Nature-Based Innovation Systems: Introducing a framework to analyse the innovation pathways of nature-based solutions

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Abstract
In the sustainability transitions literature, technologies play a predominant role and are considered as critical components in societal transitions towards sustainability. However, the emerging discourse on nature-based solutions (NBS) for sustainability transitions raises the question to what extent current technology-oriented frameworks applied to understand transition processes can adequately account for activities of agents in the development and diffusion of NBS. In other words, can they account for non-technological or hybrid innovation systems critical to a sustainability transitions? This paper represents a first attempt to address this question by exploring the validity of the Technological Innovation System (TIS) approach in explaining nature-based innovations. To this end, the paper proposes a new concept – Nature-Based Innovation Systems (NBIS). On the basis of a systematic literature review on pathways to NBS development and diffusion we find both overlaps and differences between current understandings of TIS and NBIS. These differences can be attributed to the unique nature of NBS as place-based, living interventions that by definition need to deliver multifunctional benefits and can only do so through strong embeddedness in volatile social-ecological systems. We conclude that, although TIS and NBIS cannot be conceptually equated, applying NBIS alongside the TIS approach could lead to a more holistic understanding of sustainability transitions. Future research is needed to explore the role of the broader regime context on NBIS functioning, in particular for interventions at the interface of social, technological and ecological systems.

1 Introduction

The sustainability transitions literature continues to highlight the role of technologies in sustainable development (Geels & Schot 2010). 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 technology-oriented frameworks (Hekkert et al. 2007; Geels 2002), and in 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 that on smart city visions.

This paper adds that the literature so far has paid limited attention to the role of another critical concept in sustainability transitions, i.e. ‘nature’. Because sustainable 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’. An emerging policy discourse on ‘nature-based solutions’ (NBS) is therefore of interest. This discourse is building upon earlier traditions and conceptualisations of the role of nature in sustainable development, such as ecosystem services and green infrastructure. The NBS concept also loosely refers to the innovative ‘use’ of nature for tackling societal challenges including climate change, human health and inclusive societies, in particular in urban contexts. NBS employ natural elements to address social, economic and ecological sustainability challenges simultaneously. Examples of NBS are green roofs, waterways and bioswales. NBS are increasingly recognised in policy and research as promising innovations with potential to facilitate wider urban transformation (Nesshöver et al. 2017; Nature Editorials 2017). From a sustainability transition perspective, NBS are not only interesting because they represent a novel innovation, but also because often their multifunctional focus may help to address the critique of ‘technology fixes’ being insufficient as solutions to urban challenges (Devolder & Block 2015). As such, we argue, it is relevant to develop a dialogue between NBS and sustainability transitions literatures, as they share an interest in the role of innovation (whether social-, technological- or nature-based) in resolving grand societal challenges.

Nevertheless, such a dialogue is also expected to raise new questions as innovating with nature is potentially different from innovating with technology. For instance, innovating with nature incorporates innovating with ‘living’ things, which makes issues around failure of projects normatively more challenging. Another example is that ‘nature’ is often considered a good with strong collective properties which poses the risk of free-riding. This makes capturing the value of NBS potentially more challenging.

In this paper we address the question whether technology-oriented and nature-based pathways to sustainability transitions are fundamentally different. What are the consequences for governing nature-based versus technology-based transitions? For example, NBS tend to have more co-benefits than technological innovations (e.g., health and well-being, biodiversity etc.), which cannot be conventionally marketed as is the case with technological innovations.

We do so by crafting a dialogue between the literatures on Technological Innovation Systems (TIS) and NBS. TIS is one of the core frameworks in transitions literature. It provides an elaborate model for analysing critical processes, or ‘functions’, that shape the establishment of socio-technical systems, including their structural components. The systematic analysis of such critical processes has contributed to the development of recommendations for policy and practice around technological innovations in a systematic and comprehensive way (Bergek et al. 2008). Recent contributions have suggested to interrogate the emergence of TIS in relation to wider contextual dynamics (Bergek et al. 2015). This comprehensive conceptualisation of innovation in terms of processes, structures and contexts makes TIS a promising starting point for understanding what is currently driving innovation with NBS and its further development. Simultaneously, an analysis of NBS from a

TIS perspectives offers an opportunity to reflect on how innovation with nature is similar to, or different from, innovation with technology.

The research questions of this article are: 1) How can innovation systems for nature-based solutions be conceptualized? 2) How do innovation systems for nature-based solutions relate to those for technological innovation systems (TIS)? And 3) What are the implications for the study of sustainability transitions?. We address these questions by briefly introducing the notions of NBS and TIS in section 2. Section 3 continues with presenting the research design, honing in on a recent systematic literature review on NBS in relation to urban transformation. Section 4 presents the results of the literature review to determine the processes and elements that are currently considered in the NBS literature as important for establishing, nurturing and mainstreaming NBS. Section 5 turns to a comparative discussion of the results of the literature review with the key processes, structures and contexts in the TIS framework. Section 6 concludes and presents implications for future research.

