Environmental Innovation and Societal Transitions 51 (2024) 100846

Contents lists available at ScienceDirect

Environmental Innovation and Societal Transitions

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

Towards a socio-techno-ecological approach to sustainability transitions

John Andersson [a,*], Thomas Taro Lennerfors [b], Helena Fornstedt [b]

[a] RISE Research Institutes of Sweden, Division Built Environment, Department System Transition, Gothenburg, Sweden
[b] Uppsala University, Division of Industrial Engineering and Management, Department of Civil and Industrial Engineering, Uppsala, Sweden

A R T I C L E I N F O

Keywords:
Sustainability transitions
Socio-techno-ecological systems
Socio-technical systems
Socio-ecological systems
Multi-level perspective
Innovation systems

A B S T R A C T

The literature on sustainability transitions departs from the idea that social and environmental problems call for transformative change but employs socio-technical frameworks that treat nature as a passive context. In this paper, we argue that transitions research should adopt a socio-techno-ecological approach that accounts better for ecological elements. To take steps in this direction, we review adjacent literature that engages with socio-ecological and socio-techno-ecological systems concepts. Based on insights from this literature, we discuss emerging topics for the development of a socio-techno-ecological transitions framework. Our contribution paves the way for further theoretical development and empirical validation by motivating, contextualizing and sketching a roadmap towards a more comprehensive approach to transitions research.

1. Introduction

Research on sustainability transitions departs from the idea that social and environmental problems call for transformative change (Köhler et al., 2019; Van Den Bergh et al., 2011). Concern about the dire consequences of climate change (IPCC, 2018) and biodiversity loss (IPBES, 2019) is what brings transitions scholars together in a thriving community, even though they often have different disciplinary backgrounds, methodological preferences and ontological positions (Geels, 2010; Köhler et al., 2019; Markard and Truffer, 2008). However, nature is often made invisible in the actual analysis. Theoretical frameworks explain the dynamics of transitions by highlighting the interplay of actors, institutions and technologies in socio-technical systems (Bergek et al., 2008a; Geels, 2002; Hekkert et al., 2007; Kemp et al., 1998; Markard and Truffer, 2008; Rip and Kemp, 1998; Rotmans et al., 2001), while ecological elements[1] are treated as a passive context.

Driven by a similar concern about environmental problems, adjacent research on socio-ecological systems foregrounds interactions between society and nature (Berkes and Folke, 1998; Folke, 2006; Ostrom, 2009). This literature is traditionally concerned with the governance and resilience of systems that capture the human utilization (and regeneration) of localized natural resources and ecosystem services, but increasingly engages with transformation towards sustainability (Folke et al., 2010; Reyers et al., 2022). A core proposition is that society and nature are interdependent to the extent that the two must be studied in tandem (Berkes and Folke, 1998). Not surprisingly, scholars in this tradition have criticized socio-technical approaches for treating ecological elements as

* Corresponding author.
E-mail address: johnn.andersson@ri.se (J. Andersson).

[1] We use the term ‘ecological elements’ broadly to refer to entities that constitute nature, including non-human life and its chemical, physical, geological and even cosmological environment, as well as their couplings and interactions with society.

https://doi.org/10.1016/j.eist.2024.100846
Received 26 September 2022; Received in revised form 28 February 2024; Accepted 14 April 2024
Available online 20 April 2024

background variables and thus failing to account for socio-ecological dynamics (Olsson et al., 2014).

Meanwhile, socio-ecological systems research has been criticized for neglecting the role of technology (Ahlborg et al., 2019; Anderies, 2014; Galaz, 2012; Olsson et al., 2014). As a response, a recent stream of literature engages with broader concepts such as 'social-ecological-technological' systems (McPhearson et al., 2022, 2016a, 2016b), 'human-technical-environmental' systems (Selin and Selin, 2022) and 'socio-technical-ecological' systems (Ahlborg et al., 2019). We here refer to these jointly as 'socio-techno-ecological systems concepts', to highlight that they refrain from treating neither technology nor nature as a passive context. However, most scholars use the concepts in passing, seemingly to contextualize empirical research by highlighting complexity and interconnectivity, and without describing system functions, elements, dynamics and boundaries. Since the concepts have emerged with strong links to the literature on socio-ecological systems, they are also geared towards the analysis of localized phenomena, rather than production and consumption processes embedded in economic sectors (Foxon et al., 2009; Patterson et al., 2017; Smith and Stirling, 2010).

The need to integrate socio-technical and socio-ecological approaches has been raised within the transitions community as well (Patterson et al., 2017; Smith and Stirling, 2010; Yap and Truffer, 2021). A few contributions also move in this direction by exploring ecological dimensions of innovation processes (Andersson et al., 2024; Arora et al., 2013; Dorst et al., 2022; el Bilali, 2019; Low et al., 2022; Nogueira et al., 2021; Pigford et al., 2018; Plummer et al., 2024; van der Jagt et al., 2020; Vermunt et al., 2020). However, socio-techno-ecological systems concepts developed in adjacent literature are yet to leave an imprint and the topic generally receives little attention. In fact, the latest transitions research agenda, which summarizes the state-of-the-art and highlights future directions in various strands of the literature, does not even comment on the possibility of including ecological elements in theoretical frameworks (Köhler et al., 2019).

