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Article

Towards a Cross-Sectoral View of Nature-Based Solutions for Enabling Circular Cities

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Abstract: A framework developed by the COST Action Circular City (an EU-funded network of 500+ scientists from 40+ countries; COST = Cooperation in Science and Technology) for addressing Urban Circularity Challenges (UCCs) with nature-based solutions (NBSs) was analyzed by various urban sectors which refer to different fields of activities for circular management of resources in cities (i.e., reducing use of resources and production of waste). The urban sectors comprise the built environment, urban water management, resource recovery, and urban farming. We present main findings from sector analyses, discuss different sector perspectives, and show ways to overcome these differences. The results reveal the potential of NBSs to address multiple sectors, as well as multiple UCCs. While water has been identified as a key element when using NBSs in the urban

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environment, most NBSs are interconnected and also present secondary benefits for other resources. Using representative examples, we discuss how a holistic and systemic approach could facilitate the circular use of resources in cities. Currently, there is often a disciplinary focus on one resource when applying NBSs. The full potential of NBSs to address multifunctionality is, thus, usually not fully accounted for. On the basis of our results, we conclude that experts from various disciplines can engage in a cross-sectoral exchange and identify the full potential of NBSs to recover resources in circular cities and provide secondary benefits to improve the livelihood for locals. This is an important first step toward the full multifunctionality potential enabling of NBSs.

Keywords: circularity challenges; multifunctionality; interdisciplinary; nature-based solutions; urban sectors; sustainable urban development; ecosystem-based management

1. Introduction

At present, there is a global concern regarding the effects of climate change and the long-term availability of natural resources such as water, especially in cities, where most of the world population is concentrated [1,2]. Cities consume more than 60% of the natural resources, produce 50% of all global waste, and produce more than 75% of all greenhouse gas emissions [3,4]. Therefore, the current paradigm of linear exploitation of natural capital, which is based on the principles of 'take–make–dispose' [5] is causing a significant environmental footprint. Thus, a paradigm shift moving toward the circular economy (CE), in which the use of resources is reduced through reuse and recycling approaches, is needed. Shifting toward circular management of resources requires systemic changes in human behavior and thinking, education, conceptual/technical/technological approaches, legislation, and governance. In this research, we explore nature-based solutions (NBSs) as facilitators toward circular change.

NBSs emerge as multifunctional and multiscale "green" technologies and solutions for reshaping the existing linear resource management into a circular one [6]. Currently, the design and use of NBS mostly focus on one specific urban challenge, e.g., to treat wastewater or to mitigate the urban heat island effect. However, NBSs have the potential to address several urban challenges simultaneously, specifically in relation to various Urban Circularity Challenges (UCCs). The following seven UCCs for shifting to a circular management of resources with NBSs were identified by Atanasova et al. [6]: UCC_1 "restoring and maintaining the water cycle", mainly by rainwater management; UCC_2 "water and waste treatment, recovery, and reuse"; UCC_3 "nutrient recovery and reuse" with a focus on nitrogen, phosphorus, and potassium; UCC_4 "material recovery and reuse", mainly as materials in the built environment; UCC_5 "food and biomass production" in sustainable ways in cities; UCC_6 "energy efficiency and recovery", including mitigation of the urban heat island effect, as well as heat and energy recovery from different waste streams; UCC_7 "building system recovery" related to the topic of regeneration of the built environment.

The COST Action CA17133 Circular City [7] aims to facilitate the use of NBSs to foster CE in urban environments. It defines NBSs as " … *concepts that bring nature into cities and those that are derived from nature*". This definition includes processes for resource recovery that use organisms (such as microbes, algae, plants, insects, and worms) as the principal agents [7].

As a first step of the Action's work, the state of the art of NBSs to foster CE was reviewed, while bottlenecks and research questions were also identified. These reviews were prepared by the five Working Groups of the Action, i.e., built environment (WG1 [8]), urban water (WG2 [9]), resource recovery (WG3 [10]), urban farming (WG4 [11]), and transformation tools (WG5 [12]).

Furthermore, a framework for addressing UCCs with NBSs was defined [13]. The framework is aimed at mainstreaming the use of NBS for the enhancement of resource management in urban settlements. It comprises a set of 39 NBS units (NBS_u), 12 NBS interventions (NBS_i), and 10 supporting units (S_u), as well as the analysis of input and output (I/O) resource streams required for NBS units and interventions (NBS_u/i). The framework has been discussed from different perspectives that correspond to urban sectors and activities relevant for the potential of circular management of resources for the (1) built environment [14], (2) urban water management [15], (3) resource recovery [16], and (4) urban farming [17].

This paper demonstrates that a holistic, cross-sectoral approach of implementing NBSs is necessary to account for the full potential of NBSs by presenting urban sector perspectives and identifying the interconnection of different sectoral views in various fields of application. On the basis of our findings, we conclude that the full potential of NBSs relies on multifunctional solutions which address CE and foster the path toward creating and pursuing integrated management of circular cities.

2. Materials and Methods

The overall methodology included (i) a selection of most relevant UCCs for the unban sectors and related NBS_u/i that can address those UCCs, i.e., relevant for the sectors, (ii) the evaluation of the selected NBS_u/i in terms of UCCs, (iii) analysis of the participating disciplines in the research, (iv) a discussion, defining relevant input and output (I/O) streams, and (v) the evaluation of existing gaps, opportunities, and tradeoffs. The results of these analyses were summarized by identifying the main challenges addressed by the selected NBS_u/i, within the sectoral view.

2.1. Nature-Based Solution Concept under the Perspective of Different Urban Sectors

Within the COST Action Circular City, the NBS units and interventions (NBS_u/i) were analyzed under the perspectives of four selected urban sectors, which refer to the different fields of activities for circular management of resources in cities, namely, the built environment [14], urban water management [15], resource recovery [16], and urban farming [17]. With circularity always in focus, each sector first identified the most relevant UCCs being dealt with and then the most applicable NBS_u/i to address the relevant UCCs.

2.2. Evaluation of Nature-Based Solution Relevance to Urban Sectors and Related to the Urban Circularity Challenges

The list of NBS_u/i and S_u presented in Langergraber et al. [13] and Castellar et al. [18] was used as a basis for evaluating their relevance for the following urban sectors: building systems, building sites, urban water management, resource recovery, and urban farming. In this paper, urban sectors also correspond to the working groups of the COST Action Circular City, whereby the evaluation for the overall sector of built environment was separately done for building systems (the building itself) and building sites (including the surroundings of buildings).

The evaluation was carried out during a series of elicitation workshops under the scope of the COST Action Circular City, involving 71 experts on average from 28 countries. The participants identified, for each urban sector, a series of criteria (explained in Section 3.2.2) to select the most relevant NBS_u/i. Despite very specific criteria identified, a similar methodology was used across the different urban sectors, for the data to be comparable.

The extent to which NBS_u/i can address multiple urban sectors was based on the methodology presented by Langergraber et al. [13] to evaluate the potential of NBSs to address UCCs. In this sense, the selected NBSs for each urban sector were evaluated according to the following scores: (1) the NBS_u/i are relevant (score = 1); (2) the NBS_u/i might be relevant, depending on the system design (score = 0.5); (3) the NBS_u/i is not relevant (score = 0). To analyze the overall relevance of NBS for urban sectors, we calculated the following global scores: the "sector global score", by simply averaging the NBS scores for each urban sector, and the "NBS global score", by simply averaging the sector scores for each NBS_u/i. Indeed, the NBS global score represents the potential of each NBS to be used by different sectors, thus providing a cross-sectoral performance. We also counted the number of NBSs relevant for each urban sector and the number of urban sectors related to each NBS_u/i.

Additionally, the different selection criteria of each urban sector were discussed and analyzed to identify whether an NBS_u/i is relevant or not on the basis of their fields of application, to determine why perspectives differ among the experts, and to determine the NBS potential to address multiple sectors along with the UCCs.