2 Background: nature-based solutions and technological innovation systems

2.1 Technological innovation systems

TIS development goes back to pioneering work from Carlsson and Stankiewicz (1991). Echoing wider research agendas in the evolutionary economics research community at the time, Carlsson and Stankiewicz were primarily interested in explaining economic growth of nation states for which they developed a new conceptual understanding of technology as ‘technological systems’. They defined technological systems 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). Whilst understanding innovation was part of their endeavour, later work started to shift focus explicitly from explaining economic growth as a result of technologies and innovation to the question of how *new* technologies (e.g. renewable energy technology or biofuels) are diffused by actors operating within a specific economic/industrial domain in the first place (Markard & Truffer 2008). Technology can be defined as “both hardware (e.g. products, tools and machines) and software (e.g. procedures/processes and digital protocols)” (Bergek et al. 2008, p.408). It may also refer to “technical knowledge, either in general terms or in terms of knowledge embodied in the physical artefact” (Bergek et al. 2008, p.408) – e.g. microwave technology. In particular the framework and body of literature known as Technological Innovation Systems has become influential in the context of transitions towards sustainable development.

The TIS approach has been discussed more elaborately elsewhere (Bergek et al. 2008; Hekkert et al. 2007; Jacobsson & Bergek 2011). Here we aim to provide a short introduction for unfamiliar readers and to set the stage for a comparative dialogue between TIS framework and the NBS literature. Following Carlsson and Stankiewicz, the TIS framework poses that for (radical) innovations to be successfully developed, they require the establishment of a ‘system’ that enables the development and diffusion of those innovations. Whilst writings differ in their understanding of what constitutes socio-technical systems (Geels 2004; Wieczorek & Hekkert 2012), and their ontological nature can be debated (Geels 2010), typical conceptual categories of the so-called *structures* of TIS are 1) diverse actors and their interactions, i.e. 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 organisations. We note here that the TIS literature has so far expressed a tendency to focus on the supply side of innovation, whilst few TIS studies explore the demand side or broader cultural dimensions of innovation. *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 contributed by unpacking the processes, or functions, through which TIS develop or stall. The literature distinguishes various key functions for innovation systems (Bergek et al. 2008; Hekkert et al. 2007; Jacobsson & 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 mobilisation* 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 specialised intermediate goods and service providers.

Recently, 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, i.e. they are four different lenses through which analysis can make sense of interactions between a focal TIS and its environment. First, 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. Second, 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 & Raven 2012). Third, TIS research has increasingly argued 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 and nature-based solutions

Urban nature-based solutions and similar concepts such as urban green infrastructure are relatively new concepts employed to promote sustainable urban development, i.e. development that provides long-term social, economic and environmental benefits to urban areas (Bayulken & Huisingh 2015; McCormick et al. 2013; Vandergert et al. 2015). This sits within a longer tradition of theorising about employing nature (e.g. in combating the ills of industrialisation) in urban environments 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 the sustainability transition in cities (Muñoz-Erickson et al. 2016).

NBS are defined by the EU as "actions which are inspired by, supported by or copied from nature" (European Commission 2015, p.5).The concept emerged in the late 2000s in relation to climate change and biodiversity policy and practice (Eggermont et al. 2015); the European Commission has reframed this concept by including the requirement for NBS to deliver social and economic objectives as well (Nesshöver et al. 2017). The NBS concept encompasses multiple types of nature-based interventions for addressing sustainability challenges. The concept acts as an 'umbrella' term to unite interventions varying regarding scope and size, range of functions provided, extent of nature-based components and solutions offered (ibid.).

All interventions labelled NBS have multifunctionality as a key characteristic. The element of multifunctionality, where one intervention may generate, for instance, food provision, social cohesion effects and stormwater runoff mitigation benefits, is seen as a key defining quality of NBS (Horwood 2011; Kabisch et al. 2016; Muñoz-Erickson et al. 2016). As a result, NBS contribute to urban resilience, i.e. the ability of a city to recover and/or adapt to shocks such as flooding or economic crises (Vandergert et al. 2015). They are implemented to address urban challenges such as health and well-being, food security, urban drainage, water retention, changing temperatures and air quality (Kabisch et al. 2016). The NBS concept can be criticized by casting aside negative externalities such as 'green gentrification', where greening of neighbourhoods causes displacement effects (Scott et al. 2016), or negative human responses to nature (e.g. pollen allergies, blocking of sunlight, safety concerns, etc.) (Lyytimäki et al. 2008).