The purpose of this paper is to contribute to the development of a socio-techno-ecological transitions framework. To that end, we address three interrelated questions:

1. What is the role of nature in transitions research and why should a socio-techno-ecological approach be considered?
2. What can be learnt from literature that engages with socio-ecological and socio-techno-ecological systems concepts in adjacent research fields?
3. What key topics must be addressed by future research aiming to establish a socio-techno-ecological transitions framework?

Guided by these questions, the paper paves the way for further theoretical development and empirical validation. Our main contribution is accordingly to motivate, contextualize and sketch a roadmap towards a more comprehensive approach to analyzing sustainability transitions.

After this introduction, we describe our methodology (Section 2). We then discuss the role of nature in transitions research and argue for a socio-techno-ecological approach (Section 3). Thereafter, we review adjacent literature that engages with socio-ecological and socio-techno-ecological systems concepts (Section 4). Based on insights from this review, we proceed to discuss emerging topics for the development of a socio-techno-ecological transitions framework (Section 5). The paper ends with brief concluding remarks (Section 6).

2. Methodology

This paper reviews scientific literature in relation to the guiding questions described in the previous section. When addressing the role of nature in transitions research (Section 3), we offer a brief narrative review (Sovacool et al., 2018) based on influential contributions that were identified primarily through the authors own experience. However, to reduce researcher bias in selecting and interpreting literature, we performed a complementary search in the Scopus database and let all three authors assess the role of nature independently in key publications.[2] Note also that our motivation of why a socio-techno-ecological approach should be considered partly takes the form of an immanent critique (Isaksen, 2018), since the key arguments are based on the same type of systems thinking (i.e., interdependence among heterogenous elements) that underlies socio-technical transitions frameworks.

A similar exploration of the role of nature was conducted when addressing what can be learnt from recent literature that engages with socio-ecological and socio-techno-ecological systems concepts in adjacent research fields (Section 4). While our review of the literature on socio-ecological systems presents a summarizing narrative based on influential contributions, we used a more systematic method when identifying and assessing publications engaging with socio-techno-ecological systems concepts. First, we developed a broad search string that captures multiple variations of the term 'socio-techno-ecological system' as well as several similar or equivalent notions. Second, we used this string to search the Scopus database, which resulted in a first list of 182 publications.[3] Third, we identified 60 relevant publications by reading titles and abstracts. Fourth, the relevant publications were read in-depth with a view to identify conceptualizations and theories that may be useful for developing and contrasting a socio-techno-ecological transitions framework. To strengthen rigor in this part of the research process, particularly relevant publications were read by more than one

[2] Search performed on 22-03-18 using the search string (``sustainability transition*'' OR ``multi-level perspective'' OR ``technological innovation system*'' OR ``strategic niche management'' OR ``transition* management'').

[3] Search performed on 2022-11-11 using the string (``soc*-techn*-ecological'' OR "soc*-ecological-techn*" OR "soc*-environmental-techn*" OR "soc*-techn*-environmental" OR "hum*-techn*-ecological" OR "hum*-ecological-techn*" OR "hum*-environmental-techn*" OR "hum*-techn*-environmental") AND (system OR systems).

author.

Lastly, the discussion of key topics that must be addressed by future research aiming to establish a socio-techno-ecological transitions framework (Section 5) is mainly based on the reviewed literature, but also draws on relevant transitions research.

3. The role of nature in transitions research and the rationale behind a socio-techno-ecological systems approach

Although the transitions literature has in the last decade broadened to include a plethora of theoretical and methodological approaches, the notion of socio-technical systems remains fundamental (Truffer et al., 2022). The insight that society and technology are interdependent and mutually constitutive, and that this must be reflected in conceptual frameworks used to describe and analyze technological, industrial and sectoral change, is broadly shared among transitions scholars. Indeed, the overarching phenomenon of interest is often described in terms transitions to more sustainable socio-technical systems (Edmondson et al., 2018; Geels, 2022, 2004; Kanger and Schot, 2018; Raven et al., 2012; Smith et al., 2005). For example, the influential multi-level perspective is concerned with explaining how socio-technical systems of production and consumption transition to more sustainable configurations (Geels, 2002; Rip and Kemp, 1998). The core idea is that distinguishing between structures and developments on niche, regime and landscape levels creates a useful theoretical lens through which transition dynamics can be observed and analyzed. Stable configurations at the regime level favor certain development trajectories, which makes it difficult for novel technologies emerging at the niche level to break through. At the same time, landscape developments may give rise to windows of opportunity that destabilize the regime and pave the way for transformative change. This conception of transitions also appears in related frameworks such as strategic niche management (Kemp et al., 1998) and transition management (Loorbach, 2010), which develop more explicit recommendations to policymakers and other actors.