2.3. Background Analysis of Workshop Participants and Their Experiences with Nature-Based Solutions

A short questionnaire was developed and sent to the participants of the 10 workshops held between March 2020 and April 2021, during which the new framework [13] of the COST Action Circular City was discussed and developed, to analyze the disciplines that contributed (one workshop was held in person, and the remaining nine workshops were held in a virtual setting). Each virtual Circular City workshop had an average of 71 participants—with a minimal participation of 59 members (second and third virtual workshops) and a maximal participation of 87 members (fifth virtual workshop)—from 28 countries. A total of 191 people participated in the workshops and received the questionnaire.

In addition to information on the nationality and residence country, the following questions were asked:

- What is your professional background? (Multiple answers possible)
- What is your professional activity?
- How would you rate your experience with NBS? (From 1: very low to 5: very high)
- How much did your participation in the COST Action Circular City help you to improve your expertise on NBSs?
- Please provide 1–3 keywords that summarize the potential of NBSs to address circularity in cities.

In total, 121 of the 191 persons (>60%) filled out the questionnaire. From the 57 persons that participated in at least five workshops, more than 90% responded; thus, the results can be considered as relevant for the persons mainly involved in the discussions from the Circular City workshops.

2.4. System Analyses of Resource Streams

Both environmental dimensions and urban sector conditions show how the NBS_u/i can differently address circularity, and the perception of how these NBS_u/i contribute to address UCCs can largely vary. Therefore, novel tools are required to successfully implement CE principles.

Some linear examples show the status quo regarding the urban water cycle: (1) water is a resource needed for irrigation of urban green and agriculture, as well as mitigation of the urban heat island effect, (2) runoff water needs to be managed using NBS to avoid pluvial flooding and relief pressure on the existing sewage system, and (3) wastewater is collected and transported to a treatment wetland where it is treated and discharged.

To support the transition toward circular resource flows, information on these streams is needed. System analysis was used to study the CE network topology (Figure 1). The network consists of nodes and links. Nodes are CE entities, circular city entities, or NBS units (NBS_u)—black boxes for which only input and output (I/O) are known. They are linked by resource streams. Since the nodes are seen as black boxes, system internal streams (which can also be circular) are not considered in the information model. Whether a stream is internal or external depends on the design of the model; ownership is usually a good delineation. For example, in a trans-aquaponics case, where a treatment wetland is used for aquaculture wastewater and sludge removal [19], internal streams become external if the coupled production units have different owners.

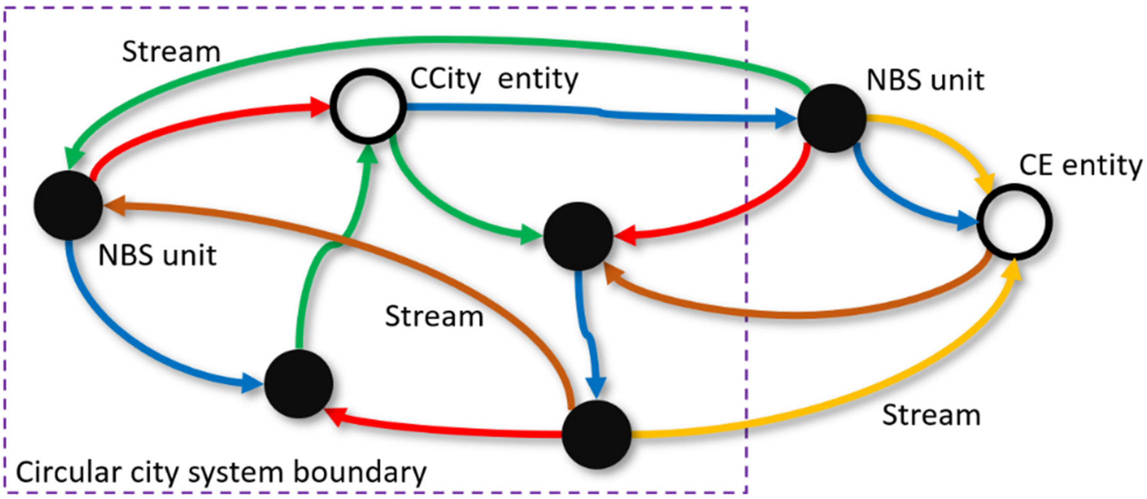

Figure 1. Schematic sketch of a CE network topology with CE and Circular City entities (referred to as "CCity entities") as black boxes (nodes) and unidirectional resource streams (links). Circular Economy entities (referred to as "CE entities") within the Circular City system boundary become Circular City entities. All full circles represent NBS units, regardless of the Circular City system boundary. The link colors symbolize the stream types of water, nutrients, biomass, living organisms, and energy but do not represent specific streams in this sketch.

A recently published model [20] was further developed by reducing its scope and concomitantly qualifying the model elements, adjusted to the requirements of the COST Action Circular City with a focus on streams as a 'streams information model'. It waived the site model element, integrated the 'extended resource specification' as stream properties, and added the circular city system boundary, allowing the circularity between NBS_u/i and other CE entities. A unified terminology was developed to describe the requirements for resource streams from and to NBS, which were applied to all streams, notwithstanding differences of the individual streams. In this model, we abbreviate NBS_u/i as NBS.

3. Results and Discussion

3.1. Nature-Based Solutions Units and Interventions and Supporting Units under the Perspective of Different Urban Sectors

The relevance of NBSs was analyzed from the perspective of different urban sectors. The main outcomes are summarized below.

- *Built environment*: Pearlmutter et al. [14] focused on building systems and identified the "wicked problem of water"; more provision of services by NBSs requires a higher water use, which is commonly solved by importing water from outside the city. The authors proposed to challenge this conundrum by focusing on those NBS_u/i classified as vertical greening systems and green roofs [13], and how they can be used to foster graywater reuse and capture available rainwater. This approach is based on the first and second urban circularity challenges (UCC_1 and UCC_2) [6] and is based on three steps: (i) how can NBS be integrated into buildings help to close the water cycle, (ii) how can water be incorporated into the life-cycle analysis (LCA) of a building as a resource, and (iii) how can the proposed solutions of graywater and rainwater reuse across different climates be modeled to allow comparisons. According to the LCA approach, the required water input was identified to have a significant impact on the water needs of NBSs and support the shift toward water reuse practices. However, as cities are often heterogeneous with diverse urban dwelling types, water reuse management needs to be planned and implemented at the neighborhood scale. This can be done successfully if existing gaps in policy are filled, and planning processes include inter- and multidisciplinary approaches from the initial stages. Building system recovery, one of the UCCs defined (UCC_7), was not directly addressed by Pearlmutter et al. [14]. Although CE itself does not distinguish among the scales of circularity, building reuse has often been agreed upon as a preferred option over material and component recycling, thanks to its higher upscaling potential. This is particularly true for "heritage" buildings and neighborhoods. In urban regeneration projects, NBSs can effectively be used to address this issue. Circular buildings positively impact materials, energy, waste, biodiversity, health and wellbeing, human culture, and society at once [21]. Additionally, they may produce multiple forms of value [22].