Here we argue that NBS, similar to technological innovations, rely on a system comprising actor networks, institutions and material infrastructures for development and diffusion. We call this the *Nature-Based Innovation System* (NBIS). Given the absence of an explicit NBIS framework, this study aims to identify critical components for NBS emergence and development based on a systematic literature review on the concepts (e.g. green infrastructure or green roof) combined under the NBS umbrella. The framework focuses on the urban context as the transformation potential of NBS is particularly high in cities (Nesshöver et al. 2017). It was developed using an inductive approach: processes and variables are identified in the literature and grouped through a grounded theory approach. The second stage of analysis took a deductive approach; factors influencing NBS transformation pathways were extracted from the literature review and compared against the TIS framework to identify overlaps and differences. These differences were further explored to identify whether these are due to fundamental differences between Technological and Nature-Based Innovation Systems or point to potential knowledge gaps in the respective research fields.

3 Research design

NBS is an umbrella term that is still lacking a substantial research base. For that reason, this review incorporates the literatures around multiple concepts that are used to describe *nature-based interventions* and meet the definition of NBS. A second set of key words served to constrain the search to papers studying NBS in *urban* contexts. In order to identify papers relevant to understanding NBS transition pathways, a third category of keywords was formulated around *innovation/transition* trajectories (see Table 1).

Table 1. Categories of keywords and search terms

Keyword category	Search terms
Nature-based interventions	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

The search made different pairwise comparisons of the three keyword categories in the fields 'article title', 'abstract' and 'keywords':

Query 1: Nature-based interventions AND Urban context
Query 2: Nature-based interventions AND Innovation/Transformation
Query 3: Urban context AND Innovation/Transformation

To bring down the number of returned results for Query 3 (>40,000 hits), we added a number of search terms to this query that filtered out all papers not relevant to sustainability topics (search terms: "sustainable development" OR sustainability OR "climate change" OR "water management"). Overall, this sampling strategy was sufficiently lenient to identify papers on e.g. urban sustainability transformations that were not specific to nature-based interventions, while still being sufficiently restrictive to filter out papers that touched on e.g. innovation without making any link to sustainability or the city. The literature search was carried out in March 2017.

We selected 39 papers for review based on four expert researchers independently evaluating titles and abstracts for relevance. We excluded duplicates and papers prior to 2014 with ≤3 citations. Next, two researchers coded the selected papers for statements regarding factors and processes influencing NBS pathways. We understand 'NBS pathways' broadly as the success of implementing NBS interventions, their goal achievement, transferability and their long-term support and survival. Statements were independently categorized using a grounded theory approach by two researchers, who then discussed categories to arrive at a common framework. Due to time constraints, we reviewed 28 out of 39 selected papers with highest relevance. We then analysed the papers using a framework honing in on 1) drivers for innovating with nature and 2) barriers for innovating with nature. The analysis finds a range of relevant variables and processes for innovating with nature, which we will discuss below.

This paper then systematically explores similarities and differences of these variables in the NBS literature with key categories in TIS literature (Bergek et al. 2008; Bergek et al. 2015; Hekkert et al. 2007), including: 1) functional processes; 2) structural TIS components; and 3) TIS contexts.

4 Results: Key drivers for urban innovation with nature

The comprehensive literature review revealed a broad range of factors influencing NBS pathways. We focus on describing the full breadth of factors and processes, highlighting the richness of the literature spanning different research traditions and epistemic logics, avoiding to impose categories from TIS or related governance and transition frameworks and accepting a degree of conceptual overlap between dimensions. Table 1 distinguishes and briefly describes the different dimensions and sub-dimensions emerging from this review, which are further discussed below.

Table 1. Overview of factors and processes influencing NBS pathways

Dimension	Sub-dimension	Description
Agency	*Leadership and power*	People and organisations expressing leadership in NBS development and uptake processes.
	Commitment	Long-term investment of resources in NBS development and upscaling by individuals and/or organisations
Discourse and vision		Aligning NBS visions in line with collective worldviews on (urban) development and sustainability
Policy paradigm and key regulations		Legislation, regulations, policies and strategies that are relevant to NBS and/or competing alternatives
Governance structures		Diffusion of responsibilities and power between decision-making units within and between scales
Collaborative arrangements	*Networks and partnerships*	Formal and informal coalitions between individuals or organisations, and attempts at supporting these
	Participation	Processes of involving and engaging citizens in the planning, development and maintenance of NBS
Learning	*Education and training*	Actors and organizations engaging in a process of active learning, with a view on increasing resources
	Experimentation	Testing or piloting projects or forms of governance aimed at change/innovation
	Research	Knowledge partners/ institutions contributing to the knowledge base (on topics such as climate change) by systematic studies
	Monitoring and evaluation	Keeping track of (changes to) the process and assessing outputs, outcomes and impacts
Resources	*Knowledge and human capital*	Relevant knowledge, skills, abilities, relevant experience of individuals, collectives or populations
	Financial factors	Funding, incentives, cashflows, market demand etc.
	Technologies	Technologies for NBS implementation and knowledge management
Place-based factors	*Built environment and structures*	Urban (infra)structures, amenities and their distribution
	Natural processes and resources	Influence of soil conditions, local flora and fauna, local climate etc. on feasibility and urgency of NBS
	Societal processes	Demographic variables, economic conditions and cultural conventions and practices influencing NBS pathways