Since they are seen as socio-technical, however, both the production and consumption systems in focus, and the niches and regimes subject to analysis, exclude factors associated with nature (Geels, 2005, 2004; Geels and Kemp, 2007; Markard and Truffer, 2008; Smith et al., 2010, 2005). Although niches and regimes are sometimes referred to as a purely institutional “rule-set or grammar” (Rip and Kemp, 1998, p. 340), they are commonly described in terms of dimensions with social and technical characteristics (e.g. industrial networks, knowledge, sectoral policy, markets, technology, infrastructure and culture) (Geels, 2002), which leaves little room to account for the influence of ecological elements. Also, while nature sometimes appears as a part of the landscape through references to “the natural environment” (Rotmans et al., 2001, p. 19), “environmental problems” (Geels, 2002, p. 1260) or “the climate” (van Driel and Schot, 2005, p. 54), this practice is inconsistent and not supported by specific concepts and categories.

A similar exclusion of factors associated with nature is made by transitions research that adopts innovation systems frameworks (Bergek et al., 2008a, 2008b; Elzinga et al., 2023; Ghazinoory et al., 2020; Hekkert et al., 2020, 2007; Markard and Truffer, 2008). This strand of the literature generally foregrounds a set of interlinked elements whose interaction results in the performance of processes, often called functions, that are seen as important for successful innovation (Bergek et al., 2008a; Hekkert et al., 2007; Wesseling and Meijerhof, 2023). The elements are described in terms of networks of actors and institutions (Bergek et al., 2008a; Hekkert et al., 2007; Markard and Truffer, 2008), with some scholars also including material elements such as infrastructure and technical artifacts (Bergek et al., 2008b; Sandén and Hillman, 2011; Suurs and Hekkert, 2009; Wieczorek and Hekkert, 2012). Like niches and regimes in the MLP framework, innovation systems thus have a socio-technical texture, which implicitly adheres ecological elements to the system context. Moreover, it is rare to find studies where the role of nature is made conceptually explicit, even as a contextual factor. Some scholars highlight that technology emerges in a context which includes natural systems (Andersson, 2020; Hojcková et al., 2020; Sandén and Jonasson, 2005), but the literature generally focuses on the role of political, sectoral and geographical contexts that are understood in socio-technical terms (Bergek et al., 2015; Wirth and Markard, 2011).

This is not to say that nature is completely absent from the transitions research, though. The ambition to understand and promote shifts to more sustainable modes of production and consumption (Köhler et al., 2019; Truffer et al., 2022; Van Den Bergh et al., 2011) implies that ecological elements are (positively) affected by the phenomenon in focus (i.e., sustainability transitions). Indeed, concern about environmental problems clearly motivates and inspires large strands of the transitions literature. The very concept of ‘transitions’ is even said to have “its roots in biology and population dynamics” (Rotmans et al., 2001, p. 16).

Furthermore, factors associated with nature sometimes appear in the analysis even though they are not represented in analytical frameworks. Some publications engage with natural resources as phenomena that socio-technical systems can draw upon and even control (Andersson et al., 2018; Geels, 2004; Sandén and Jonasson, 2005), even though nature is generally absent from theoretical discussions about resources in sustainability transitions (Farla et al., 2012; Musiolik et al., 2018, 2012). It is also common to account for ecological elements indirectly, for instance by highlighting how they give rise to debates and a sense of urgency among (social) actors (Loorbach, 2010) or constitute a physical environment for technical elements (Rotmans et al., 2001).

In addition, a few recent transitions studies explore ecological dimensions of innovation processes. Some highlight that transitions are embedded in local ecological contexts that provide resources with a common-pool character (Nogueira et al., 2021; Vermunt et al., 2020). This is particularly evident in the agri-food sector, where scholars highlight how nature shapes innovation dynamics (Andersson et al., 2024; Arora et al., 2013; el Bilali, 2019; Pigford et al., 2018; Plummer et al., 2024). There is also an emerging literature on nature-based innovation, which focuses on solutions inspired by and adapted to the function of ecosystems, often in urban contexts (Dorst et al., 2022; Low et al., 2022; van der Jagt et al., 2020). But even though these contributions acknowledge the role of nature in sustainability transitions and call for more attention to ecological elements, they most often use socio-technical frameworks and refrain from proposing and engaging with socio-techno-ecological approaches.[4]

The transitions literature thus fails to account for the role of nature in a systematic and consistent way. Scholars certainly acknowledge the presence and importance of natural resources and environments, but generally render ecological elements invisible in analytical frameworks. A telling example is how Geels (2002) first refers to Hughes' (1987) notion of a seamless web "in which physical artefacts, organisations, natural resources, scientific elements, legislative artefacts are combined in order to achieve functionalities." (Geels, 2002, p. 1257); but then, after highlighting natural resources as components in this seamless web, refrains from explicitly including them when the multi-level perspective is introduced as way to analyze transitions; and finally, after this act of sublimation, lets nature return in an empirical discussion about the transition from sail to steam, where close attention is paid to factors such as winds, waves, rain, weather and the taming of waterways.

