Environmental Innovation and Societal Transitions 35 (2020) 202–216

Contents lists available at ScienceDirect

Environmental Innovation and Societal Transitions

journal homepage: www.elsevier.com/locate/eist

Original Research Paper

Nature-based innovation systems

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ARTICLE INFO

Keywords:
Technological innovation systems
Nature-based solutions
Sustainability transitions
Urban development
Environmental governance
Geography of transitions

ABSTRACT

Transitions literature regards technologies as critical components in shifting systems towards sustainability, which has informed the development of the technology-oriented Technological Innovation System (TIS) framework. The emerging discourse on nature-based solutions (NBS) – multifunctional nature-integrated spatial planning and design innovations – raises the question to what extent TIS can account for the development and diffusion of NBS. Following a literature review, we present the Nature-Based Innovation System (NBIS) framework delineating critical factors for urban nature-based innovation. We find both commonalities and differences between TIS and NBIS, suggesting that the roles of place-based dynamics, agency and governance structure are more central to nature-based innovation, and market formation is more central to technological innovation. This has implications for the study of sustainability transitions, which has likely underplayed the potential of innovations at the nexus of socio-technical and socio-ecological systems. Future research is needed to refine the NBIS framework, for example by studying evolutionary developmental trajectories.

1. Introduction

The sustainability transitions literature continues to highlight the role of technologies in sustainable development (Geels and Schot, 2010; Kanger and Schot, 2018). Technologies, on the one hand, are considered to be a structural component in maintaining the unsustainable status quo through, for instance, sunk investments (Geels, 2004). On the other hand, technological *innovation* is considered critical in realizing sustainability transitions, because future sustainable societies are difficult to imagine without radical technological change. This has manifested in the development of corporate and policy imaginaries about future sustainable societies, which are often articulated around large technological breakthroughs such as self-driving electric vehicles, low-carbon housing and smart grids. This technology focus is also present in many contemporary discourses on urban transitions such as in smart city visions. Technology-oriented frameworks are also popular in the transition community to analyse the successful development and diffusion of innovations that contribute to sustainable development (Bergek et al., 2015; Geels, 2002; Geels et al., 2017; Hekkert et al., 2007).

Because sustainable urban development is closely related to rebalancing relationships between nature and society (often through the use of technologies), it is notable that the transitions literature so far has remained rather silent about 'nature'. The urgency to turn this around has become even more profound given recent reporting by the IPBES on critical levels of biodiversity loss posing an existential threat to human survival and well-being (Díaz et al., 2019). An emerging policy discourse on 'nature-based solutions' (NBS) is therefore of interest. This discourse is building upon earlier traditions and conceptualizations of the role of nature in

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https://doi.org/10.1016/j.eist.2019.09.005
Received 1 October 2018; Received in revised form 18 September 2019; Accepted 24 September 2019
Available online 09 October 2019
2210-4224/

sustainable urban development. However, the literature on NBS and urban green infrastructure takes the debate one step further with its focus on integrating socio-ecological and socio-technical systems, opening up the academic conversation on socio-ecological-technical systems (Depietri and McPhearson, 2017; McPhearson et al., 2016). An improved integration of nature in cities allows for hybrid green-grey urban development in which technical systems for e.g. urban flood mitigation could provide co-benefits such as biodiversity, air filtration and social cohesion that would not be generated by a socio-technical innovation in isolation, as well as providing complementary stormwater capture (Depietri and McPhearson, 2017).

Urban NBS can therefore be utilized to address social, economic and ecological sustainability challenges simultaneously, often in cost-efficient ways, and for that reason are increasingly recognized in policy and research as promising innovations with potential to facilitate wider urban transformation (Nature Editorials, 2017; Nesshöver et al., 2017). The European Commission, in particular, has made NBS a critical part of their investments in the European research and innovation agenda (European Commission, 2015). Examples of urban NBS are external building greens (e.g. green roofs), parks and semi-natural areas, community gardens, bioswales for stormwater capture, green indoor areas, green infrastructure and urban forests on derelict land (Bulkeley and Raven, 2017). Even though NBS can be found in cities across the globe, their diffusion is patchy at best with a risk of further loss of urban nature as a result of current urban densification policies in many cities (Pauleit et al., 2005; Xu et al., 2018).

From a sustainability transitions perspective, urban NBS are not only interesting because they represent a 'living' innovation system, i.e. they represent socio-ecological-technical rather than a socio-technical system innovations, but also because their multifunctional potential may help to address the critique of 'technology fixes' being insufficient as solutions to urban challenges (Devolder and Block, 2015). For that reason, and given the way the concept highlights the role of innovation in resolving grand societal challenges, there is a need to develop a dialogue between the literatures on urban NBS and sustainability transitions. Such a dialogue is also expected to raise new questions as innovating with nature is potentially different from innovating with technology. For instance, 'nature' is often considered a public good (Bockarjova et al., 2018), which poses the risk of free-riding and resistance to market-based approaches to manage it. Therefore, capturing associated value, and return on investments, is potentially more challenging compared to other types of innovation (Kronenberg and Andersson, 2019). Nature-based innovation is also uniquely co-dependent on the activities, and therefore agency, of non-human species within a city (Bush, 2017), which is not always easy, or in fact desirable, to control.

We aim to bridge this gap between the literatures on NBS and sustainability transitions by developing a framework for the analysis of Nature-Based Innovation Systems (NBIS), which involves the institutions, networks and actors that are initiating, advancing and diffusing NBS. This framework serves to analyse, assess and inform the innovation process during the formative phase of a transition in which new actor configurations emerge to "pursue different innovation strategies and/or control a set of different resources" (Markard and Truffer, 2008, p.611) based on the identification of system-level dimensions influencing the development and diffusion of nature-based innovations. These dimensions act as performance indicators, signalling the extent to which an enveloping innovation system is able to leverage transformative change in dominant urban development practices, although so-called regime and landscape factors outside the innovation system such as competing technologies, cultural movements or macro-economic trends (e.g., Geels, 2002), co-determine the scope for mainstreaming NBS.

In developing this framework we draw inspiration from the Technological Innovation System (TIS) framework – one of the core theoretical approaches in the transitions literature to study the nature of socio-technical innovation – in particular concerning the way in which systems are conceptualized in terms of structures and processes shaping their establishment. The systematic and comprehensive analysis of such critical processes across empirical domains has contributed to the development of recommendations for policy and practice around technological innovations (Bergek et al., 2008), and we envisage the NBIS framework to play a similar role for nature-based innovation. A second objective of this research is to formulate recommendations for the future study of sustainability transitions more broadly based on a first explorative analysis of overlaps and differences between the TIS and NBIS frameworks.

2. Background: Technological innovation systems and nature-based solutions

2.1. Technological innovation systems

One of the key approaches used to study sustainability transitions is the framework and body of literature known as Technological Innovation Systems (TIS). The development of the TIS framework goes back to pioneering work from Carlsson and Stankiewicz (1991). They were primarily interested in explaining development and early diffusion of new technologies for which they developed a new conceptual understanding of technology as 'technological systems'. These were defined as the "networks of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilization of technology" (ibid: p.111). Later work focused explicitly on the question of how new 'green' technologies (e.g. renewable energy technology or biofuels) are developed (and diffused) by actors operating within a specific economic/industrial domain (Markard and Truffer, 2008).