4.1 Agency

This dimension refers to the actions that individuals and organisations are taking to influence NBS pathways. Driven by agents of change – or ‘champions’ – organisations may demonstrate *leadership and power* in the development and uptake of NBS. Authorities can implement best practice interventions (Bayulken & Huisingh 2015), advocate particular planning processes and environmental regulation (Young et al. 2014), and influence actions of others through public-private partnerships and/or community engagement (Bayulken & Huisingh 2015; Brown 2008; Mguni et al. 2015). Mayors in particular can play an important role in influencing discourses or opening up new markets (Young et al. 2014). Organisations and enterprises can take on the role of early adopter or ‘frontrunner’ (Brown et al. 2013; Hendricks & Calkins 2006). Available strategies include: setting agendas for state-of-the-art research, information sharing, demonstration projects, product innovation, creating product quality standards, training and upskilling, shadow advocacy and lobbying (Bayulken & Huisingh 2015; Brown et al. 2013; Mees et al. 2015; Wolfram 2018; Zhang et al. 2012).

When done right, leadership in NBS development prompts institutional *commitment* to sustainability, which is expressed as long-term, as opposed to piecemeal, support for change (Brown et al. 2013). Commitment is manifested in institution-wide policies, such as the introduction of interdepartmental sustainability committees and dedicated resources for sustainability-related projects (Brown 2008). Commitment can also manifest itself in institutions actively supporting multi-stakeholder participation and local initiatives on sustainability (Bayulken & Huisingh 2015; Dupras et al. 2015).

4.2 Discourse and vision

Urban discourses of development and sustainability (e.g., 'eco city' or 'innovative city') translate into norms of action, which influences the "social momentum for change" (Rohracher & Späth 2014, p.1425) regarding NBS (Mees et al. 2015; Young 2011). For urban NBS visioning to be effective, it needs to include goals and objectives that align with (emerging) discourses; it needs to be developed collaboratively with the input from various societal and professional groups (Chaffin et al. 2016; Mguni et al. 2015; Young 2011). To be effective, it is important to frame NBS as an 'enabler' as opposed to a 'barrier' to growth (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., focus on innovation and reinvention in a post-industrial city) (Treemore-Spears et al. 2016). Public discourse may also undermine NBS upscaling; e.g., green roofs are often perceived as unsafe and high-maintenance (Hendricks & Calkins 2006).

4.3 Policy paradigm and key regulations

Different types of regulation can be effective in promoting sustainable development. For example, government can impose duties of care (e.g., flood management) on local authorities, (Mees et al. 2015). Planning authorities can apply environmental regulation and zoning to influence landowners and private developers (Young et al. 2014), as well as building regulation, such as the compulsory inclusion of green roofs or stormwater regulation in new developments (Mees et al. 2015; Young et al. 2014), and environmental levies (Brown 2008). Organisations can also promote NBS by adopting sustainability principles and performance indicators within their internal strategies and policies for all departments (ibid.).

The inclusion of NBS in strategic plans and policies at different levels can be highly beneficial to support their development, stewardship, financing and public engagement (Young 2011). Plans and policies are most effective if prepared holistically taking into account broader regional dynamics (Haaland & van den Bosch 2015), and if they apply a broad perspective by considering multiple political, financial and local aspects of urban planning (Bayulken & Huisingh 2015; Young et al. 2014) and a long-term vision (Haaland & 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., urban forest strategy) can be effective in the delivery of high priority NBS (Mees et al. 2015).

4.4 Governance structures

The actors involved and the distribution of power and responsibilities across the stakeholder landscape as a whole strongly influence development and diffusion of NBS. 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 optimise administrative and organisational capacity as well as flexibility (Chaffin et al. 2016). Related to this, others have called for decentralised management approaches engaging actors beyond traditional governance structures and from multiple disciplines and policy arenas (Brown 2008; Muñoz-Erickson et al. 2016). Such a polycentric system can also encourage a wider variety of stakeholders 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 decentralised 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 & Bulkeley 2013; McCormick et al. 2013). Organisations 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 those operating at different scales (Young et al. 2014). At the municipal level, allocating responsibility for green spaces to a single unit may actually be more effective than a decentralized approach (Haaland & van den Bosch 2015).