While it is beyond the scope of this paper to fully address why this came to be, it is worth reiterating that the field has strong roots in a historical stream of thought that emphasized how society and technology are mutually constitutive (Hughes, 1987; Pinch and Bijker, 1987). To accentuate this crucial observation, the 'socio-technical' became a widespread concept, used as a prefix to notions of both systems and transitions, and eventually, possibly, influencing the structure of theoretical frameworks. It could thus be that the exclusion of nature was not an intentional choice based on scholarly debate, but rather an unintentional side-effect deriving from efforts to highlight the intricacies of the socio-technical domain.

There are, however, strong arguments for a broader socio-techno-ecological approach that better accounts for factors associated with nature. On the one hand, it is beyond doubt that *nature influences sustainability transitions*. This is particularly evident in sectors that draw directly on natural resources and ecosystems to produce goods and services. For example, it has been shown that the geographical distribution of tidal currents shapes the innovation system for tidal power technology (Andersson et al., 2018); that the characteristics of natural resources and environments influence transition dynamics in industries such as oil and gas, mining and forestry (Andersen et al., 2018; Andersen and Wicken, 2021; Ville and Wicken, 2013); and that ecological factors influence which actors that are key for transformative change in the agri-food sector, shape the focus of transition dynamics towards institutional change and hinder rapid scaling of novel practices due to need for adaptations to local conditions (El Bilali, 2019; Pigford et al., 2018; Vermuntet al., 2020). But also more generally, the fact that technology ultimately depends upon natural phenomena implies that any shift in modes of production and consumption is deeply linked to ecological elements (Arthur, 2009). Indeed, the characteristics of nature have throughout history been decisive for technological change and economic development (Grubler, 1998; Rosenberg, 1994).

Proponents of a socio-technical approach may here counter that it is appropriate to treat nature as contextual.[5] However, we believe that this may guide the attention of researchers away from potentially important factors. After all, theoretical frameworks not only reveal, but also distort and conceal aspects of reality (Maxwell, 2012). Moreover, and as we will see in the next section, treating nature as contextual stands in sharp contrast to insights from socio-ecological systems research, which emphasizes that society and nature are systemically interdependent and cannot be analyzed in isolation (Berkes et al., 2003; Folke, 2006; Ostrom, 2009). Particularly as we have entered the Anthropocene, in which human civilization is the main driver of accelerating environmental change (Steffen et al., 2007; Waters et al., 2016), there are strong reasons to adopt a co-evolutionary view on society, technology and nature, operationalized through socio-techno-ecological systems concepts that endogenize ecological elements (Andersen and Wicken, 2021).

On the other hand, *sustainability transitions influence nature*. With a socio-technical approach, however, possibly adverse environmental impacts of sustainability transitions are concealed (Olsson et al., 2014). Instead, the desirability of a particular development trajectory is often seen as a given, rather than contested and subject to continuous debate (Stirling, 2011). Informing the participatory processes needed to collectively define and promote desirable development trajectories requires that transitions scholars engage with both innovation processes and their outcomes (Andersson et al., 2021), particularly since today's interrelated environmental problems make simplistic operationalizations of 'sustainability' (e.g., carbon emissions) increasingly insufficient (Susur and Karakaya, 2021).

A possible counterargument is that transitions scholars should refrain from engaging with technology assessment. To some extent we agree with this view; understanding the dynamics of sustainability transitions requires focused and specialized research. But at the same time, it is not sufficient to passively contend that a particular development trajectory will contribute to sustainability and proceed to investigating how it can be promoted. After all, any technological or social solution that is first perceived as desirable may evolve in a way that leads to unintended outcomes (Andersson et al., 2021; Susur and Karakaya, 2021). In this sense, we believe that informing efforts to govern sustainability transitions reflexively calls for research that pays continuous attention to environmental impacts. This in turn requires analytical frameworks that make the role of, and impacts on, ecological elements explicit, something that may also open up participatory processes to stakeholders that represent nature rather societal interests (Foxon et al., 2009). In the next section, we direct our attention to literature that does just that by engaging with socio-ecological and socio-techno-ecological systems concepts.

4. A review of literature on socio-ecological and socio-techno-ecological systems

Scholars that study socio-ecological systems have for long emphasized that society and nature are systemically interdependent

[4] Two recent studies experiment with different types of socio-techno-ecological approaches (Andersson et al., 2024; Plummer et al., 2024).

[5] Another counterargument is that ecological elements should be captured through their manifestation in the socio-technical domain. However, this corresponds to a decontextualization of nature (Feenberg, 2005), which may lead scholars, and their audience, to diminish its (by some perceived) inherent value.