Drawing on Carlsson and Stankiewicz (1991), the TIS framework poses that for (radical) innovations to be successfully developed, these require the existence or establishment of a 'system' that enables the development and diffusion of those innovations (Bergek et al., 2008; Hekkert et al., 2007; Jacobsson and Bergek, 2011). Whilst writings differ in their understanding of what constitutes a socio-technical system (Geels, 2004; Wieczorek and Hekkert, 2012), and their ontological nature can be debated (Geels, 2010), typical conceptual categories of the so-called *structures* of TIS are: 1) heterogeneous actor networks; 2) institutions; and 3) material infrastructures. The notion of *heterogeneous actor networks* refers to the observation that innovations are embedded in effective relations between a range of actors, including, but not limited to, suppliers, regulators, knowledge institutes and financial organizations. *Institutions* refer to both formal rules, such as regulatory frameworks or technical standards, and informal rules, such as traditions, cognitive schemes, values and norms influencing the legitimacy of innovations. *Material infrastructures*, finally, refer to physical aspects, such as machinery, pipelines, cables, buildings, tools and techniques, that enable the production, diffusion and use of innovations.

Whilst there is a long tradition of analysing structural components in technological systems, recent TIS literature has also started to unpack the 'functions' through which TIS develop or stall. Functions describe the processes that "directly influence the development, diffusion and use of a new technology and, thus, the performance of an innovation system" (Bergek et al., 2008, p. 408). The literature distinguishes various key functions for innovation systems (Bergek et al., 2008; Hekkert et al., 2007; Jacobsson and Bergek, 2011). *Entrepreneurial experimentation* refers to testing and learning about new technologies, applications and markets through which new entrepreneurial opportunities are created. *Knowledge development and diffusion* refers to the breadth and depth of the knowledge base regarding a particular innovation and to the ways in which knowledge is developed and travels. *Direction, or guidance, of search* refers to incentives and pressures that shape the direction of innovation, for instance through collective industry visions, expectations of future market potential or policy ambitions. *Resource mobilization* refers to the processes through which resources such as finance and human capital become available. *Market formation* refers to the various processes through which new markets are developed for the innovation. This includes for instance the articulation of user preferences and demand and (changes in) price mechanisms. *Legitimation* refers to socio-cultural and political processes through which new innovations become seen as socially appropriate and legally acceptable. Legitimation is often closely linked with the development of new discourses and cultural categories. Finally, the *development of positive externalities* refers to the ways in which an innovation system aligns with and benefits from 'external economies', such as a pooled labour market or specialized intermediate goods and service providers.

Among other debates (e.g. on the roles of agency and politics, interactions with different regions and countries and its normative use by researchers to support particular technologies), the TIS framework has been criticized for not sufficiently dealing with the role of the system's environment (Markard et al., 2015). Consequently, scholars have started to further expand understanding of the successful development and expansion of TIS by unpacking how these evolve in relation to various contexts (Bergek et al., 2015). Four different kinds of contexts are distinguished, which need to be understood as embedded and overlapping. Firstly, emerging TIS may draw on, or be constrained by, networks, institutions and resources embedded in *existing sectors*. For instance, the development of electric vehicles does not occur in a vacuum but in close (competitive and symbiotic) interactions with incumbent car producers. Secondly, an emerging TIS may interact with *political systems*, such as the existence or absence of beneficial political coalitions or policy champions lobbying for change beneficial to the TIS (Smith and Raven, 2012). Thirdly, TIS research increasingly argues for understanding the influence of *geographical context* on the development of TIS and vice versa (Coenen et al., 2012). Finally, a focal TIS may emerge, draw on and be constrained by *other TIS*, for instance, because they are competing for the same resources or, alternatively, draw on each other's value chains.

2.2. Urban nature-based solutions

Nature-based solutions is a relatively new concept employed to promote sustainable development, particularly in cities (European Commission, 2015). By sustainable urban development we refer to development that provides long-term social, economic and environmental benefits to urban areas (Bayulken and Huisingh, 2015; McCormick et al., 2013; Vandergert et al., 2015). This sits within a longer tradition of theorizing on the integration of nature (e.g. in combating the ills of industrialization) in cities within the urban planning literature (Van Schendelen, 1997). However, current theorizing is advancing the field in stressing the multifunctional benefits of urban nature as a solution to a broad range of urban sustainability challenges, which goes beyond highlighting the role of nature in the provision of isolated services such as recreation, air purification or biodiversity. As such, urban nature can come to be understood as an integral component of sustainability transitions in cities (Muñoz-Erickson et al., 2016).

Being part of the European Union's Research & Innovation agenda, NBS have been defined as "actions which are inspired by, supported by or copied from nature" (European Commission, 2015, p.5). The NBS concept acts as an 'umbrella' term for a range of nature-based innovations addressing sustainability challenges, varying regarding scope and size, spectrum of functions provided, extent of nature-based components and solutions offered (Nesshöver et al., 2017). The element of multifunctionality, where an innovation may generate multiple benefits simultaneously (e.g., a community garden providing healthy food, social cohesion and stormwater runoff mitigation), is another key feature of NBS (Dorst et al., 2019). As a result, they can be implemented to deal with complex urban sustainability challenges such as healthy urban living, food security, urban drainage, water retention, changing temperatures and air quality (Kabisch et al., 2016).

Similar to established understandings of innovation, an NBS can be a technological innovation in its own right (e.g. green roof technology) (Mees et al., 2013), albeit one of a hybrid green-grey quality. Others have argued, however, that an NBS concerns a type of innovation that aims to integrate ecological principles into traditional urban planning and development frameworks (Gulsrud et al., 2018). It follows from this that in some cases the innovation component rests less strongly in the final end-product and more so in the development of novel governance approaches and planning instruments, as well as innovative business models and citizen engagement approaches. All of which is required to accelerate their development and optimize their contribution to addressing multiple sustainability challenges simultaneously (European Commission, 2015; Kabisch et al., 2016; Lafortezza et al., 2018).

NBS have the potential to be cost-effective alternatives to technology-based infrastructure, with lower environmental footprints. However, their societal uptake is hindered by a lack of knowledge on systemic factors influencing upscaling processes (European Commission, 2015). Here we argue that the successful development of NBS in the context of urban sustainability transitions, similar to technological innovations, relies on a system comprising actor networks, institutions and infrastructures for development, diffusion and mainstreaming.

Any framework to analyse the development and diffusion of NBS is, however, unlikely to depend on the exact same sets of functions and structural factors as conceptualized for the TIS framework for reasons outlined previously: 1) NBS can be a product *or* a process phenomenon; 2) NBS aim at providing multifunctional benefits that often do not sit well with the sectoral organization of urban planning and development; and 3) NBS generate dispersed, mainly public, values that are difficult to capture by markets. Furthermore, NBS add an ecological component to socio-technical systems, which means that aspects such as ecosystems, landscape structure and environmental justice become part of the equation of a successful innovation (McPhearson et al., 2016). To this end, we coin the term Nature-Based Innovation System (NBIS), for which we develop a framework based on a literature review on enabling and constraining factors for nature-based innovation in cities.

2.3. Conceptualizing nature-based innovation systems

A first step in conceptualizing the NBIS framework is to articulate its focus and boundaries, i.e. its delineation. A TIS analysis is normally carried out at the level of a particular technology (e.g., wind turbines) or at the level of a knowledge or policy domain (e.g., renewable energy). However, for emerging fields lacking clear system boundaries, a TIS analysis on the field as a whole – charting the complexities of the broader system into which such new types of technologies are embedded – needs to be carried out before zooming in on individual technologies (Bergek et al., 2008). Likewise, we argue that there is a need to first explore the complete field of NBS – comprising a potpourri of different innovations varying from carefully planned sustainable urban drainage systems to spontaneous community gardens and from high-tech rooftop parks to a new governance instruments empowering urban greening by citizens – before studying individual types of NBS (e.g., green roofs) from an innovation system perspective. That is, NBS is explicitly conceptualized as an umbrella notion for all nature-based innovations (Dorst et al., 2019; Nesshöver et al., 2017).