4.5 Collaborative arrangements

Networks and partnerships between a variety of stakeholders such as public-private partnerships, interagency agreements, science-practice interfaces and transdisciplinary knowledge systems are key to overcoming challenges associated with fragmentation across scales and between sectors (Castán Broto & Bulkeley 2013; Kabisch et al. 2016; McCormick et al. 2013; Muñoz-Erickson et al. 2016; Treemore-Spears et al. 2016; Wolfram 2018). Partnership working fosters commitment (Brown 2008), builds trust (Muñoz-Erickson et al. 2016), promotes mutual learning, knowledge exchange and 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), and enlarges capacity to attract funding (Ghose & Pettygrove 2014). Doing so therefore improves success rates of NBS implementation (Brown 2008).

A distinction can be made between formal and informal networks. The latter, also known as shadow networks, enable actors to act relatively independent of their organisational mandate (Brown et al. 2013). Bridging organisations are key to building formal partnerships by supporting processes of participation, agenda setting, information exchange and alliance-building (Bayulken & Huisingh 2015; Brown et al. 2013). Individual intermediaries, such as mediators, knowledge brokers or institutional entrepreneurs also contribute to the establishment of new connections between stakeholders (Ghose & 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 & Pettygrove 2014).

Active public *participation* and empowerment of civil society are particularly important for NBS implementation (Bulkeley et al. 2016; Wolfram 2018), especially in cities with high levels of private landownership (Young 2011; Young et al. 2014). Public participation in the full process of NBS planning (Treemore-Spears et al. 2016) has been evidenced to improve public support and acceptance of sustainability interventions (Bayulken & Huisingh 2015); it can provide leverage for sustainability transformations (Rohracher & Späth 2014; Young 2011). Active forms of public participation can have the added benefit of resolving issues of social justice and equity (Treemore-Spears et al. 2016).

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 interventions 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 relative ease of adopting it. This is an issue with e.g. green roofs which add a layer of complexity to conventional practices (Hendricks & 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 & 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. 2015; Tillie & van der Heijden 2015; Young et al. 2014), empowerment (Treemore-Spears et al. 2016; Wolfram 2018) and support for sustainable development (Haaland & van den Bosch 2015; Tian et al. 2012; Tillie & 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 and scientific knowledge represents an important foundation for urban planning and governance (Treemore-Spears et al. 2016). Knowledge actors, such as scientific bridging organisations, have been identified as drivers 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 (Naylor et al. 2012). Relevant research knowledge can be provided on topics as varied as ecosystem service valuation, assessing and monitoring (local) socio-ecological qualities (e.g. biodiversity), citizen preferences for sustainability interventions and the effectiveness of collaborative governance arrangements (Dupras et al. 2015; Tillie & van der Heijden 2015; Young 2011).

Experimentation, learning-by-doing and focus projects contribute to (social) learning (Brown et al. 2013; Rohracher & Späth 2014), rethinking of values, identities and governance arrangements (Wolfram 2018). They can also shape discourses (Rohracher & Späth 2014) and serve to overcome concerns and maintain engagement (Naylor et al. 2012; Young 2011). Furthermore, they provide an opportunity to test innovations (Naylor et al. 2012; Treemore-Spears et al. 2016). Innovations either be of a ‘technological’ (e.g., materials, designs, technologies) or a ‘social’ (e.g. valuation, financing, co-governance arrangements) nature (Castán Broto & Bulkeley 2013). Finally, they add to urban resilience by broadening the spectrum of available solutions to sustainability challenges (McCormick et al. 2013).

Monitoring and evaluation of NBS interventions contributes to a sustained delivery of benefits (Bayulken & Huisingh 2015; Naylor et al. 2012; Treemore-Spears et al. 2016). Benefits include a better understanding of the outcomes of different approaches (Kabisch et al. 2016; Treemore-Spears et al. 2016) and more effective strategy development (Dupras et al. 2015; McCormick et al. 2013; Naylor et al. 2012). Weak or neglected monitoring undermines stakeholders’ commitment to projects (Zhang et al. 2012) and makes comparison across interventions difficult (Bayulken & 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; Kabisch et al. 2016), and these positive externalities can therefore not be easily incorporated into the decision-making frameworks of profit-oriented enterprises (Horwood 2011).