(Berkes et al., 2003; Folke, 2006; Ostrom, 2009) and a recent stream of publications engage with socio-techno-ecological systems concepts (Chang et al., 2021; Markolf et al., 2018; McPhearson et al., 2022; van der Leer et al., 2018). In this section, we take stock of these developments to pave the way for a socio-techno-ecological transitions framework.

4.1. The governance and resilience of socio-ecological systems

A theoretical framework based on the socio-ecological systems concept was introduced in the late 1990′s (Colding and Barthel, 2019). Since then, two major strands of research have emerged. The first one is associated with the seminal work of Elinor Ostrom, who developed a socio-ecological systems framework to support the generation of multi-disciplinary knowledge about how local communities utilize common-pool resources such as fish, forests and fresh water (McGinnis and Ostrom, 2014; Ostrom, 2009, 2007). The framework specifies variables that can be used to describe and compare socio-ecological systems across different geographies and focal resources. This has resulted in findings showing that local communities have a propensity to self-organize in a way that results in a sustainable utilization of natural resources as well as insight into the factors that determine whether such self-organization emerges or not (Colding and Barthel, 2019; Partelow, 2018). However, while Ostrom's framework has had an immense impact on research and policy,[6] the research focus is on the governance and internal dynamics of socio-ecological systems under varying contextual conditions, rather than on how socio-ecological systems emerge, transform and decline as a response to sustainability challenges.

The second strand of socio-ecological systems research revolves around the concept of resilience, which was introduced in the 1970′s to describe the capacity of ecosystems to absorb external disturbances and shocks (Holling, 1973). In the 1990′s, the interest in resilience broadened to cover not only mechanisms in nature, but also the social structures which govern the utilization of natural resources and ecosystem services (Berkes and Folke, 1998). This resulted in a growing literature on the resilience of socio-ecological systems (Colding and Barthel, 2019). The focus was initially on the ability of systems to persist and reproduce in changing environments (i.e., adaptability), but the resilience concept has gradually been re-interpreted to also include the ability of systems to fundamentally transform when circumstances yield existing configurations untenable (i.e., transformability) (Folke, 2006; Folke et al., 2010; Walker et al., 2004). Resilience scholars acknowledge multi-scalar interactions between processes of adaptation and transformation, specifically noting that maintaining functions and structures at one level may call for transformation at another level (Gunderson and Holling, 2002; Olsson et al., 2014). This is further pronounced in the related field of Earth system science, which calls for the transformation of various socio-ecological and socio-technical systems, to increase the resilience and adaptability of the global Earth system (Rockström et al., 2009; Steffen et al., 2009, 2007). In addition, an adaptive governance framework has been developed to support policymakers and other actors in their efforts to address sustainability challenges (Chaffin et al., 2014; Folke et al., 2005; Foxon et al., 2009).

There are accordingly many similarities with transitions research, especially as the interest in transformability has recently increased among resilience scholars (Reyers et al., 2022). For starters, both communities are normatively oriented towards sustainable development, in the sense that scholars are generally driven by an ambition to not only analyze, but also promote change that addresses social and environmental problems (Berkes et al., 2003; Folke, 2006; Köhler et al., 2019; Van Den Bergh et al., 2011). Moreover, systems thinking serves as a common foundation, manifested in how the multi-scalar, complex, collective, cumulative and path dependent nature of transformative change is a shared emphasis in both fields (Markard et al., 2012; Olsson et al., 2014; Smith and Stirling, 2010). Indeed, the crucial observation that interdependency and feedback results in the emergence of dynamically stable system configurations that are difficult to transform, even though the same mechanisms may occasionally propel rapid change as systems settle into new regimes, is made by transitions and resilience scholars alike (Bergek et al., 2008a; Folke, 2006; Folke et al., 2010; Geels, 2002; Rip and Kemp, 1998; Walker et al., 2004).

Not surprisingly, there has been scholarly debate about the merits of transitions and resilience research, together with attempts at cross-fertilization (Ahlborg et al., 2019; Moore et al., 2014; Ollivier et al., 2018; Patterson et al., 2017). In particular, several contributions compare and integrate insights from the transition management and adaptive governance frameworks, to further develop the capacity among actors to promote and shape transformative change (Foxon et al., 2009; Pahl-Wostl, 2007; Van Der Brugge and Van Raak, 2007). It seems, however, as if these efforts mainly inform the resilience community rather than the other way around.[7] It is also apparent that work at the intersection between the two fields is still limited and that there is little momentum towards an integration of their respective analytical approaches.

A salient difference between the two fields—which is also the focus of this paper—is that the systems in focus capture different types of elements. As observed already at the outset, transitions research pays little attention to ecological elements and their interactions with the socio-technical domain. Conversely, the resilience community engages with socio-ecological systems that treat technology as a sub-system in the social domain or as a contextual factor (Markolf et al., 2018; Smith and Stirling, 2010). This difference has been highlighted and problematized in the literature, but mainly by resilience scholars. On the one hand, it is (rightfully) argued that the transitions community fails to account for ecological elements when theorizing and investigating transformative change (Olsson et al., 2014). On the other hand, an inward-looking critique highlights the lack of attention to technology in research on socio-ecological systems (Ahlborg et al., 2019; Galaz, 2012; Markolf et al., 2018; Olsson et al., 2014). While the first argument has thus far had little influence on transitions research, the second observation has resulted in a stream of literature that engages with different

[6] Elinor Ostrom was awarded the 2009 Nobel Memorial Prize in Economic Sciences.