What currently holds the NBIS (for NBS) together appears to be strongly guided by a vision and 'discursive strategy' as well as the associated distribution of resources through formal R&D programs such as the European Union's Horizon2020 program. This vision and discursive strategy intend to mobilize diverse and distributed innovation networks around the topic of urban nature, which is positioned to act as a boundary object for more coordinated and integrated efforts across a range of related activities, with the aim to shape urban transformation (Klerkx et al., 2010; Späth and Rohracher, 2010). This discursive and resource provisioning process has subsequently led to the formation of new actor networks adopting and acting upon this discourse and these resources (Lafortezza and Sanesi, 2019). Exactly if and how the vision of the nature-based city will inform shifts in urban infrastructures, institutions and development practices on a larger scale remains unknown.

Secondly, there is a need for identifying the factors or dimensions of the NBIS framework. As described in Section 2.1, a TIS is typically described along both its functions and its structures, with the former referring to the processes and activities that drive the performance and functioning of the system and the latter referring to its constitutive components (i.e. actor networks, institutions & infrastructures). Unlike the TIS approach, the NBIS framework does not (yet) distinguish between functions and structures. Instead, we refer to 'NBIS dimensions', which are the enabling and constraining factors for a well-functioning NBIS. As discussed previously, the boundaries of an NBIS have not yet crystallized. While we draw inspiration from TIS conceptualizations of structures and functions, we must give due regard to the opportunity that alternative conceptual categories could provide a better way of grasping what constitutes and drives innovating with urban nature. For instance, the role of the ecological component of the socio-ecological-technical system influencing NBS development and diffusion points toward the need for considering 'nature' or 'ecological infrastructure' as an NBIS structure, next to actor-networks, institutions and material infrastructures.

It should also be noted that, concerning process-types of NBS innovations (e.g., a new policy framework or business model), it may be particularly challenging to draw a clear boundary between structures and functions. For instance, activities to support the systemic integration of urban nature are in many cases about creating innovative *institutions*, such as the introduction of new green infrastructure or green roof strategies, or about innovative *actor networks* (e.g. the government and business community forging a Green Deal to explore new business models for green roofs), rather than about creating innovative (hybrid green-grey) technologies. In those cases, forging new *institutions* or *actor networks*, known as 'structures' in TIS, can also be characterized as 'functions' that are driving the performance and functioning of the innovation system. In short, factors defined as structures in the TIS framework (e.g., *institutions* or *actor networks*) often represent more than simply the constitutive elements of a well-functioning NBIS; they can also be directly created or reformed by those wishing to establish and accelerate nature-based urban innovation (Hillman and Sandén, 2008; Walrave and Raven, 2016), which is a practice more strongly resembling the definition of functions. For that reason, we do not attempt to distinguish between structures and functions in the current version of the NBIS framework, encompassing both innovative process and product phenomena.

3. Research design

The literature review was largely developed using an inductive approach: factors enabling and constraining nature-based innovation were identified in the literature, coded and categorized. NBS is an umbrella term that is still lacking a substantial research base. For that reason, the review incorporates the literatures around all types of *nature-based innovations* meeting the definition of an NBS. A second set of keywords served to constrain the search to papers studying NBS in *urban* contexts. In order to identify papers relevant to sustainability transitions, a third category of keywords was formulated around *innovation/transition* trajectories (see Table 1). All keywords were developed based on expert opinion by the authors of this manuscript and in consultation with

Table 1
Categories of keywords and search terms.

Keyword category	Search terms
Nature-based innovations	nature-based solution" OR "nature-based infrastructure" OR "engineering with nature" OR "ecological engineering" OR "catchment systems engineering" OR "green infrastructure" OR "blue infrastructure" OR "green wall" OR "green roof" OR "bioswale" OR "sustainable urban drainage system" OR "urban farm" OR "community garden" OR "multifunctional green space"
Urban context	urban OR city
Innovation/Transition	innovat* OR upscal* OR transition OR transformation OR experimentation

researchers from two other universities undertaking a review of how NBS is conceptualized as part of the EU Horizon 2020 NATURVATION Research and Innovation project on advancing assessment and enabling uptake of nature-based solutions in cities.

The search strategy was determined in an iterative way – we refined the approach based on the relevance and currency of returned materials. All searches were run in Scopus as the search engine with 'keywords' as search field and document type limited to article or review. We excluded all papers from before 2014 with 3 or fewer citations. To identify relevant literature, we ran three independent search queries, each with a different two-way combination of (the search terms corresponding to) keyword categories in Table 1 (Query 1: Nature-based innovations AND Urban context; Query 2: Urban context and Innovation/Transition; Query 3 Nature-based innovations AND Innovation/Transition). This strategy was chosen because the fields of NBS and innovation sciences have evolved largely independent from each other. Therefore, innovation scholars could have relied on cases describing nature-based innovations, while not applying the term 'NBS'. Likewise, scholars studying NBS could have identified factors enabling and constraining nature-based innovation without using any of the innovation or transition terminology.

Together, the three search queries returned a large number of results (c. 5000 hits), which was mainly due to a large number of hits (> 4000) for Query 2. To filter out relevant results for this query, we extended Query 2 with a third keyword category "Sustainability" (search terms: "sustainable development" OR sustainability OR "climate change" OR "water management") to exclude all papers not relevant to sustainability topics. This brought down the total to 1234 papers. The literature search was carried out in March 2017.

After this, each researcher from the author team independently evaluated and scored titles and abstracts for relevance, which resulted in the selection of 39 papers for review based on cumulative scores. Next, two researchers read the papers and coded statements regarding factors enabling or constraining nature-based innovation. Three papers were discarded, as a full read did not reveal any relevant statements. The resulting 36 papers were mostly empirical research papers drawing on case study research, but also on surveys, database analysis, expert workshops and discourse or document analysis. Two of the papers were reviews, while one paper was an overview article of a special issue; see Appendix A for a table of all reviewed papers. We focused the analysis only on claims and conclusions that could be supported by empirical data or reviewed material.

Next, we inductively derived themes accounting for the identified enabling or constraining factors in the literature. Two researchers independently identified claims and conclusions regarding enabling and constraining factors of NBS and coded all relevant extracts for a sample of the data in NVivo taking an incident-by-incident coding approach. They then reviewed each other's work and discussed the provisional codes. Based on this, the codes were refined using abductive reasoning, i.e. "paying attention to data that do not fit under existing interpretive rules" (Charmaz, 2014, p.201), to improve the delineation of themes and overall fit with the data. Subsequently, relevant extracts from all papers included in the review were coded based on the set of focused codes agreed by both researchers. Axial coding was applied to organize the focused codes into dimensions and subcategories of these (Charmaz, 2014), an overview of which is presented in the next section. Applying abductive reasoning, the researchers discussed the suitability of categories after finishing a first full round of the review, leading to additional modifications of a number of nodes and recoding of extracts. The final set of categories make up the dimensions of the NBIS framework.

4. Results

The literature review revealed a broad range of factors enabling or constraining nature-based innovation and these were aggregated into NBIS dimensions following the approach described in the previous section. Table 2 distinguishes and briefly describes the NBIS dimensions and their subcategories, which are further discussed below. These are presented in no particular order, all are considered to be relevant for an NBIS to perform well. This is followed by more detailed descriptions of the dimensions, highlighting the richness of the literature spanning different research traditions and epistemic logics.

