dialogue between people and plants which transmit their state of health as recorded by the sensors. Finally, low-tech participation protocols can facilitate the inclusion of nature and NBS as stakeholders. For instance, nature enters decision-making processes by right, through different tools, e.g., role-playing and immersion in nature, or figures enlisted with the task of acting as guarantors of nature itself. It is, therefore, crucial to sensitize people to understand the multiple benefits (Zilio et al. 2022) related to these innovative NBS solutions and to translate them into values (societal, ecological, governance, and economic ones).

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