- *Urban water management*: Oral et al. [15] discussed the urban water management perspective with a special focus on UCC_1 and UCC_2. The 51 NBS_u/i and 10 S_u [13] were assessed in relation to their contribution to UCC_1 and UCC_2, by applying identification, categorization, and a semiquantitative ranking system for selecting the most relevant NBSs. Critical water streams for NBS_u/i and their use in addressing UCC_1 and UCC_2 were identified and complemented with case studies and evaluation tools. In this regard, challenges and barriers, as well as the opportunities and potential of NBSs to address urban water circularity, were identified and expanded.
- *Resource recovery*: Resource recovery from solid and liquid urban waste streams with the application of NBS units (NBS_u) was discussed by van Hullebusch et al. [16]. In the same study, supporting units (S_u) for producing recycled fertilizers, as well as disinfecting recovered products and separate streams, were presented. The efficiency of resource recovery was assessed for the systems where NBS_u/i and S_u were already tested and operated at micro- or mesoscale, and which are applicable in the urban environment (i.e., they have a Technology Readiness Level higher than 5). It has been pointed out that circular systems for resource recovery entail collection and transport infrastructure, treatment and recovery technology, and urban agricultural or green reuse. To enhance the efficiency of these systems for resource recovery, existing circularity, and application challenges dealing with infrastructure, legislation, social and environmental services, and multiple stakeholders must be tackled.
- *Urban farming*: Canet-Martí et al. [17] highlighted that urban agriculture plays a key role in circular cities. Urban agriculture can use recovered resources to produce food and biomass and, thus, contribute significantly toward closing the urban cycle, maximizing the (re)use of resources while reducing the need for external resource inputs. The expanded deployment of urban agriculture would help to address UCCs in general and UCC_5 in particular. This requires a better understanding of the food-related urban streams in order to recover resources and adapt to the distribution system accordingly.

3.2. Nature-Based Solution Relevance to Urban Sectors Related to Urban Circularity Challenges

3.2.1. Criteria to Define the Relevance of NBS Units and Interventions for Urban Sectors

For selecting relevant NBS_u/i for the four selected urban sectors, each sector identified the most relevant UCCs (Figure 2). During the evaluation process, all sectors had the generic UCCs in mind, i.e., maximizing efficiency in the use of water, energy, and materials, and minimizing waste products that cannot be cycled into further productive activities.

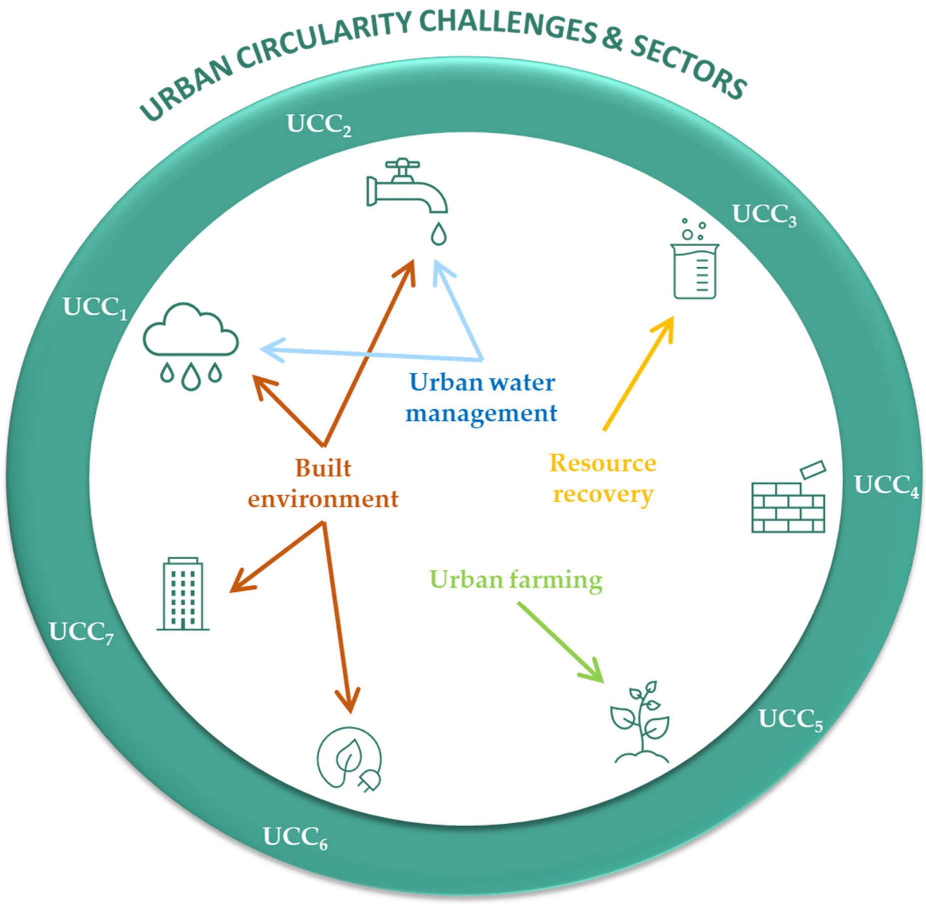

Figure 2. Most relevant Urban Circularity Challenges (UCCs) defined by the urban sectors for selecting relevant nature-based solution units and interventions (NBS_u/i). The arrows highlight the focus of the discussions in the urban sectors. Urban Circularity Challenges: UCC_1 = restoring and maintaining the water cycle; UCC_2 = water and waste treatment, recovery, and reuse; UCC_3 = nutrient recovery and reuse; UCC_4 = material recovery and reuse; UCC_5 = food and biomass production; UCC_6 = energy efficiency and recovery; UCC_7 = building system recovery.

Other specific criteria for selecting relevant NBS_u/i are described below.

- *Built environment*: In general, the relevance of NBS_u/i and S_u for the built environment was decided on the basis of their potential to address UCC_1, UCC_2, UCC_6, and UCC_7 (Figure 2). Furthermore, the different relevance of NBS_u/i for green building systems and sites [8] was considered. For the category of building systems, only NBSs directly connected to individual buildings are relevant. This mainly includes vertical greening systems and green roofs, as well as bioretention cells and S_u for rainwater harvesting. UCC_4 "material recovery and reuse" is part of the built environment as green building materials [8], although green building materials were not considered here except as components of vertical greening systems and green roofs. Food and biomass production is represented by NBS_u/i, which can be integrated as urban blue infrastructure, as green infrastructure in/on buildings, as green infrastructure as parks and landscapes, and/or as green infrastructure as urban farms, such as hydroponic and soilless technologies, and aquaponic farming (blue infrastructure, green infrastructure in/on buildings, and/or as urban farm), as well as productive gardens (as green infrastructure as parks and landscape and/or urban farms) [17]. For building sites, NBS_u/i are relevant when implemented within the urban landscape. This implementation requires the interaction of multiple disciplines, from landscape architecture to urban climatology, to successfully realize the potential of these nature-based strategies and integrate them into the city fabric [21].

- *Urban water management*: As water is intrinsic for the design and operation of most NBSs, almost all NBS_u/i from the urban water management point of view were selected as relevant (or "might be relevant", as defined in Section 2.2.), except for composting and a few S_u. The relevance of NBS_u/i and S_u was determined on the basis of their ability to address UCC_1 and UCC_2, by enabling processes such as conveyance, infiltration, retention, and treatment (including sedimentation, biodegradation, and sorption) [15]. In total, only 13 NBS_u/i were marked as "might be relevant", mainly NBS_i for soil and water bioengineering, as well as NBS_u for food and biomass production.
- *Resource recovery*: Relevant NBS_u/i and S_u can generate new or recover resources from urban solid and liquid resource flows, whereby the focus was on UCC_3 "nutrient recovery and reuse" to gain appropriate quantity and quality of resources. Not surprisingly, van Hullebusch et al. [16] identified most of the NBS_u/i and S_u that are targeted to remediation, treatment, and recovery as relevant. However, they did not focus on other resources such as materials (UCC_4) and energy (UCC_6), water (UCC_1 and UCC_2, as already covered by urban water management), and biomass (UCC_5, covered by urban farming).
- *Urban farming*: NBS_u/i and S_u were assessed for potentially contributing to UCC_5, evaluating food and biomass production separately. The NBS_u/i and S_u considered relevant for urban farming were (i) those with food and/or biomass production as their main purpose (addressing and contribution to the UCC_5), i.e., those that produce a relevant amount of food and/or biomass (outputs) or consume it for their operation (inputs), e.g., "composting" and "biochar", as well as (ii) those that can produce food and/or biomass (potential contribution to UCC_5) when designed for that purpose (system design), such as those classified as vertical greening systems and green roofs, and (public) green space [17]. The 10 NBS_u/i considered as "might be relevant" are intrinsically composed of vegetation although they are not designed for food and/or biomass production. Most of them are used for rainwater management. NBS_i such as "coastal soil erosion", "erosion control", and "riverbank engineering" were included as "might be relevant" as the actions and infrastructures can be designed to function as areas for food and/or biomass production [17].