4.1. Agency

This dimension refers to the roles that individuals and organizations are playing in the stakeholder landscape to support nature-based innovation by inspiring or pressing others to take action. Driven by agents of change – or 'champions' – organizations may demonstrate *leadership and power* in the development and uptake of NBS. Authorities can implement best practice interventions (Bayulken and Huisingh, 2015), advocate particular planning processes, introduce new forms of environmental regulation (Young et al., 2014), and influence actions of others through forging public-private partnerships and/or supporting community engagement (Bayulken and Huisingh, 2015; Brown, 2008; Mguni et al., 2015). Mayors in particular have a powerful impact on discourses or the emergence of new markets (Young et al., 2014), which demonstrates the important role of local government and politics in urban

Table 2
Overview of the dimensions and associated subcategories of the Nature-Based Innovation System (NBIS) framework.

Dimension	Dimension subcategory	Description
Agency	*Leadership and power*	People and organizations in the stakeholder landscape taking up leading roles to support NBS development, e.g. champions, mayoral leadership, frontrunners
	Commitment	Long-term support of NBS development by individuals and/or organizations is key to scaling of NBS
Discourse and vision		Framing NBS as an approach to urban reinvention addressing multiple locally relevant sustainability challenges in order to strengthen actor networks around NBS
Legislation and policies		The development of legislation, regulations, policies and strategies supportive of NBS or dissuading competing alternatives
Governance structure		Processes of governing that involve a broad range of stakeholders across horizontal and vertical scales, and across different sectors, domains and disciplines, with a diffusion of responsibilities and power
Collaborative arrangements	*Networks and partnerships*	Learning and experimentation with NBS relies on the development of formal and informal coalitions between individuals or organizations, and attempts to strengthen and diversify these by boundary spanners and intermediaries
	Participation	Processes of involving and engaging citizens in the planning, development and maintenance of NBS contributes to experimentation and the integration of local knowledge and place-based factors in NBS development
Learning	*Education and training*	Actors and organizations engaging in a process of active learning, with a view on increasing confidence and capacity around NBS development and scaling
	Research	Knowledge production in relevant areas such as assessment of ecosystem services and environmental governance, and developing a science-policy interface, contribute to effective value delivery of NBS
	Experimentation	Testing or piloting local-level projects or governance arrangements aimed at nature-based innovation contributes to learning about how to effectively design and implement NBS
	Monitoring and evaluation	Systematically assessing outputs, outcomes and impacts of NBS is crucial to ensure ongoing alignment with place-based factors
Resources	*Knowledge and human capital*	The availability of explicit knowledge concerning e.g. technical implementation of NBS, values of NBS, established governance structures and tacit knowledge on socio-ecological systems, as well as skills to e.g. create and manage NBS and engage in partnership working contribute to the effectiveness of NBS delivery
	Financial factors	The availability of funding, financial incentives or market demand for the development of NBS
	Technologies	The availability of technologies supporting NBS development, implementation and knowledge management
Place-based factors	*Built environment*	Adapting to urban (infra)structures, amenities and their distribution influences the capacity for NBS development and scaling
	Natural processes and endowments	Responding to local soil conditions, local flora and fauna, climatic conditions etc. in the planning, design and maintenance of NBS
	Societal conditions and dynamics	Aligning NBS with population dynamics and socio-economic change across space by involved actors
	Cultural frames of reference	Aligning NBS with broadly shared (i.e. societal) practices, norms and attitudes in order to improve the use and uptake

sustainability approaches (Bai et al., 2010; Ferguson et al., 2013). Non-profit organizations and enterprises can take on the role of early adopter or ‘frontrunner’ (Brown et al., 2013; Hendricks and Calkins, 2006), setting agendas for state-of-the-art research and the government, disseminating knowledge, initiating demonstration projects, engaging in product innovation, creating product quality standards, providing training and upskilling opportunities, and organizing shadow advocacy and lobbying (Bayulken and Huisingh, 2015; Brown et al., 2013; Mees et al., 2013; Schilling and Logan, 2008; Wolfram, 2018; Zhang et al., 2012).

Effective leadership in NBS development can inspire institutional *commitment* to sustainability, which is expressed as long-term, as opposed to piecemeal, support for change (Brown et al., 2013), and development of a shared change trajectory (Ferguson et al., 2013). It is crucial to avoid barriers to the development of sustainable practices and their upscaling, such as lack of a shared vision (Dupras et al., 2015), limited dissemination or marketing (Williams, 2016), lack of competencies, and organizational cultures inhibiting a sustainability transition (Bai et al., 2010). Commitment can translate in, for example, interdepartmental sustainability committees and dedicated resources for sustainability-related projects (Brown, 2008).

4.2. Discourse and vision

Urban sustainable development discourses (e.g., ‘eco city’ or ‘innovative city’) translate into norms of action, which builds up the ‘social momentum for change’ regarding nature-based development (Mees et al., 2013; Rohracher and Späth, 2014; Young, 2011). Social movements encouraged in this way may prompt the reorganization of social-ecological systems towards improved ecosystem service delivery (Ernstson et al., 2010). Urban reinvention visions need to incorporate the viewpoints of various societal and professional groups to be effective (Chaffin et al., 2016; Mguni et al., 2015; Young, 2011), which explains why government policies and goals are sensitive to discourse shifts (Ferguson et al., 2013).

In addition, it is important to frame NBS as an 'enabler' (or driver) as opposed to a 'barrier' to growth if wanting to appeal to a broader set of decision-makers influencing urban development (Horwood, 2011); socio-economic goals need to be presented alongside environmental goals (Matthews et al., 2015). They need to take into account locally important challenges and opportunities (e.g., provide a focus on innovation and reinvention in a post-industrial city) (Treemore-Spears et al., 2016). The public discourse may also undermine NBS upscaling; e.g., green roofs are often perceived as unsafe and high-maintenance (Hendricks and Calkins, 2006). Government campaigns and the media play an important role in influencing discourses while in some cases also triggering the vocalization of opposing viewpoints (Bai et al., 2010; Ferguson et al., 2013).

4.3. Legislation and policies

Different types of regulation can be effective in supporting NBS in cities. This includes duties of care (Mees et al., 2013), environmental regulation and zoning (Young et al., 2014), and building codes, which can lead to e.g. compulsory stormwater regulation (Mees et al., 2013; Young et al., 2014). Land zoning has been reported to sometimes act as a barrier to NBS development (Schilling and Logan, 2008).

Public policy also plays a crucial role in fostering sustainable urban development (Bai et al., 2010). For example, strategic plans and policies focused on developing green infrastructure at different scales enhances opportunities for its development, stewardship, financing and public engagement (Young, 2011). Plans and policies are most effective if prepared holistically taking into account broader regional dynamics (Haaland and van den Bosch, 2015), and if they apply a broad perspective by considering multiple political, financial and local aspects of urban planning (Bayulken and Huisingh, 2015; Young et al., 2014) and a long-term vision (Haaland and van den Bosch, 2015). They benefit from a data-driven approach (Young, 2011) and extensive consultation (Treemore-Spears et al., 2016). Specific policy documents for individual NBS (e.g., an urban forest strategy) can be effective in the delivery of high-priority NBS (Mees et al., 2013). Individual organizations can also promote NBS development by adopting sustainability principles and performance indicators using their internal strategies and policies for all departments (Brown, 2008).

In addition to regulatory instruments, communicative and financial instruments can also be employed to encourage NBS development (Mees et al., 2013). For example, information campaigns were used in Basel to overcome resistance to green roof implementation. They are particularly effective when combined with financial incentives such as subsidies (Mees et al., 2013). Land marketing (e.g., vacant land for urban forest development) and alternative forms of financing (e.g., foundation grants, tax incremental finance or voter-supported bonds) are alternative types of financial instruments (Schilling and Logan, 2008). Finally, disincentivizing unsustainable practices (e.g. through environmental levies or stormwater fees) can also support investment in NBS (Brown, 2008; Dupras et al., 2015; Hendricks and Calkins, 2006).