[7] Publications at the intersection of the two fields are generally published in journals associated with the resilience community rather than the transitions community (one notable exception is Patterson et al. (2017)).

socio-techno-ecological systems concepts.

4.2. Socio-techno-ecological systems concepts in urban studies and other fields

A search for literature that engages with socio-techno-ecological systems concepts yields 60 relevant publications in scientific journals (see Section 2 for methodology). However, half of these only mention some type of socio-techno-ecological systems concept in passing or use it without any explanation. Among the remaining ones, 20 publications originate from urban studies, where researchers that had traditionally adopted socio-ecological systems frameworks realized that this approach failed to account for the role of technical infrastructure in urban environments (McPhearson et al., 2016a, 2016b). This resulted in the development a conceptual framework referred to as 'social-ecological-technical systems' (SETS), which focuses on interactions between an ecological-biophysical, social-behavioral and technological-infrastructural domain (Depietri and McPhearson, 2017). A recent and seemingly growing strand of the literature uses the SETS framework to analyze a variety of issues pertaining to urban environments, including risks and vulnerabilities (Chang et al., 2021; Gulsrud et al., 2018; Hellin et al., 2021), resilience (Andersson et al., 2021b; Chang et al., 2020; Krueger et al., 2022; Muñoz-Erickson et al., 2021), ecosystem services (Andersson et al., 2021a), ecological justice (Pineda-Pinto et al., 2021) and nature-based solutions (McPhearson et al., 2022). Outside the realm of urban studies, the approach has also been used to analyze empirical phenomena such as infrastructure systems (Markolf et al., 2018; Mehvar et al., 2021) and marine conservation (Jenkins, 2022), as well as to discuss the governance of complex systems (Cosens et al., 2021) and methodological challenges when investigating resilience (Hamborg et al., 2020).

The SETS framework is most often used to contextualize empirical research by highlighting the complexity and interconnectedness of urban environments. It thus engages with phenomena in specific places, although analyses sometimes focus on challenges related to more specific sectors such as water supply (Krueger et al., 2022). However, the systems concept at the core of the framework remains rather vague and indefinite. Many publications either describe system elements in overarching terms (e.g., with reference to "green", "blue" and "grey" infrastructure (McPhearson et al., 2022)) or fail to specify them at all (c.f., Hellin et al., 2021; Razzaghi Asl, 2022). Other publications provide some level of detail, but the terms used are yet to converge conceptually (c.f., Branny et al., 2022; Markolf et al., 2018; Pineda-Pinto et al., 2021). It is clear, however, that the general understanding of social and technological system elements is in line with the transitions literature, while the ecological domain is conceived broadly to include a variety of attributes associated with nature (e.g., ecosystems, biodiversity, biotic and abiotic components, and biophysical processes).

Although studies that use the SETS framework rarely focus on transformation, some publications elaborate on system dynamics. Gulsrud et al. (2018) highlight the reciprocal influence between SETS and wider governance elements (i.e., rules of the game, discourses, actors and power), while emphasizing couplings and interactions between social, ecological and technological system domains. Similarly, Pineda-Pinto et al. (2021) argue that such interactions manifest through the mediation, enabling, transformation and enhancing of relationships, which results in a dynamic shaping that can both reproduce and alleviate complex problems. Indeed, relations between social, ecological technological sub-systems are often highlighted and subject to analysis in SETS studies that focus on system dynamics (e.g., Branny et al., 2022). Some publications are also inspired by ideas from the transitions literature, particularly the distinction between niches, regimes and landscapes in the multi-level perspective (Kaae et al., 2019; Razzaghi Asl, 2022). However, they remain focused on questions pertaining to spatially delineated systems and do not attempt to contribute to analytical frameworks used in transitions research.

Beyond the SETS framework, a few publications engage with other socio-techno-ecological systems concepts. Nilsson et al. (2021) analyze the impacts of mining in Arctic Sweden and use a 'social-ecological-technological' systems framework (i.e., not the SETS framework discussed above) to capture the complexities associated this specific geography, while Sorge et al. (2022) analyze governance innovation in the forestry sector with a 'social-ecological-technological-forestry-innovation-systems' framework. These contributions are both inspired by the transitions literature, but mainly use their respective systems concepts to organize data and thus leave elements, dynamics and boundaries obscure. Another approach is offered by Selin and Selin (2022), who propose a generic 'human-technical-environmental' systems framework intended to facilitate cross-disciplinary collaboration. The framework outlines a procedure for analyzing the dynamic interactions among human, technical and environmental components, but in contrast to transitions research, knowledge and institutions are portrayed as contextual. In addition, Ahlborg et al. (2019) criticize the literature on socio-ecological systems for neglecting the role of technology and propose a general 'socio-technical-ecological' systems approach. They also highlight how technology impacts on interfaces and mediation, brings ambivalence, influences agency and power, and transforms the scale of relationships between humanity and nature.