4.7 Resources

The implementation and maintenance of NBS depends on the accumulation of *knowledge and human capital*. For example, on the technical implementation and maintenance of green roofs or urban trees (Hendricks & Calkins 2006; Zhang et al. 2012). NBS need to be adapted 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 & van den Bosch 2015), while knowledge of governance structures plays a role in effective decision-making on *who* to target (Young et al. 2014). Several relevant 'soft skills' for partnership working and outreach are identified as well. These include negotiation skills, conflict management and confidence building (Bayulken & Huisingh 2015; Wolfram 2018).

Financial factors such as diverse funding sources and "sound financial planning" (Bayulken & Huisingh, 2015, p. 158) were often listed as essential to the success of nature-based interventions (Naylor et al. 2012; Wamsler 2015; Wolfram 2018; Young 2011; Zhang et al. 2012). Institutionalised spending, grant programmes and subsidies are prominent financing instruments for NBS (Bayulken & Huisingh 2015; Mees et al. 2015; Young et al. 2014; Zhang et al. 2012). Private investment can be catalysed through regulation as well as public-private partnerships; the former can serve to either *enable* or *prescribe* the implementation of NBS (Mees et al. 2015; Young et al. 2014). Disincentivizing unsustainable practices (e.g. through environmental levies or stormwater fees) can also support investment in NBS (Brown 2008; Dupras et al. 2015; Hendricks & Calkins, 2006). Financial incentives are particularly effective when they are clearly embedded in a broader policy approach (Mees et al. 2015).

The development of *technologies* for NBS implementation is another important condition for some types of NBS (e.g. green rooftops) (Wolfram 2018). Due to limited adoption rates, the financial cost of these technologies can be high, which can limit access (Hendricks & Calkins, 2006). Knowledge management technologies – for example, the 'smart city planner' drawing together different types of social, environmental and structural data in an interactive GIS system and highlighting different combinations of challenges across neighbourhoods (Tillie & van der Heijden 2015) – can also support the uptake of multifunctional NBS.

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 and structures* is an important factor influencing nature-based innovation in cities because urban NBS are either attached to or situated between built structures 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 as nature-based interventions' functionality varies based on proximity to e.g. stormwater flows in streets or drainage pipes (Chaffin et al. 2016). The availability of vacant space is another factor influencing the feasibility of NBS; compact cities call for alternative greening approaches (Haaland & 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 (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 on the stability of the urban development regime: existing urban infrastructures "serves 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 and structures is that it is known to shape local identities and sense of place, which can prompt sustainable development action or inaction (Bayulken & Huisingh 2015)

Natural processes and resources influence the functioning of nature-based interventions. For example, plants productivity is influenced by local soil characteristics and climatic conditions (Chaffin et al. 2016; Tian et al. 2012). Natural disasters (e.g. floods) can act as 'pulses' influencing the perceived urgency of action on underlying issues such as climate change or sea-level rise (Munoz-Erickson et al. 2016; Young et al. 2014).

Societal processes similarly influence the availability of and scope for nature in cities. For example, urbanisation 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 revitalisation (McCormick et al. 2013; Tian et al. 2012). The regional economic role of a city and its natural environment (e.g. as tourist destination) also influences scope for NBS (Young et al. 2014), while an unequal distribution of wealth in the city acts as a barrier to sustainable development (Treemore-Spears et al. 2016). Another factor that is likely to play a role on the effectiveness of urban greening approaches 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 (Munoz-Erickson et al. 2016). A sense of urgency around sustainability challenges is predictive of regime actors changing their attitude or commitment to sustainable development (Munoz-Erickson et al. 2016; Rohracher & Späth 2014).

Finally, local cultural frames are also an important factor for nature-based innovations. Consumption habits, entrepreneurial orientation, artistic activity, aesthetic preferences and other place-based conventions, practices and meanings influence the diffusion of sustainability innovations (Chaffin et al. 2016; Hendricks & Calkins 2006; McCormick et al. 2013; Murphy 2015; Treemore-Spears et al. 2016; Wolfram 2018, Young 2011).