4.4. Governance structure

An approach to governing that involves different actors, along with a distribution of power and responsibilities across the stakeholder landscape as a whole as well as within individual organizations, exerts a positive influence on the development and diffusion of nature-based innovation. A first important factor is the presence of complex structures (Mguni et al., 2015) or 'institutional thickness' (i.e. the density of the network of institutions and intermediaries concerned with sustainability interventions) (Wolfram, 2018). It is important that there is a balanced variety of actors in such a network to optimize administrative and organizational capacity as well as flexibility (Chaffin et al., 2016). Related to this, others have called for decentralized management approaches engaging actors beyond traditional governance structures (i.e. private & societal actors) and from multiple disciplines and policy domains (Brown, 2008; Ferguson et al., 2013; Muñoz-Erickson et al., 2016). Such a polycentric system can also encourage a wider variety of stakeholders to engage with sustainability topics (Vandergert et al., 2015). However, this requires a balanced distribution of power (e.g., a small-scale farmer typically has less influence than a large-scale food retailer) (ibid.).

A drawback of decentralized governance is that fragmentation can lead to diffusion of responsibility, preventing strong leadership from emerging (Mguni et al., 2015; Muñoz-Erickson et al., 2016), and blurring of authority, undermining the perceived threat of sustainability issues (Castán Broto and Bulkeley, 2013; McCormick et al., 2013). Organizations and departments or sections therein therefore need to clarify responsibilities and coordinate actions (Kabisch et al., 2016; McCormick et al., 2013; Tian et al., 2012; Wamsler, 2015), also across different scales (Young et al., 2014). At the municipal level, allocating responsibility for green spaces to a single unit may in some cases actually be more effective than a decentralized approach (Haaland and van den Bosch, 2015).

4.5. Collaborative arrangements

Networks and partnerships between different types of stakeholders, variably called public-private partnerships, interagency agreements, science-practice interfaces, urban living labs and transdisciplinary knowledge systems are key to overcoming challenges associated with fragmentation across scales and between sectors (Bulkeley et al., 2016; Castán Broto and Bulkeley, 2013; Ernstson et al., 2010; Kabisch et al., 2016; McCormick et al., 2013; Muñoz-Erickson et al., 2016; Schilling and Logan, 2008; Treemore-Spears et al., 2016; Wolfram, 2018). Partnership working is conducive to organizational commitment (Brown, 2008), trust building (Muñoz-Erickson et al., 2016), mutual learning, knowledge exchange and the negotiation of dissimilar viewpoints (Mguni et al., 2015; Muñoz-Erickson et al., 2016; Wolfram, 2018), experimentation (McCormick et al., 2013), shared visioning (Kabisch et al., 2016), the development of workable policies and plans (Schilling and Logan, 2008), rethinking regulation and rules (Farrelly and Brown, 2011), and expanding capacity to attract funding (Ghose and Pettygrove, 2014). Doing so therefore improves success rates of sustainability interventions (Brown, 2008) and their likelihood of upscaling, in particular when vertical links with national government are established (Bai et al., 2010).

Bridging organizations are key to understanding transition pathways by providing policy recommendations based on a breadth of experiments, encouraging the exchange of complimentary capital, knowledge and good practices between sustainability initiatives and building overall confidence in the outcomes of experiments (Bayulken and Huisingh, 2015; Brown et al., 2013; Farrelly and Brown, 2011). Individual intermediaries, such as mediators, knowledge brokers or institutional entrepreneurs also contribute to the establishment of new connections between stakeholders (Ghose and Pettygrove, 2014; Wolfram, 2018) by enhancing buy-in, resourcing and alignment with policy (Naylor et al., 2012; Vandergert et al., 2015).

Trust building in networks is important to create relational proximity: "a circumstance where mutual understandings or a common "gaze" (inter-subjectivity) emerges regarding what constitutes success, sustainability, innovation, etc." (Murphy, 2015, p.79). Process transparency and stakeholder legitimacy are key to this (Kabisch et al., 2016). To ensure sustained network functioning, the process needs to align with the interests and capacity of stakeholders (Treemore-Spears et al., 2016). A clear discrepancy in interests and concerns of stakeholders can act as a barrier to partnership working (Wamsler, 2015); housing associations, developers and investors are particularly important to get on board for urban NBS (Kabisch et al., 2016). Networks have also been initiated to oppose the implementation of NBS (Ghose and Pettygrove, 2014).

Active public *participation* and empowerment of civil society can be important strategies for NBS development and implementation (Bulkeley et al., 2016; Wolfram, 2018), especially in cities with high levels of private landownership (Young et al., 2014; Young, 2011). Community engagement also has the potential to improve the public support and acceptance of sustainability interventions (Bayulken and Huisingh, 2015), ultimately leveraging sustainability transformations through positive feedbacks on political and economic support systems (Rohracher and Späth, 2014; Young, 2011; Schilling and Logan, 2008). Public participation can have the added benefit of more inclusive planning and decision-making (Treemore-Spears et al., 2016; Williams, 2016), building community capacity (Schilling and Logan, 2008), while also allowing for an improved understanding of the city as a socio-ecological system (Ernstson et al., 2010). Billboards, brochures, websites and advertisements are important tools to encourage public participation (Chini et al., 2017; Schilling and Logan, 2008).

4.6. Learning

Processes of learning and experimentation help to build capacity for nature-based urban development (Chaffin et al., 2016). That is, it enables decision-makers to make an appropriate assessment of current urban challenges (e.g., climate change impacts; McCormick et al., 2013) and potential solutions to these (Young, 2011). Learning about challenges and the potential of nature-based innovations to address these facilitates demand, support and acceptance for NBS amongst the public, private and third sectors as well as the general public (Naylor et al., 2012; Young, 2011; Zhang et al., 2012). Sharing best practices from elsewhere (Dupras et al., 2015) and learning from, hence documenting, previous mistakes or unexpected results are good starting points for learning (McCormick et al., 2013; Wamsler, 2015). In addition, learning benefits from observing the practice elsewhere and from a relative ease of adopting that practice. This is an issue with e.g. green roofs which add a layer of complexity to conventional practices (Hendricks and Calkins, 2006). Learning needs to go beyond perfecting current actions within a given mental model to also include reconsidering value and motivational models themselves (i.e. second-order learning) (Wolfram, 2018). An important condition for this is that actors and institutions respond flexibly to new and unexpected information (Muñoz-Erickson et al., 2016).

Education and training, including on-the-job training, improve the understanding and awareness of stakeholders regarding the benefits of sustainable alternatives to existing infrastructures (Hendricks and Calkins, 2006; Treemore-Spears et al., 2016; Young, 2011). When provided to citizens (i.e. 'outreach'), it is predictive of community engagement (Mees et al., 2013; Tillie and van der Heijden, 2015; Young et al., 2014), empowerment (Treemore-Spears et al., 2016; Wolfram, 2018) and support for sustainable development (Haaland and van den Bosch, 2015; Tian et al., 2012; Tillie and van der Heijden, 2015; Treemore-Spears et al., 2016). Rather than sharing information in a single format, it is more effective to make use of knowledge brokers or mentors who speak to stakeholders in their own language (Naylor et al., 2012) and to communicate using a variety of (social) media outlets (Young, 2011).