4.3. Implications for a socio-techno-ecological approach to sustainability transitions

The reviewed literature has shown repeatedly that society and nature are interdependent, which is the core argument as to why a socio-techno-ecological transitions framework ought to be developed (Section 3). The interdependence stems from couplings and interactions that link heterogenous elements across social, technological and ecological domains. Indeed, a relational perspective is reoccurring and highlights that most, if not all, properties of interest emerge from the dynamic interaction of system elements. This is emphasized in the literature on socio-technical systems as well (Geels, 2004; Geels and Kemp, 2007), but a socio-techno-ecological systems approach acknowledges and makes explicit that decisive dynamics appear across socio-technical and ecological domains. Ecological elements not only influence the socio-technical domain by providing resources and services, but are also influenced in return through modification or destruction, by serving as sinks for different types of waste streams or (possibly) as subjects to regeneration and conservation efforts (Jenkins, 2022; Markolf et al., 2018; McPhearson et al., 2022; Nilsson et al., 2021). These socio-techno-ecological relations are particularly evident in sectors that have a close and direct relation to nature, such as forestry (Sorge et al., 2022) and mining (Nilsson et al., 2021), but they are general since any production activity depends upon some natural phenomena (Arthur, 2009).

An important difference between the reviewed literature and transitions research is the point of departure when defining and delimiting systems. The reviewed literature is mainly concerned with infrastructure, natural resources and ecosystem services in local contexts, which brings a spatial point of departure when defining and delineating systems (Foxon et al., 2009; Patterson et al., 2017; Smith and Stirling, 2010). In contrast, transitions research generally foregrounds a meso-level societal function in some domain (e.g., energy, transportation or agriculture) and at a given technological scale (e.g., production and consumption of solar power, renewable electricity or electricity in general), and then lets the socio-technical system in focus include structures that are relevant in relation to this function (Andersson et al., 2021; Bergek et al., 2008b; Geels, 2004). Although transitions scholars often set additional boundaries that limit systems to specific geographies (Hansen and Coenen, 2015), the point of departure is accordingly sectoral. It should be emphasized, though, that also socio-technical systems have spatial characteristics, while socio-ecological systems involve functions associated with sectors. The point here is rather that scholars *depart* from either a sectoral and spatial perspective when imagining, mapping and analyzing complex systems that are inherently multi-dimensional (Andersson et al., 2021).

The differing points of departure have consequences for the normative appreciation of system attributes such as stability, resilience and adaptability (Smith and Stirling, 2010). When theorizing and empirical investigation departs from the sectoral perspective, the persistence of established system structures is often seen as problematic, since they are perceived as causes of social and environmental problem. This implies that efforts to promote sustainability may involve undermining established systems, in order to enable the emergence of fundamentally different structures (Kivimaa and Kern, 2016; Turnheim and Geels, 2013). But when research departs from the spatial perspective, the same persistence of established systems is generally seen as positive, since it becomes associated with the conservation of ecosystems (and possibly local cultures). In turn, efforts to achieve sustainability become oriented towards enhancing resilience and adaptability (Berkes et al., 2003; Folke et al., 2005).

In the end, it is quite clear that the reviewed literature fails to offer an analytical framework that can readily be applied to transitions research. Instead, there is a need to develop a specific socio-techno-ecological transitions framework. What this entails is further discussed in the next section.

5. Emerging topics for the development of a socio-techno-ecological transitions framework

This paper has thus far argued that transitions research should pay more attention to factors associated with nature, and reviewed how adjacent literature engages with socio-ecological and socio-techno-ecological systems concepts. In this section, we draw on this literature and related conceptual transition research, as we discuss emerging topics and key questions for the development of a socio-techno-ecological transitions framework (Table 1).

To begin with, the reviewed literature highlights the importance of nurturing a constructive and reflexive discussion about the aim and scope of transitions (i.e., change of what, when, why and how). Our view is that a socio-techno-ecological transitions framework based on systems thinking may here provide support in not only emphasizing complexity, but also defining and delineating a phenomenon subject to analysis. However, this presumes a shared definition of the underlying system concept, which needs to emerge through future research. In particular, scholars must collectively establish whether a socio-techno-ecological transitions framework should support a sectoral or spatial point of departure. Our position is that transitions research should maintain its focus on sectoral functions, but a future framework may be applicable to both lines of inquiry and thereby serve as a useful boundary object. There is also a need to address whether the socio-techno-ecological transitions framework revolves around an innovation system, a production and consumption system or both (see Andersson et al. (2023) for a longer discussion about the functional scope of systems concepts). While including ecological elements is relevant for both types of systems, it is important that the overarching system function is made explicit when developing and applying a socio-techno-ecological transitions framework. After all, it is very different to analyze a system that produces and consumes a given focal product than it is to analyze a system that innovates (i.e., develops and diffuses) a new

Table 1
Emerging topics and key questions for the development of a socio-techno-ecological transitions framework.