5 Discussion: Exploring synergies and trade-offs between Technological and Nature-Based Innovation Systems

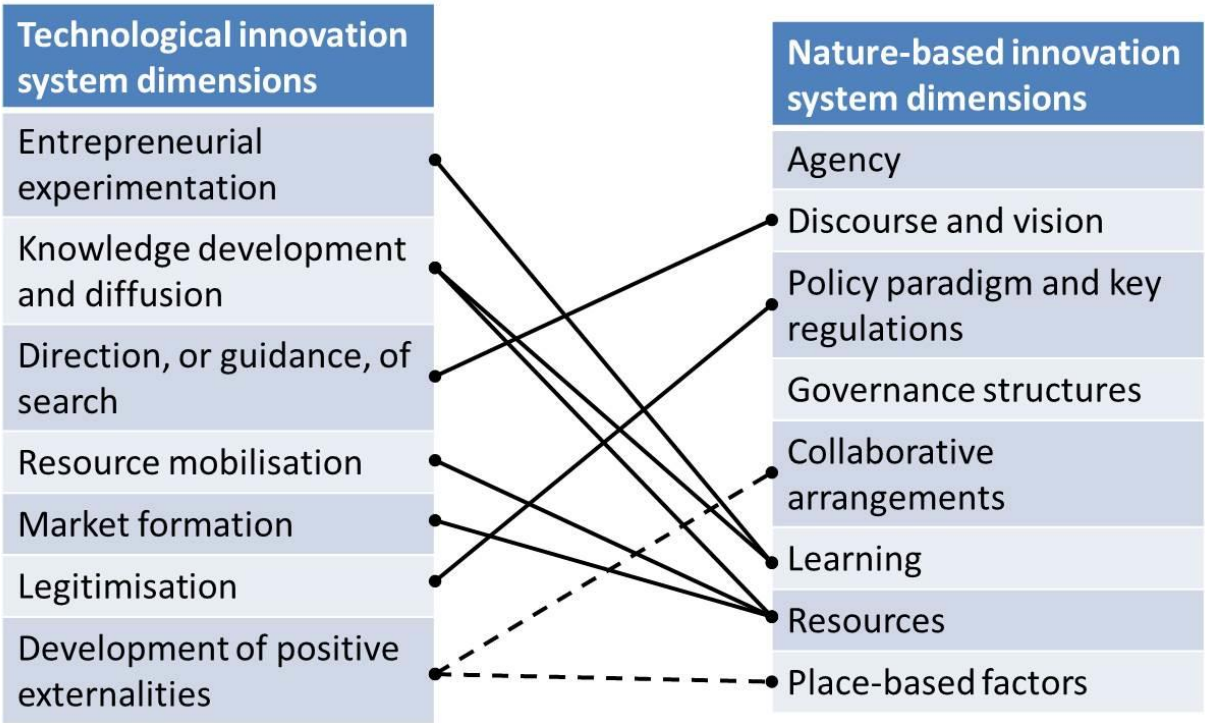

Figure 1. Overlapping dimensions between the Nature-Based Innovation System (NBIS) and Technological Innovation System (TIS) frameworks. A distinction is made between strong overlap (solid lines) and moderate overlap (dashed lines).

Key points:

- We provide a new framework – NBIS – which is the first framework tailored to describing and explaining nature-based innovation systems. This provides the first systematic approach to explaining barriers and opportunities for urban NBS such as green roofs, community gardens and bioswales. They complement existing environmental governance frameworks such as the policy arrangement approach (van Tatenhove et al. 2000) and the urban forest governance framework (Lawrence et al. 2013) that are optimised to analysing the situation at a fixed point in time (Arnouts et al. 2012), and do not necessarily take the full spectrum of NBS into account.
- By focusing on NBS as crucial aspects of sustainability transitions, applying the NBIS framework along with the TIS approach will lead to a more comprehensive understanding of challenges and opportunities for creating more resilient societies.
- A comparison of dimensions between the NBIS and TIS frameworks (Fig.1) shows that all TIS dimensions have at least some overlap with the NBIS dimensions, whereas the reverse does not apply. There is also a clear difference in labelling style with the TIS functions including many action verbs and the NBIS dimensions also includes many dimensions referring to relatively stable states or features of the innovation system.
- The *contextual* factors interacting with TIS that are identified in the literature – *existing sectors; political systems; geographical context; other innovation systems* – map on a

variety of NBIS dimensions, most notably: *agency, governance structures, collaborative arrangements, resources* and *place-based factors*. Taking these contextual factors from the TIS literature into account improves the synergy between both frameworks.