Research represents an important foundation for urban planning and governance (Treemore-Spears et al., 2016). Knowledge providers, such as scientific bridging organizations, have been identified as enabling factors of innovation diffusion during transitions (Brown et al., 2013). The frequent gap between research and practice is seen as a barrier to sustainable development (McCormick et al., 2013). Consequently, there is a need for more interdisciplinary research and engagement of end-users (Ernstson et al., 2010; Naylor et al., 2012). What is considered relevant research or knowledge is influenced by local circumstances, and may tackle topics as varied as ecosystem service valuation, assessing and monitoring (local) socio-ecological qualities (e.g., datasets on urban biodiversity or socioeconomic neighbourhood conditions), citizen preferences for sustainability interventions and the effectiveness of collaborative governance arrangements (Dupras et al., 2015; Tillie and van der Heijden, 2015; Young, 2011; Schilling and Logan, 2008).

Experimentation, alternatively called learning-by-doing, can be defined as "interventions to try out new ideas and methods in the context of future uncertainties" (Castán Broto and Bulkeley, 2013, p.93). Due to the multi-actor nature of experimentation (Castán Broto and Bulkeley, 2013; Chini et al., 2017), it contributes to new forms of social learning (Brown et al., 2013; Rohracher and Späth, 2014), and the rethinking of values, identities and governance approaches (Wolfram, 2018), or even business models. Iterative experimentation is crucial to sustainability transitions as it encourages new sustainability ideas to enter public and political discourses (Ernstson et al., 2010; Rohracher and Späth, 2014), broadens the spectrum of available solutions to sustainability challenges (McCormick et al., 2013), provides increased confidence to further invest in innovations and helps to maintain engagement of committed people (Ferguson et al., 2013; Naylor et al., 2012; Young, 2011). Furthermore, it provides an opportunity to test and refine innovations (Naylor et al., 2012; Treemore-Spears et al., 2016).

Playing a crucial role in iterative experimentation, *monitoring and evaluation* of NBS contributes to the refinement of NBS in order to ensure a sustained delivery of benefits (Bayulken and Huisingh, 2015; Naylor et al., 2012; Treemore-Spears et al., 2016; Chini et al., 2017). Advantages of this practice include a better understanding of the outcomes of different approaches (Kabisch et al., 2016; Treemore-Spears et al., 2016), more effective strategy development (Dupras et al., 2015; McCormick et al., 2013; Naylor et al., 2012) and a sense of urgency amongst key stakeholders (Ernstson et al., 2010). Weak or neglected monitoring undermines stakeholders' commitment to projects (Zhang et al., 2012) and limits opportunities for comparison between interventions (Bayulken and Huisingh, 2015). A challenge around monitoring and evaluating NBS is that some social and environmental benefits are difficult to quantify (e.g., cultural ecosystem services) (Chaffin et al., 2016; Ferguson et al., 2013; Kabisch et al., 2016), which inhibits the process of incorporating these positive externalities into the decision-making frameworks of profit-oriented enterprises (Horwood, 2011).

4.7. Resources

The standard of NBS implementation and maintenance is strongly influenced by the availability of *knowledge and human capital.* Knowledge needs to be developed in different areas. Firstly, knowledge is needed regarding the technical implementation and maintenance of green roofs, urban trees and other greenery (Hendricks and Calkins, 2006; Zhang et al., 2012). Secondly, NBS need to be tailored to socio-ecological contexts; therefore knowledge about local ecological, climatological and social-cultural conditions, and how they interact with NBS, is also crucial (Dupras et al., 2015; Naylor et al., 2012; Treemore-Spears et al., 2016). Furthermore, data on current distribution and quality of NBS across the city leads to better informed decisions on *where* to invest resources (Haaland and van den Bosch, 2015), while having an understanding of established governance structures can increase the effectiveness of local coalitions spearheading nature-based innovation (Young et al., 2014). Finally, relevant 'soft skills' for partnership working and outreach have been identified as well. These include negotiation skills, conflict management and confidence building (Bayulken and Huisingh, 2015; Wolfram, 2018).

Financial factors such as diverse funding sources and "sound financial planning" (Bayulken and Huisingh, 2015, p. 158) were often listed as essential to the success of nature-based innovations or, if inadequate, as constraining factors to urban sustainable development (Bai et al., 2010; Farrelly and Brown, 2011; Naylor et al., 2012; Wamsler, 2015; Wolfram, 2018; Young, 2011; Zhang et al., 2012). Institutionalized spending, grant programmes and subsidies are prominent financing instruments for NBS (Bayulken and Huisingh, 2015; Mees et al., 2013; Young et al., 2014; Zhang et al., 2012). The analysis of *how* this funding is being acquired, e.g. through environmental regulation, exploring public-private partnerships as collaborative arrangement or by building networks focused on the development of new business models (Bayulken and Huisingh, 2015; Ghose and Pettygrove, 2014; Young et al., 2014) is analysed in other parts of the NBIS framework.

The availability of *technologies* for NBS implementation is another important condition for some types of NBS (e.g. green rooftops) (Wolfram, 2018), although not in all cases (Bai et al., 2010). Due to limited adoption rates, the financial cost of these technologies can be high, which can limit access (Hendricks and Calkins, 2006). Technology can support processes of inventorying, resource monitoring and knowledge management (Schilling and Logan, 2008). An example of the latter is the 'smart city planner', an interactive GIS system drawing together different types of social, environmental and structural data and highlighting different combinations of challenges across neighbourhoods (Tillie and van der Heijden, 2015).

4.8. Place-based factors

The pathways of nature-based innovations tend to be bound to a specific place: "As urban and political geographers have shown, place […] can have a significant influence on urban-regional or community development processes" (Murphy, 2015, p.83). The *built environment* dimension is also significant because urban NBS are either attached to or situated between built structures such as green or blue space (Kabisch et al., 2016). For example, cities with large areas of low-rise development are more suitable for extensive green roofs given easier rooftop accessibility and because they typically have less of their surface taken up by building services (Zhang et al., 2012). Grey infrastructures are also important given that the functionality of NBS varies based on proximity to e.g. stormwater flows in streets or drainage pipes (Chaffin et al., 2016). Conversely, the availability of vacant space influences the feasibility of NBS; compact cities call for alternative greening approaches (Haaland and van den Bosch, 2015; Tian et al., 2012; Wamsler, 2015). At the macro level, city size matters in capacity building for, and scaling of, NBS as different types of information are exchanged more frequently in bigger cities (Ernstson et al., 2010; Young, 2011).

The important role of the built environment is further compounded by the fact that it cannot be easily changed – it has high obduracy (Chaffin et al., 2016; Muñoz-Erickson et al., 2016). This has repercussions for the stability of the urban development regime: existing urban infrastructures "serve specific constituencies and interests connected to specific property and appropriation regimes" (Young et al., 2014, p. 2581). A third argument for considering the built environment is that it is known to shape local identities and sense of place, which can prompt sustainable development action or inaction (i.e. agency) (Bayulken and Huisingh, 2015)

Natural processes and endowments influence the functioning of nature-based innovations. For example, plants productivity is co-determined by local soil characteristics and climatic conditions (Chaffin et al., 2016; Tian et al., 2012). They can also act as 'pulses', in the form of natural hazards and disasters (e.g., increased rainfall variability inducing floods or droughts), influencing the perceived urgency of action through NBS implementation on underlying issues such as climate change and sea-level rise (Muñoz-Erickson et al., 2016; Young et al., 2014; Ferguson et al., 2013). However, a sense of urgency as a result of natural hazards may also lead to rushed decision-making causing decision-makers to cast aside innovative fit-for-purpose solutions in favor of centralized infrastructure (Ferguson et al., 2013). There is a continuous dynamic interplay between the city and the landscape, which is acknowledged by social-ecological systems theory (Ernstson et al., 2010)