3.2.2. Evaluation of the Relevance of Nature-Based Solutions for Urban Sectors

Table 1 presents the relevance of the NBS_u/i and S_u for the different sectors, according to the selection criteria discussed in the previous chapter. The NBS global scores and number of relevant sectors for each NBS_u/i are shown in Figure 3.

Table 1. Relevance of NBS units and interventions (NBS_u/i) and supporting units (S_u) for different sectors, i.e., working groups of the COST Action Circular City (• = relevant; ○ = might be relevant, depending on system design). NBS_tu = technological units; NBS_su = spatial units; NBS_is = soil interventions; NBS_ir = river interventions; S_u = supporting unit.

Classification		(#) NBS Units and Interventions, and Supporting Units	Urban Sectors				
			Building Systems	*Building Sites*	*Urban Water Management*	*Resource Recovery*	*Urban Farming*
Rainwater Management	*NBS_tu*	(1) **Infiltration basin**		•	•	•	○
		(2) **Infiltration trench**		•	•	•	
		(3) **Filter strips**		•	•		
		(4) **Filter drain**		•	•		
		(5) **(Wet) retention pond**		•	•	•	○
		(6) **(Dry) detention pond**		•	•		
		(7) **Bioretention cell**	•	•	•		○
		(8) **Bioswale**		•	•		○
		(9) **Dry swale**		•	•		○
		(10) **Tree pits**		•	•		○
		(11) **Vegetated grid pavement**		•	•		○
		(12) **Riparian buffer**		•	•		•
	S_u	(S1) **Rainwater harvesting**	•		•		
		(S2) **Detention vaults and tanks**	•		•		

Table 1. *Cont.*

Classification		(#) NBS Units and Interventions, and Supporting Units	Urban Sectors				
			Building Systems	*Building Sites*	*Urban Water Management*	*Resource Recovery*	*Urban Farming*
Vertical Greening Systems and Green Roofs	*NBS_tu*	(13) **Ground-based green facade**	●		●		●
		(14) **Wall-based green facade**	●		●		●
		(15) **Pot-based green facade**	●		●		●
		(16) **Vegetated pergola**	●	●	○		●
		(17) **Extensive green roof**	●		●		●
		(18) **Intensive green roof**	●		●		●
		(19) **Semi-intensive green roof**	●		●		●
		(20) **Mobile green and vertical mobile garden**		●	○		●
Remediation, Treatment and Recovery	*NBS_tu*	(21) **Treatment wetland**	●	●	●	●	●
		(22) **Waste stabilization pond**			●		
		(26) **Anaerobic treatment**			●	●	
		(27) **Aerobic (post) treatment**			●	●	
	NBS_is	(23) **Composting**	●	●		●	●
		(24) **Bioremediation**		●	○	●	
		(25) **Phytoremediation**		●	○	●	●
	S_u	(S3) **Phosphate precipitation** (for P recovery)			●	●	
		(S4) **Ammonia stripping** (for N recovery)			●	●	
		(S5) **Disinfection** (for water recovery)	●		●	●	
		(S6) **Biochar/hydrochar production**			●	●	●
		(S7) **Physical unit operations for solid/liquid separation**			●	●	●
		(S8) **Membrane filtration**			●	●	
		(S9) **Adsorption**			●	●	
		(S10) **Advanced oxidation processes**			●	●	
(River) Restoration	*NBS_ir*	(28) **River restoration**		●	●		●
		(29) **Floodplain**		●	●		●
		(30) **Diverting and deflecting elements**		●	○		
		(31) **Reconnection of oxbow lake**		●	●		
		(32) **Coastal erosion control**		●	●		○
Soil and Water Bioengineering	*NBS_is*	(33) **Soil improvement and conservation**		●	○	●	●
		(34) **Erosion control**		●	○		○
		(35) **Soil reinforcement to improve root cohesion and anchorage**		●	○		
		(36) **Riverbank engineering**		●	○		○
(Public) Green Space	*NBS_su*	(37) **Green corridors**		●	●		●
		(38) **Green belt**		●	●		●
		(39) **Street trees**		●	●	●	●
		(40) **Large urban park**		●	●	●	●
		(41) **Pocket/garden park**		●	●	●	●
		(42) **Urban meadows**		●	●		●
		(43) **Green transition zones**		●	●		●
Food and Biomass Production	*NBS_tu*	(44) **Aquaculture**					●
		(45) **Hydroponic and soilless technologies**	●		○		●
		(46) **Organoponic/bioponic**	●		○		●
		(47) **Aquaponic farming**	●		○		●
		(48) **Photo bioreactor**			○	●	●
	NBS_su	(49) **Productive garden**	●	●	●		●
		(50) **Urban forest**		●	●		●
		(51) **Urban farms and orchards**		●	●		●

Only five NBS_u/i were selected as relevant by all sectors (whereby building systems and building sites are considered as one sector, i.e., built environment), namely, treatment wetlands, phytoremediation, street trees, large urban parks, and pocket gardens/parks:

1. Treatment wetland (#21) is a treatment technology inspired by natural wetland processes, being a highly versatile system that can be adapted to spaces and designed on the basis of their specific application [23]. Treatment wetlands can retain rainwater, as well as treat wastewater and graywater at the building scale for reuse as irrigation water (relevant for built environment and urban water management) and have the potential to recover nutrients taken up by roots and generate new resources such as biomass for bioenergy or as building material (relevant for resource recovery and urban farming).
2. Phytoremediation (#25) is a bioremediation process involving plants and microorganisms that removes, stabilizes, and/or degrades contaminants in the soil, water, and/or

air. The process can be deployed in the built environment, with consequent protection of water resources (urban water management). This may generate resources such as biomass, metals, and treated/regenerated soils, water, and air and is, thus, relevant for resource recovery and urban farming.

3. Street trees (#39) are important NBS_su, which are already systematically included in urban planning (built environment). They have the capacity for water retention, shading, and evapotranspiration, contributing to cooling, restoring the water cycle, enabling water reuse (urban water management, resource recovery), and reducing noise and air pollution (built environment). Street trees generate biomass for different applications, as well as food—either for direct consumption or for the food industry (relevant for resource recovery and urban farming). Thanks to their shading and evapotranspiration, trees are also very effective in reducing the energy needs of buildings and the thermal stress of pedestrians (built environment).
4. Large urban parks (#40), with a surface area greater than 0.5 ha, offer many possibilities to address UCCs. They constitute important green infrastructure for sustainable urbanization (built environment). Their vegetation and the expanse of permeable soil make them an outstanding NBS_su for water infiltration and retention, facilitating water reuse. They reduce further mitigation of pollutants along urban cycles and food chains, regulate the microclimate, and mitigate extreme weather events (urban water management). Their evapotranspiration and shading have a cooling effect, as well as an effect of reducing noise and air pollution (built environment). Their size allows for significant biomass and food production (resource recovery and urban farming) or covering renewable energy needs (built environment). Large urban parks offer several ecosystem services, e.g., space for recreation and social gatherings and, as such, contribute to human health.
5. Pocket/garden parks (#41) contribute to the same processes and address the same UCCs as large urban parks, albeit at a different scale (<0.5 ha); therefore, they can also be considered relevant for all urban sectors.