- The formulation of TIS functions stands out by highlighting strategic marketing or promotional activities using action verbs such as 'market formation', 'legitimation' and 'development of positive externalities' aimed at system innovation and transition. The formulation of NBIS functions is mostly *descriptive* as opposed to *prescriptive* with a strong focus on factors pertaining to the state, condition and capacity of agents exerting power, place-based factors, and structural conditions (e.g. governance structures, policy paradigm). This suggests different starting points between both bodies of literature with the NBIS literature focusing more on individual NBS interventions (inside-out) and the TIS literature more on regime conditions (outside-in).
- This tendency of NBS scholars to focus on NBS interventions *vis-à-vis* their context rather than the other way around can be explained by a number of factors. Firstly, nature-based interventions are *living* solutions, their functioning is dependent on the right set of conditions (e.g., adequate soil composition, temperature range, light and water levels, etc.). Secondly, NBS are usually literally place-bound (i.e. immovable because they are physically attached to a building structure or particular open space), which is unlike some types of technology (e.g., telephones or cars). This increases the significance of the social and environmental context of the intervention. Thirdly, NBS are by definition *multifunctional* interventions with social, economic and environmental benefits, which implies that they need to align with local environmental and economic priorities and multiple stakeholder values and objectives simultaneously. Fourthly, it is more challenging to influence a broad range of players together making up a regime to support NBS given the fundamental nature of NBS as solutions to sustainability challenges. NBS are not a self-evident outcome of the free market logic under neoliberalism; they cannot be equated with technologies that can be marketed, distributed and sold. Instead, NBS refer to public goods that are accessed or 'consumed' free of charge. For example, benefits of NBS for community development and biodiversity cannot be straightforwardly marketed, yet are crucial to addressing sustainability challenges such as health and well-being of urban populations and biodiversity loss.
- We can derive from the above that for NBS to be successful they need to take into account and respond to contextual conditions. This is why place-based factors are relatively important in the NBIS framework. Collaborative arrangements, often involving non-market actors such as active citizens and non-profits along with government actors, are at the basis of many NBS initiatives. This can offer an explanation for why governance structures and agency (e.g. commitment to sustainable development) emerge as stand-alone factors in the NBIS framework whilst this is not the case for TIS that have higher levels of private investment.
- Since there is a level of overlap between NBIS and TIS, i.e. some NBS have a strong technological component (e.g., rooftop parks), it could be argued that the NBS literature has insufficiently explored measures aimed at transforming the incumbent regime influencing nature-based innovations whilst the TIS literature has underplayed the roles

of agency, place-based factors and other structural conditions in shaping innovation systems, although see recent publications in this area (e.g. Bergek et al., 2015).

- Integrating TIS and NBIS frameworks could have important policy implications for governing green assets in cities. For example, there may be missed opportunities in (local) governments taking a more active lead in creating markets for nature-based products (e.g. through the provision of subsidies or public outreach around nature-based products) and seeking to pursue public-private partnerships around supporting experiments with innovative greening solutions. There could also be underused potential in marketing the public benefits generated by NBS (e.g. insurers co-funding NBS that mitigate risk) and in *reversing* cash flows from publicly or privately funded NBS to commercial parties (e.g., hotels and cafés) and private individuals (e.g. increased property prices).

6 Conclusions and implications for future research and practice

Taking a data-driven approach, this systematic literature study revealed a broad range of variables influencing the emergence and diffusion of NBS. The emerging NBIS framework shows clear parallels with the TIS approach developed to explain the innovation pathways of sustainable technologies within socio-technical systems; all factors in the TIS framework can to some extent be mapped on those in the NBIS framework. However, an important gap between both approaches is that the TIS framework *prescribes* strategic activities predictive of system transformation whereas the NBIS framework describes relatively stable person-based, place-based and structural factors shaping innovation pathways.

This can be explained by the unique nature of nature-based innovation. That is, NBS are place-bound, deliver multiple benefits as public goods and, most importantly, need to align with social-ecological systems in order to qualify as NBS in the first place. The effectiveness and value of NBS is highly dependent on place-specific priorities and requirements regarding e.g. economic development, species richness and migration, urbanisation and health challenges, which means their benefits are not stable across time and space. This spatio-temporal volatility of value is further compounded by the *living* nature of NBS – e.g. an ancient tree delivers different services and disservices than a sapling.

For TIS scholars the NBIS framework raises new research questions regarding 1) the spatiality of TIS functions and structures and 2) the relevance of particular governance contexts. For NBS scholars, it is important to better understand what actions can be taken by actors, networks and institutions to influence the emergence and scaling of NBS from a socio-technological regime perspective, especially if NBS have a technological component (e.g. vertical gardens or artificial wetlands). The TIS provides an interesting starting-point for exploring regime conditions and how to strategically influence these.

Given climate change, ongoing urbanisation and the pressure on cities to meet their sustainability targets through urban densification, cities are expected to increasingly often look into alternative solutions that allow for a smarter use of limited space, including innovative nature-based interventions attached to built structures. These types of NBS, provided by measures such as vertical forests, rooftop parks and rooftop gardens, tend to have a strong technological component. This indicates a need for developing an innovation system framework that is valid from an integrated socio-techno-ecological perspective. To this end, more research is needed on the barriers and opportunities for the development and upscaling NBS in dense urban contexts. Importantly, such research needs to go beyond the studying of single NBS interventions by looking at the incumbent system or regime in which these NBS are embedded as a whole.

We conclude that by integrating knowledge on technological and nature-based innovation systems cities will be equipped to more adequately respond to current urban sustainability challenges. This paper provides a first attempt at integrating the two bodies of literature and indicates clear areas of overlap while also highlighting the need for additional research to conceptualise nature-based innovation from a hybrid socio-techno-ecological perspective.

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