Societal processes similarly influence the availability of and scope for nature in cities. For example, urbanization and population growth may lead to environmental degradation, yet could also prompt demand for nature-based innovation by stimulating processes of economic transformation and urban revitalization (McCormick et al., 2013; Tian et al., 2012). The regional economic role of a city and its natural environment (e.g. as tourist destination) similarly influences scope for NBS (Young et al., 2014), while an unequal distribution of wealth in the city acts as a barrier to urban sustainable development (Treemore-Spears et al., 2016). However, public health, poverty and employment issues have also been described as triggers (Bai et al., 2010). Another factor that is likely to play a role in the effectiveness of urban NBS is the public–private land ownership ratio (Dupras et al., 2015; Mguni et al., 2015; Wamsler, 2015). High-impact events or societal trends (e.g., riots, home abandonment or rising living costs) can serve to increase perceived urgency of addressing sustainability challenges such as poor environmental quality (Muñoz-Erickson et al., 2016). A sense of urgency around sustainability challenges is predictive of regime actors changing their attitude or commitment to sustainable development (Muñoz-Erickson et al., 2016; Rohracher and Späth, 2014).

Finally, local *cultural frames of reference* shaped by historical and geographical processes are also an important factor for nature-based innovations and their propensity to be translated to different geographic contexts. Consumption habits, entrepreneurial orientation, level of trust in government, attitudes to co-production, artistic activity, aesthetic preferences and other place-based conventions, practices and meanings all influence the diffusion of nature-based innovations (Chaffin et al., 2016; Hendricks and Calkins, 2006; McCormick et al., 2013; Murphy, 2015; Treemore-Spears et al., 2016; Williams, 2016; Wolfram, 2018; Young, 2011).

5. Discussion

5.1. A comparison between the NBIS and TIS frameworks

When comparing the NBIS and TIS frameworks, we observe a varying level of overlap between NBIS dimensions and TIS functions. Strong parallels can be found between the NBIS dimension of Resources and the TIS function of Resource Mobilization. Likewise, there is good correspondence between: (1) the NBIS dimension *Discourse and vision* and the TIS function *Direction, or guidance, of search* with the latter having a stronger focus on how this shared goal is translated into policies, regulations and plans; and (2) the NBIS dimension of *Learning* and TIS function of *Knowledge development and diffusion* with the latter arguably having a more explicit focus on technical knowledge, production and marketing systems required for innovation system performance and the former a stronger emphasis on monitoring and evaluation.

Two of the NBIS dimensions – *Legislation and policies* and *Collaborative arrangements* – more closely resemble TIS structures – *Institutions* and *Heterogenous actor networks*, respectively. This is in line with the observation made previously, in Section 2.3, that functions and structures cannot be straightforwardly separated concerning the study of NBS from a systemic perspective.

The remaining three NBIS dimensions – *Place-based factors, Governance structure* and *Agency* – relatively have the weakest correspondence with TIS functions or structures, which likely points to underlying differences between technological and nature-based innovations, and provides cues as to how the study of NBS from a systemic perspective could enrich understandings of sustainability transitions.

Whilst the *place-based* analysis of a TIS has received substantial attention over the previous years and can very well be part of a TIS analysis (Truffer et al., 2015), nature-based innovation arguably harbours an even stronger dependence on local conditions such as urban ecosystem features (e.g., species and soil features, climatic conditions) and socio-economic and -cultural dynamics such as urban densification and changes in recreational patterns (Dorst et al., 2019). Although a similar argument could be made for technologies – TIS are strengthened by mobilizing complementary technologies (e.g., Bergek et al., 2008) – the actual design of the technical product or service is often consistent across different contexts, whereas for an NBS like a multifunctional park the optimal choice of e.g. plants, paths and area of playing fields varies from place to place. NBS are also place-dependent in the sense that their functioning is influenced by their connectivity with other nature. For example, a green roof that is connected with other green roofs delivers biodiversity value above and beyond an isolated green roof (Braaker et al., 2014). The place-based and context-sensitive character of NBS raises questions in relation to the ease in which nature-based innovations can scale and diffuse in an unmodified way beyond their initial place-specific applications.

The role of *Governance structure* – in particular network governance – has likewise been acknowledged in the TIS literature as a type of resource at the level of an actor network, which is key to trust building, goal formulation and problem solving (Musiolik et al., 2012). Concerning the NBIS framework, governance structure is not a sub-category but a dimension in its own right because it refers to the mode of governance in the stakeholder landscape as a whole (e.g. dominant polycentric governance vs. centralized governance), which goes beyond the structure of formalized networks. For example, adopting a holistic and polycentric governance approach in urban areas can strengthen the role of civil society in carving out new NBS pathways (Buijs et al., 2016; Raymond et al., 2017). Traditionally, such meso-scale analysis of governance structure has been conceived to be beyond the boundaries of a TIS, which is limited to the actors operating within a particular knowledge field around new product and/or technology development in which firms and academics qualify as major players (Bergek et al., 2008; Markard and Truffer, 2008). However, our findings indicate that this is not necessarily so for NBIS where different levels of government across different geographical areas are often amongst key agents experimenting with nature in cities and may purposively adapt governance structures to enable further experimentation by other actors and networks (also see the point made on why we are not distinguishing between NBIS structures and functions in

Section 2.3). Although this dimension is perhaps more relevant for the formation of NBIS when compared to TIS given the central role of local government, non-profits and community groups in the former, a notable exception would be when studying a TIS from the perspective of new user practices as opposed to an emerging technology, e.g. see Dewald and Truffer (2012), given that (the activation of) informal institutions such as citizen associations, local government and their resources have been shown to strongly affect this.

The NBIS dimension *Agency* is not conceptually excluded from the TIS literature (e.g., Farla et al., 2012), but the TIS literature has tended to focus on supply-side agency of innovation systems, perhaps with the exception of explicit attention for market formation, and some notable exceptions that have highlighted the important role of local communities and civil society in early market formations for sustainable technologies (Dewald and Truffer, 2012). In addition, agency has been attributed to TIS structures using notions such as 'prime movers' (Jacobsson and Johnson, 2000) and 'system builders' (Hellsmark and Jacobsson, 2009). However, agency has never been formally acknowledged as a TIS function, i.e. system building is formally not considered to be a key innovation processes. This is surprising given the identification of positive interactions of this factor with all of the other TIS functions (Hellsmark and Jacobsson, 2009), which is unlike system structures that are thought to have no predictive power over the performance of systems (Markard and Truffer, 2008). The present review suggests a critical role for strong *public* sustainability leadership in predicting nature-based innovation – NBS provide mainly public values which cannot straightforwardly monetized on the market (Bockarjova et al., 2018). However, this not to say that the same does not apply, at least to some extent, to technological innovation – e.g. networks developing in response to policy instruments such as subsidies to support the uptake of renewable energy (Jacobsson and Johnson, 2000). Agency is therefore not *de facto* more central to the development of socio-ecological-technical than socio-technical systems. These findings could also account for why the NBIS framework does not include a dimension that can be likened to the TIS function of *Market formation*. Alternatively, it could be explained by market formation processes being understudied in the NBS literature in which a systemic focus is largely lacking as "for an emerging TIS, or one in a period of transformation, markets may not exist, or be greatly underdeveloped" (Bergek et al., 2008, p. 416). Some indications for market formation processes taking place can be found in the present review such as non-profits taking the role of early adopters (*Agency* dimension), the development of regulation to stimulate the uptake of NBS (*Legislation and policies* dimension) and the need for collaborative networks for the scaling of interventions (*Collaborative arrangements* dimension). This suggests that market formation processes can be studied as part of an NBIS analysis, although likely playing a less central role than in TIS – nature provides many collective instrumental and relational values (Chan et al., 2016).