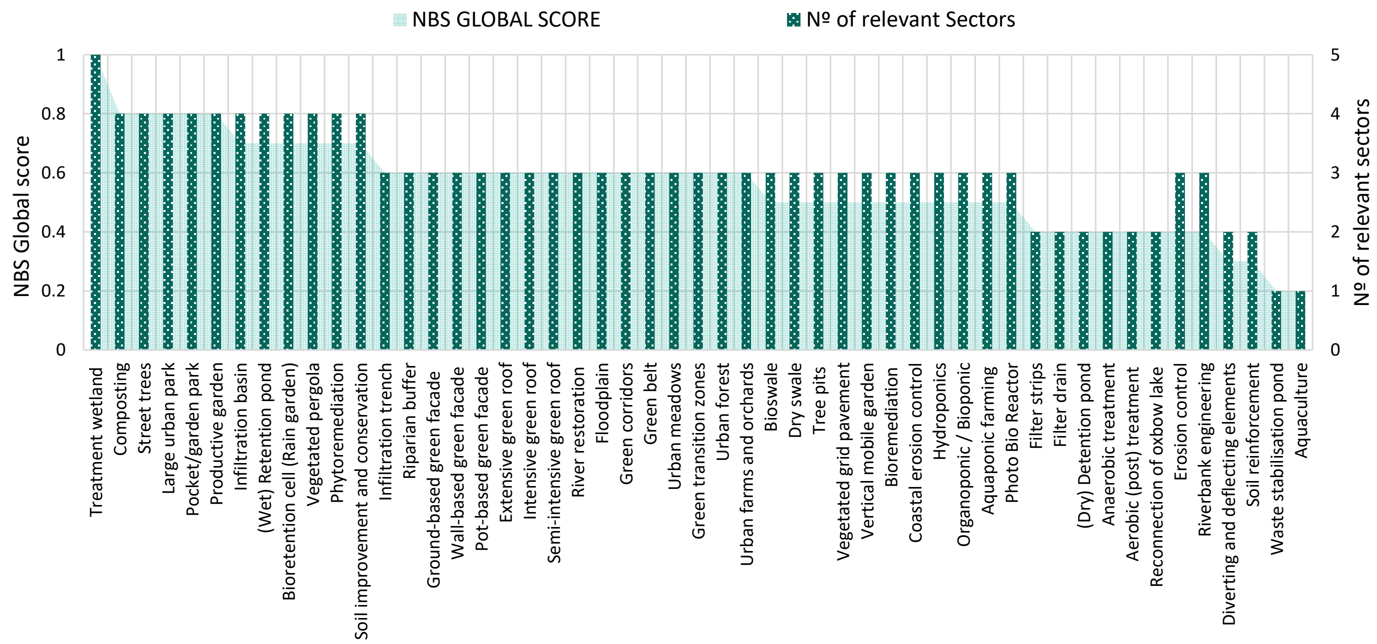

Figure 3. NBS global scores and number of relevant sectors for each unit and intervention (NBS_u/i). The NBS global score describes how many urban sectors selected a specific NBS_u/i as relevant (data from Table 1).

Not only are NBS_u/i selected by all urban sectors (Table 1) of interest, but those that have not been selected by specific sectors are also of interest, as well as the reason for their non-selection. As an example, the built environment did not select S_u for "remediation, treatment, and recovery" (#21–25 and S3–S10). This is of interest as those S_u can be identified as key technologies for onsite resource recovery and need to be integrated in the buildings to support circularity [16,24]. On the other hand, resource recovery did not select "vertical greening systems and green roofs" (#13–20). This can be explained by the applied criteria, specifically, the primary focus on nutrient recovery and usage within the city, including quantity and quality, and not on water circularity. Vertical greening systems and green roofs represent very effective NBSs for closing the water cycle at the building scale [24–27]. Both vertical greening systems and green roofs are suitable to be implemented in buildings across district and neighborhood scales, thus contributing to UCC_7 "building system recovery". NBS_u/i for "(river) restoration" and "soil and water bioengineering" were also not selected by resource recovery, thus indicating a low potential for nutrient recovery in the city.

Figure 4 summarizes the global sector scores and number of relevant NBS_u/i for each urban sector. The global sector scores are correlated with the number of relevant NBS_u/i. Urban water management was found to have the highest global sector score and most NBS_u/i were selected by this urban sector. On the contrary, building systems and resource recovery had the lowest global sector scores, and the fewest NBS_u/i were selected by these sectors. However, it should be considered that the list of NBS_u/i [13] does not include all possible NBS_u/i but only those with relevance to at least one UCC. Additionally, resource recovery discussions in the COST Action have focused, as mentioned above, on nutrient recovery, and other resources such as water, energy, and materials have not been the main focus or have been included in discussions of other sectors (e.g., water in urban water management).

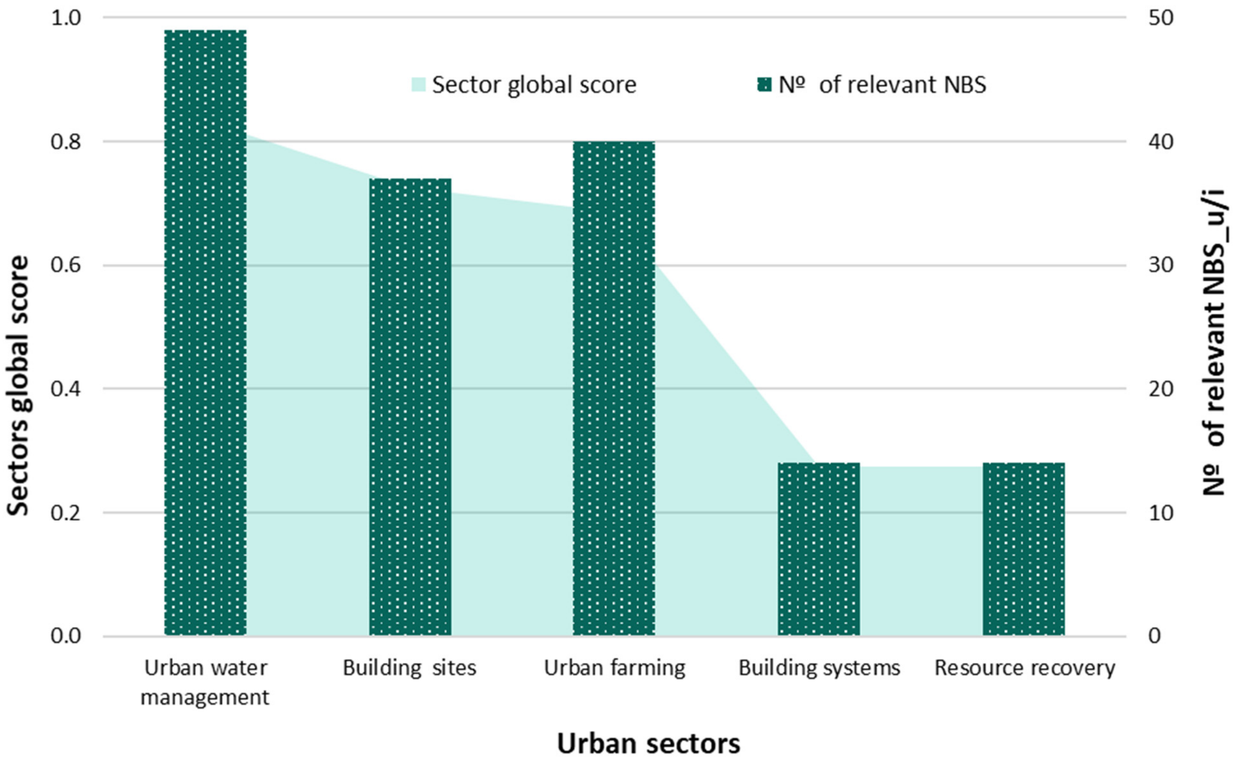

Figure 4. Global sector scores and number of relevant NBS units and interventions (NBS_u/i) for each sector. Global sector scores describe how many NBS_u/i were identified by each urban sector.