5.2. Implications for future research

The above has revealed a range of enabling and constraining factors for nature-based innovation in cities based on an inductive approach to framework development, which have been aggregated to a number of NBIS dimensions. It should be noted that the identified dimensions are strongly interrelated and mutually reinforcing. For example, a holistic and polycentric governance structure contributes to overcoming policy fragmentation and is therefore essential to policy development supportive of NBS development and the mobilization of resources, which in turn contributes to facilitating collaborative arrangements and the development of nature-based discourses on urban sustainability. It is therefore essential to understand this list of dimensions as the first step towards developing a more nuanced systems perspective on innovation with nature, with further work to be done on unpacking their mutual relations (see Suurs and Hekkert, 2012, for a similar argument on interrelatedness of functions in TIS).

To our knowledge, the present review provides the first attempt to apply an innovation system perspective to the study of NBS. We argue that the ongoing pursuit of system-level studies of NBS dynamics would advance understanding of nature-based innovation in a number of ways. First of all, it provides insight into pathways through which NBS evolve over time. TIS are rooted relatively strongly in a process-based and evolutionary understanding of the dynamics of innovation. Explanations of the success, failure and direction of technological innovation pathways are found to rest in the ways in which events and interventions evolve over time. For example, knowledge development and diffusion may spur the entrance of new entrepreneurs into an innovation system, who subsequently design experiments in niche markets, which, when successful, shape wider legitimacy and regulatory developments, which then enhance the conditions for new market developments and knowledge demands, and so on and so forth. Tracing such evolutionary developmental trajectories over time has been a key achievement of TIS literature and has enabled the identification of particular process patterns in innovation system dynamics (e.g., Suurs and Hekkert, 2012). Similarly, the sustainability transitions literature more generally has advocated the relevance of such process-based analysis, leading to the identification of different transition pathways, which are dependent on the timing of events and agency of actors at different levels (Geels et al., 2016). Future iterations of the NBIS framework should attempt to more explicitly integrate such a process perspective and explore its relevance for the analysis and governance of NBS.

Moreover, work in the field of TIS, and sustainability transitions literature more generally, has resulted in a comprehensive understanding regarding the role of various contextual dynamics in the development of particular innovation pathways. A key insight from this literature of relevance to scholars studying NBS innovation processes is that new pathways emerge out of the interplay between incumbent sectors and an emerging innovation system in focus. Empirical analysis, for instance in the energy and mobility domains, has demonstrated how incumbent systems have strong path dependencies and are supported by powerful actors (Avelino and Rotmans, 2009; Geels, 2014; Smink et al., 2015), which makes shifts and adaptation to more sustainable alternatives notoriously difficult. Such an explicit conceptualization of 'systemic contexts' beyond project-based contexts may generate a more modest and realistic account of what may be achieved in the shorter term regarding innovating with urban nature. Given that NBS are understood to have multiple social, economic and ecological benefits for urban developments, we expect that their systemic contexts will have a high order of complexity, relating to path dependencies in political and financial systems as well as industrial systems related to urban development. Future research concerning NBIS would need to take into account the roles of these systems on the development and diffusion on NBS that may not become apparent in case studies at local project-level.

Finally, it is important to stress that there is also a need for additional research on the NBIS framework in order to validate the present set of dimensions and gain a better understanding if and in what way these can be split into functions and structures (see Section 2.3). We do not rule out that future studies of a more systemic nature would provide evidence justifying changes to the NBIS framework, such as the addition of a 'market formation' dimension if this is a process that is required for the innovation system to perform well (Wieczorek and Hekkert, 2012). At the same time, it should be acknowledged that NBS are conceived by some to be incompatible with a neoliberal market logic, which would intensify social-ecological trade-offs, including 'green gentrification' (Haase et al., 2017), and commodification of place in which "use value is superseded by exchange value" (Crossan et al., 2016, p.953). Therefore, the role of market formation could vary between different types of NBS, potentially supportive of (private) green roofs and facades, while posing a threat to community gardens – a question that needs to be explored in future research.

6. Conclusion

Drawing on a literature review on nature-based innovation in cities, the present study has revealed clusters of enabling and constraining factors for a well-functioning nature-based innovation system (NBIS). These show parallels, as well as profound differences, with the functions and structures of the TIS framework, a popular tool used for studying innovation system dynamics of sustainable technologies. These findings challenge current understandings of sustainability transitions, which have been based on studies of socio-technical rather than socio-ecological-technical systems. First of all, these studies have likely underestimated the influence of place-specific priorities and requirements regarding e.g., economic development, natural endowments, urbanization and health challenges, on sustainability transitions. Secondly, the present findings point towards a need for including agency in the analysis of innovation systems. Thirdly, the central role of governance structures in the NBIS framework highlights a need for acknowledging the mode of governance prevalent in urban societies and, associated with this, the role of power relationships in relation to innovations. Given that a systemic perspective has been largely lacking in the literature on NBS, additional research is required to develop a more elaborate understanding of the processes through which nature-based innovation develops over time as well as the way that the NBIS interacts with the broader urban development regime. This could help to further develop the NBIS framework, and to better understand the pathways to overcoming systemic barriers faced by NBS advocates. We conclude that an ongoing dialogue between the literatures on NBS and sustainability transitions is required. This would provide a much-needed understanding of how NBIS become established, grow over time, and eventually may challenge dominant institutions, values and belief systems driving unsustainable urban development. In addition, it would pave the way to the system-level study of sustainability solutions that are deliberately devised to take into account the mutual interplay between socio-technical and socio-ecological systems, which is a much needed endeavour in a time where interlinked sustainable development challenges call for integrated and multifunctional solutions benefiting both people and their natural support systems.

Declaration of Competing Interest

This research has been funded by the European Commission's Horizon 2020 research and innovation programme under grant agreement no. 730243 and participating partners in the NATURVATION project.

Acknowledgement

We thank two anonymous reviewers for their valuable reflections and detailed comments, which helped us to improve the quality of this paper. This research has been funded by the European Commission's Horizon 2020 research and innovation programme under grant agreement no. 730243 and participating partners in the NATURVATION project.

Appendix A. Overview of reviewed papers

- (Bai et al., 2010)
- (Bayulken and Huisingh, 2015)
- (Brown, 2008)
- (Brown et al., 2013)
- (Bulkeley et al., 2016)
- (Castán Broto and Bulkeley, 2013)
- (Chaffin et al., 2016)
- (Chini et al., 2017)
- (Dupras et al., 2015)
- (Ernstson et al., 2010)
- (Farrelly and Brown, 2011)
- (Ferguson et al., 2013)
- (Ghose and Pettygrove, 2014)
- (Haaland and van den Bosch, 2015)
- (McCormick et al., 2013)
- (Mees et al., 2013)
- (Mguni et al., 2015)
- (Muñoz-Erickson et al., 2016)
- (Murphy, 2015)
- (Naylor et al., 2012)
- (Rohracher and Späth, 2014)
- (Schilling and Logan, 2008)
- (Tian et al., 2012)
- (Tillie and van der Heijden, 2015)
- (Treemore-Spears et al., 2016)
- (Vandergert et al., 2015)
- (Wamsler, 2015)
- (Williams, 2016)

- (Hendricks and Calkins, 2006)
- (Horwood, 2011)
- (Kabisch et al., 2016)
- (Matthews et al., 2015)
- (Wolfram, 2018)
- (Young, 2011)
- (Young et al., 2014)
- (Zhang et al., 2012)

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