An important aspect related to systems design requires special attention; most of the NBS_u/i were selected as appropriate by more than one urban sector. However, to be multifunctional, i.e., address more UCCs simultaneously, a proper design and circular thinking are essential. For example, a vertical greening system may be designed for energy efficiency of a building only, where the design requires the use of tap water. Employing circular thinking would guide toward different designs, i.e., one that uses wastewater for irrigation and possibly utilizes plants used for biomass production. In this way, multiple challenges are addressed simultaneously by implementing different (resource oriented) designs, as explained in more detail in the next section.

3.2.3. Relationship between Sector Relevance and Ability to Address Urban Circularity Challenges

The potential of different NBS_u/i to address multiple UCCs and multiple sectors is shown in Figure 5. The potential to address multiple UCCs was presented by Langergraber et al. [13], and the values were derived from there.

Overall, there is a tendency that NBS_u/i with potential to address multiple UCCs also have the potential to address multiple sectors. NBS_u/i in quadrant I (potential for addressing multiple UCCs and sectors, both below 0.5) address only a limited number of UCCs and are relevant only for a few sectors. For instance, three out of four NBS_u/i from the category "soil and water bioengineering" can be found in quadrant I. In contrast, NBS_u/i in quadrant IV (potential for addressing multiple UCCs and sectors, both higher than 0.5) address various UCCs and are relevant for most sectors. For instance, seven out of eight NBS_u/i from the category "vertical greening systems and green roofs" can be found in quadrant IV. All NBS_u/i from the category "(river) restoration" are in quadrants I and II, indicating that the potential to address multiple UCCs is limited, whereas all NBS_u/i from the category "(public) green space" can be found in quadrants III and IV, indicating that they all have a very high potential to address multiple UCCs. The majority (seven out of eight) of the NBS_u/i from the category "food and biomass production" can be found in quadrants II and IV, indicating that they all have a high potential to address multiple sectors.

Defining the scale of environmental dimensions is essential to adequately define the system boundary of the impacts and the circularity of NBS. The environmental dimensions include spatial, temporal, thematic, and sectoral dimensions. The definition and the characterization of these dimensions are essential for the overall efficiency assessment of any NBS.

The spatial dimension can range from household to building to community scale, and to city, to regional, countrywide, continental, or even global scale. For instance, on a global scale, the water cycle is closed through evaporation/evapotranspiration and precipitation; however, on a local scale, reusing and recycling water can be of vital importance to reduce wastage and enhance sustainability. The temporal scale is just as important, as resources might regenerate in the long term, whereas, on a short timescale, they might be overused. The thematic dimension limits the system boundary to relevant topics. A restricted system boundary might exclude relevant cycling aspects and provide a biased impact of the holistic approach. The sectoral dimension accounts for the activities involved in the NBS. If a specific urban sector is excluded, it might reveal bias in the entire circularity of the NBS.

An illustrative example is represented by vertical greening systems, which contain different types of plants. The plants are mostly planted in a growth medium. Their spatial dimension is often limited to one building; accordingly, their system boundary is frequently limited to one wall. While some water can be recovered and purified by vertical greening systems, most precipitation water on a larger scale is lost, and the vertical greening systems do not appear to be an efficient water circulator. However, in the direct vicinity of the wall, vertical greening systems appear to have a significant effect on storing water in the soil and recovering evaporated water. A similar conclusion can also be drawn for the temporal dimension; in the short term, vertical greening systems can limit water runoff by storing or even recycling through evapotranspiration and condensation. However, on a longer timescale, water will eventually cross the local system boundary, revealing a low circularity efficiency. The thematic dimension is also crucial, since the benefits of vertical greening systems are not limited to local water recovery but extend to water purification, local cooling effects, enhancing biodiversity, improving air quality, and upgrading the comfort for residents. Lastly, depending on the sectoral perspective, the same effects can be considered with contradicting annotations. For instance, the increase in biodiversity might be perceived as a welcome benefit, while others might perceive the increase in insect population as a nuisance.

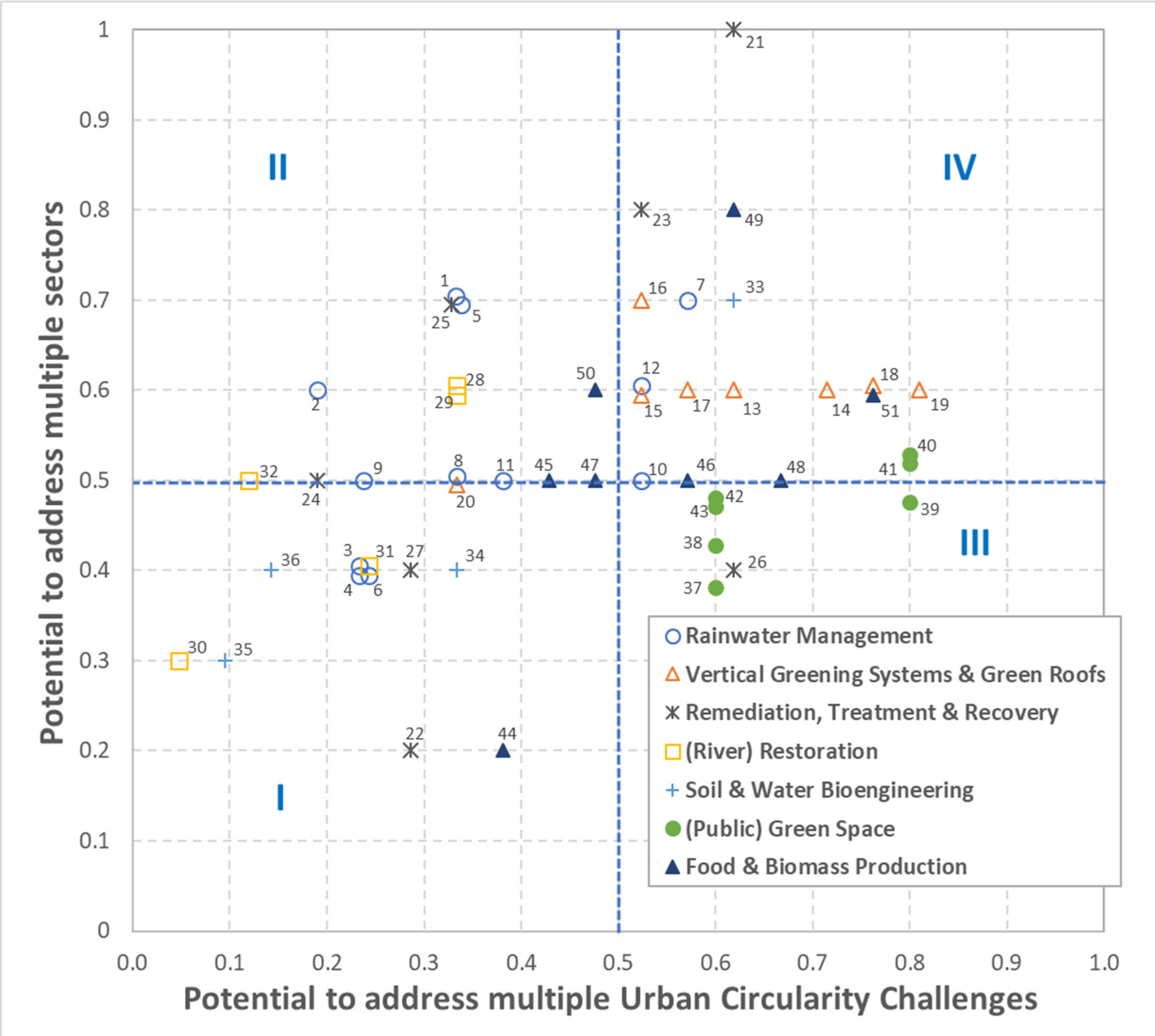

Figure 5. Potential of NBS units and interventions (NBS_u/i) to address multiple Urban Circularity Challenges (UCCs) and sectors. The numbers refer to numbers of the NBS_u/i in Table 1, and the different symbols refer to the categories of NBS_u/i [13]. NBS_u/i in quadrant I have lower potential to address multiple UCCs and sectors compared to NBS_u/i in quadrant IV.

Overall, the environmental dimensions of the system boundary of an NBS should be defined in careful consideration of spatial, temporal, and thematical aspects to assure a proper consideration of the full circularity. Lastly, a holistic system analytical approach is essential to provide a full assessment of the NBS. Accordingly, it is recommended to design NBSs while considering that they account for multiple challenges, including the complementarity of NBS_u/i, and they require the involvement of a wide variety of sectors and disciplines.

3.3. Participant Survey

The distribution of the professional background of participants was rather similar between all participants and those that participated in more than 50% of the workshops (Table 2). Although the participants had various professional backgrounds, engineers were dominant, and natural and social scientists were the minority. This reflects the composition of scientists participating in this COST Action.

When compiling the answers from all participants of the Circular City workshops, the keyword summarizing the potential of NBSs to address circularity in cities most often mentioned was "*water*" (Figure 6, hexagon in the left). However, when analyzing the keywords related to the professional background of the participants, the most often mentioned keywords were "*water management*" (agronomy, architecture), "*resources management*", "*resource reuse*", and "*recycling*" (agronomy, chemistry, urban and landscape planning), "*sustainability*" (engineering), "*climate change*" (chemistry, social sciences), and "*biodiversity*" (biology and geosciences). This highlights the different focus of the sectors on the use of NBSs and the importance of having a diverse and multidisciplinary research team to harness the full potential of NBS application in cities.

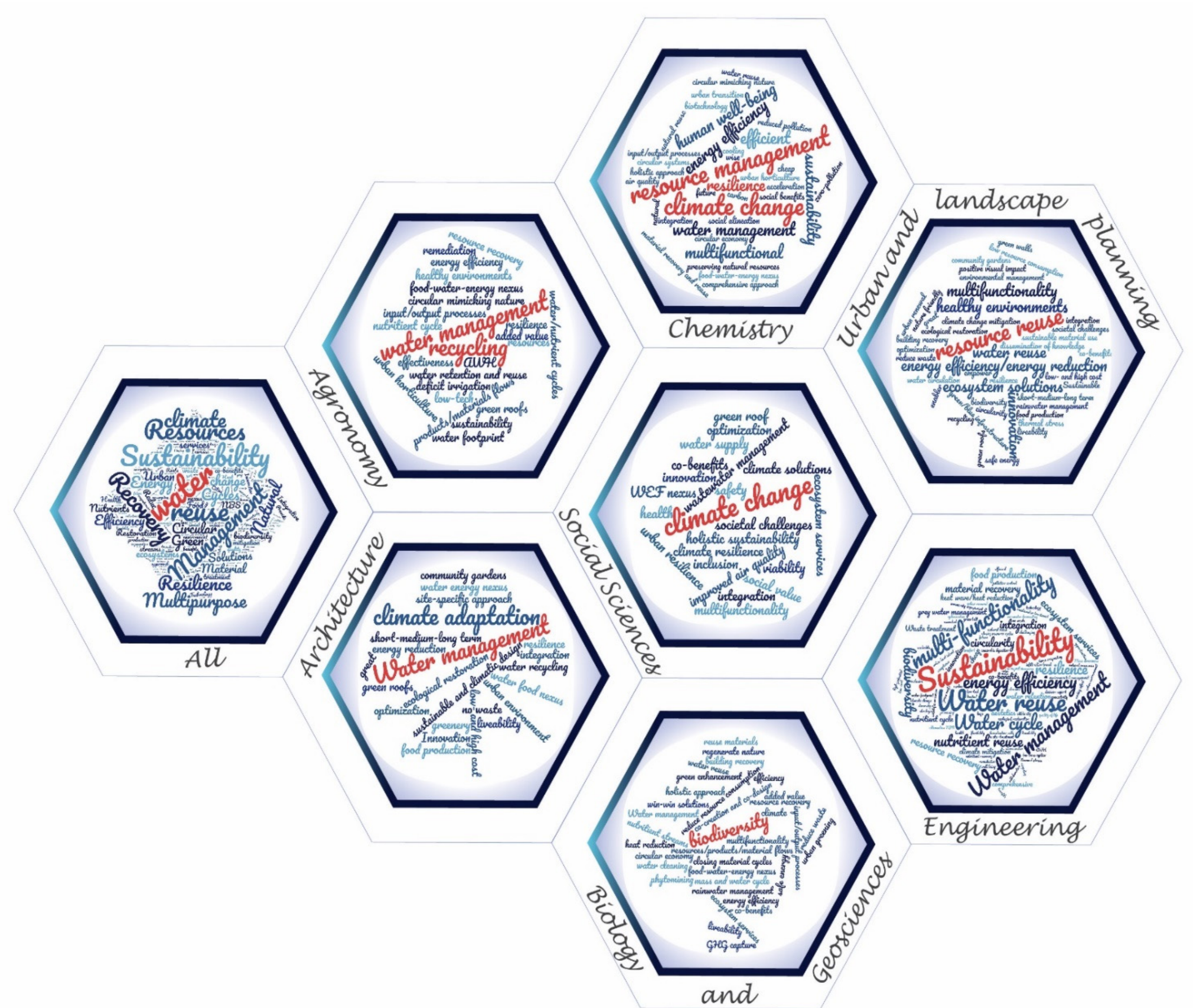

Figure 6. Word cloud of submitted keywords summarizing the potential of NBS to address circularity in cities, based on the reply from all participants (hexagon in the left) and participants with different professional backgrounds.

Table 2. Professional background of participants in the Circular City workshops.

Professional Background	Civil/Sanitary/ Env. Engineering	Agronomy/ Agricultural Engineering	Architecture	Urban/Landscape/ Rural Planning	Chemistry/ Biotechnology	Biology/ Geo Sciences/ Geology	Social Sciences
Participants >50% participation	52.5%	6.5%	5.6%	9.0%	11.6%	10.7%	4.0%
All participants	48.5%	5.3%	5.8%	10.4%	12.4%	8.6%	9.0%

3.4. A Streams Information Model to Describe Inputs and Outputs

A streams information model was developed to be able to represent the elements of a CE network topology in a unified way. This model is a specialization and further development of a predecessor [20].

The first part of the model (Figure 7) comprises CE entities as the nodes and refer to an entity type which is qualified by attributes, e.g., 'is natural feature'. In the present model, NBSs are considered special cases of CE entities, marked as 'is NBS unit', and comprise all NBS_u/i and S_u [13]. The concrete instance of an NBS_u/i or S_u has a name as a unique identifier and is located at a concrete place, and, if this location is within the system boundaries of the circular city, the property 'within circular city boundary' is set, making the NBS an entity of the circular city (CCity entity). In an implementation of the model, the assignment can be done automatically by a geographical information system (GIS).

The links between the CE entities are resource streams, which are hierarchically ordered by a complete set of types (water, nutrients, biomass, living organisms, and energy), divided into categories and subcategories, depicted by a comprehensive set of examples. Furthermore, they have a measuring unit which qualitatively describes a stream and can be used to quantify the flow volume. Streams have different endpoints: CE/CCity entities, NBS_u/i, or natural features, such as the atmosphere as a source of precipitation. Each NBS_u/i has at least one input (I) and one output (O) stream such that their cardinality is 1 to n in each case.

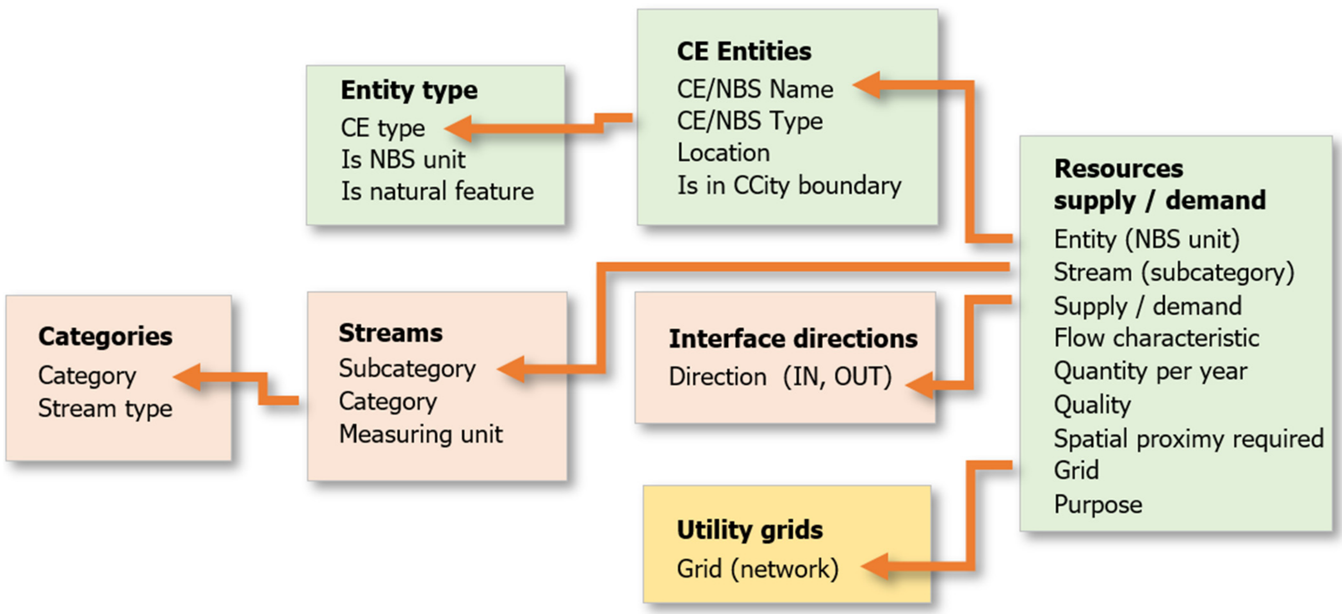

Figure 7. An information model on NBS_u/i and interconnecting streams (Figure 1). Green: entities and their resources; red: streams; yellow: grids (optional).

In conjunction with the endpoints, streams represent resources that are uniquely identified by (1) the entity (e.g., NBS_u/i or S_u) which is using a stream, (2) the stream subcategory, and (3) the interface direction of the NBS_u/i where 'input' is equal to demand

and 'output' is equal to the supply of the respective stream. Whether a stream is output (O) or input (I) depends on the respective endpoint. The resources have optional properties, such as flow characteristics, which describe whether a resource is permanently available, discontinuous, on demand, or adaptable. However, the annual quantity, statements on quality, whether spatial proximity is required, the possible use of utility grids, or the purpose of the resource can also be specified.

A stream connects two endpoints directionally and runs as output (O) from one endpoint to the input (I) of the other endpoint. This simplest form of resource use is linear and can occur in isolation in many places in the city. However, to implement a resource network which features circularity, it is necessary to connect these linear elements so that they form loops. Various loops can be formed within the system boundaries of the circular city; however, to create this network of loops, data on the quality and quantity of streams are required to fit the supply/demand of the respective endpoints. Nevertheless, there is still a considerable need for interdisciplinary research in order to be able to determine these stream characteristics.

The streams information model can be understood as a template, and there are many options to operationalize it. It can be reduced to a simple table, placing the information range into rows and columns. For example, the columns 'type, category and the subcategory of stream' in conjunction with 'output from/input to NBS' applied to the rows 'biomass' and 'living organisms' give a good overview on the material flows and their possible circularities within the sector of urban farming [17]. Resources are required or produced during operation and maintenance of NBS, input and output (I/O) streams need to be defined, and there is a gap between potential users and providers of resources [13]. To solve this problem, a relational database schema can be derived from the streams information model to implement a database, thus improving the resource management in cities.

3.5. The Current Sectoral View against a Much-Needed Holistic/Systemic Approach to Circular Management of Resources in Cities

While, conceptually, the solutions for closing material cycles are clear and favorable, practical implementation can be quite problematic, simply due to realistic mass balances of elements. Specifically, closing the nitrogen cycle, for example, by recovering it from urine may require a great deal of plant consideration to be effectively assimilated and later used for food. Plant seasonality is also one of the important aspects to be considered. All this requires innovative thinking and an adaptable design approach, and the proposed streams information model can be of great assistance. Another way to approach the coupling of processes is via the stoichiometry of the elemental composition. Both nutrient limitation and accumulation of undesired substances in a circular process reflect the matching of elemental composition of the material streams.

There are 92 naturally occurring elements on Earth. Only about 30 of the naturally occurring elements are widespread on Earth, and very few are important for life [28]. The frequency and the availability of elements in the Earth crust do not match their frequency in living beings. Furthermore, living beings contain different fractions of some elements. Plants, for example, require 17 essential nutrient elements [29] and generally contain lower fractions of nitrogen (contained mainly in proteins) and phosphorus than animals.

This can be illustrated using the case study of aquaponic systems, which approaches the emerging and inclusive CE paradigm [30], boosting its rich runoff effluents in terms of nutrient recycling (e.g., from nitrogenous fish waste) and fish wastewater treatment (i.e., in recirculating aquaculture systems) and, thus, minimizing external waste (nutrients and water) streams. Aquaponics is a sustainable food and/or biomass production NBS_u in which aquatic organisms (aquaculture) are coupled with horticultural soilless crop production (hydroponics), with the metabolic wastes produced by the fish being transformed via nitrification (bioremediation) for use as fertilizers (nutrients) for plants. These processes were recently investigated in depth [30–33]. A case study in Berlin (Germany) showed that the total demand for fish and vegetable production (tomato and lettuce) could be provided by aquaponics [34].

The aquaculture part of the aquaponic system provides most plant nutrients at lower concentrations as compared with the standard hydroponic solutions used for vegetable cultivation [35]. Moreover, the ratios between these elements are highly variable, ranging from 1.2 to 138.7 [36].

On one hand, this mismatch causes nutrient limitations of plant growth, which requires targeted nutrient supplementation to ensure healthy and abundant crop. On the other hand, non-assimilated nutrients accumulate in the recirculating water [37]. This problem must be tackled by adding technological steps to the aquaponic system, such as denitrification [38] or desalination [39], or by extending the system with specific crops that can utilize the available excessive elements [40]. This case study indicates the complexity of circular management of resources in cities.

4. Conclusions

The following conclusions can be drawn:

- Water is a key element when using NBS in the urban environment.
- The relevance of NBSs in different sectors is changing on the basis of their application in the Circular City. However, there is still a disciplinary bias toward the classical field of application, whereby different sectors implement the same NBS units and interventions with different designs and purposes.
- Multifunctionality is often discussed; however, it is rarely fully implemented. Thus, the potential of NBSs to address multifunctionality is usually not fully utilized.
- Cross-sectoral collaboration is essential in the design process for utilizing the full potential of NBSs in simultaneously addressing multiple urban challenges. New tools, such as the presented streams information model, can represent complete loops, i.e., resource flows through NBSs. Thus, they can facilitate circular thinking in the design process and integrate sectoral views for a better and multifunctional design of NBSs.
- The environmental dimensions of the NBS system boundary should be defined in careful consideration of spatial, temporal, and thematical aspects to assure circularity.
- Illustrative examples of vertical greening system and aquaponics show that the need for closing cycles is clear and favorable, but this requires innovative thinking and an adaptable design approach where input and output streams and users and providers of resources are well defined to facilitate practical implementation.
- Lastly, the COST Action Circular City served as an excellent platform for communicating and working across disciplines and sectors. Experts in engineering, architecture, planning, and natural and social sciences contributed to the work. Despite most participants belonging to the first group, this is a valuable attempt at crossing disciplinary gaps toward implementing the full potential of NBSs for the circular management of resources.

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