Topic	Key questions
Defining the socio-techno-ecological system concept	• Does the system concept describe interacting elements that perform a sectoral function or exist in a spatial area? Can it be applied to both points of departure? • Is the system function to produce and consume, innovate, or both?
Describing and categorizing ecological system elements	• Are ecological elements seen as resources or can they fulfill a broader variety of roles in the system? • How can ecological elements be represented conceptually in different types of research? Are there key distinctions that should be made (e.g., between lining and non-living elements)?
Describing and explaining system dynamics	• What aspects of existing transitions frameworks, such as the multi-level perspective and innovation systems approach, can (and should) be transposed to the dynamics of socio-techno-ecological change? • What theoretical adaptations and modifications are needed when applying existing transitions frameworks to socio-techno-ecological change?
Operationalizing the socio-techno-ecological transitions framework in empirical research	• What types of system boundaries are needed to define the phenomenon subject to analysis in different types of research? How can (and should) these system boundaries be drawn? • How can the ecological domain be studied at an appropriate level of detail for different lines of inquiry? Is there a need to apply methods than are new to the transitions literature?

technology (Andersson et al., 2023).

Another task for the future development of a socio-techno-ecological transitions framework is to decompose the ecological domain into a more fine-grained and possibly multi-scalar typology of system elements. One approach is to use concepts such as natural resources and ecosystem services. While this kind of representation is used widely in science and beyond, and appears in most parts of the reviewed literature, it implies a bias towards parts of nature that are supportive and raises the question of how to account for ecological elements that may play an obstructive, limiting or hindering role. Another approach is to develop representations that enable ecological elements to play a broader variety of roles in the system: they may provide resources and services, constitute factors that hinder performance and transformation, or be subject to degradation due to overexploitation, waste and emissions. The role of ecological elements is thus not made explicit in their representations, but rather becomes a circumstance that may be found through analytical efforts, which is more in line with the way social and technological elements are generally represented in socio-technical frameworks (Bergek et al., 2008b; Geels, 2004; Hughes, 1987; Rip and Kemp, 1998; Sandén and Hillman, 2011; Wieczorek and Hekkert, 2012). It should be emphasized, however, that there are many possible ways to represent and organize system elements. This, together with the diversity of transitions research, suggests that conceptual development should be carried-out with a view to establish both generally applicable representations and more detailed descriptions and categorizations adapted to different research questions, empirical domains and scales of observation.

Apart from defining the system function and elements, a socio-techno-ecological transitions framework must offer a conceptual apparatus for describing and explaining system dynamics. Here, the relational perspective discussed above highlights that system transformation does not necessarily involve changes in the inherent characteristics of system elements, but rather that their couplings and interactions are altered. This is particularly important in relation to ecological elements, whose conservation and independence in relation to industrial activities is often seen as desirable. Indeed, one may frame the broader transition to a more circular economy in terms of the liberation of ecological elements from production and consumption systems. Beyond the relational perspective, however, the reviewed literature offers little guidance for the conceptualization of system dynamics. Instead, future work in this direction will likely depart from existing transitions frameworks such as the multi-level perspective and innovation systems approach. As demonstrated in recent publications, it is quite straight-forward to superficially apply these frameworks to the dynamics of socio-techno-ecological systems (Andersson et al., 2024; Plummer et al., 2024). At the same time, a deeper conceptual exploration may reveal a need for theoretical modification or replacement. For example, the conception of resource mobilization as a key process in innovation systems is most often limited to resources in the socio-technical domain, such as skilled labor, financial capital and technical infrastructure (Jacobsson and Karltorp, 2012; Karltorp, 2016; Karltorp et al., 2017; Musiolik et al., 2012), and thus fails to capture the role of ecosystem services and natural resources (Gong and Andersen, 2024). It is also up for debate whether the theoretical foundation of the multi-level perspective allows for understanding niches and regimes in terms of socio-techno-ecological rather than socio-technical systems (see Svensson and Nikoleris (2018) for a related discussion about material structures and the multi-level perspective).

An additional topic is to develop methodological guidelines for empirical operationalization of the socio-techno-ecological transitions framework. On the one hand, this concerns how to set appropriate system boundaries given the aim and scope of a study. While many insights from the literature on socio-technical systems are likely transferrable to a socio-techno-ecological approach, the inclusion of ecological elements may have implications. For example, interactions across socio-technical and ecological domains often occur at different spatial and temporal scales, which may call conventional system boundaries into question (Ahlborg et al., 2019). On the other hand, methodological guidelines are needed to support transitions researchers in their efforts to collect and analyze data. In particular, supplementary methods may be needed to study the characteristics and role of ecological elements at an appropriate level of detail.

Common for the topics raised in this section is the need to address key questions by combining theoretical development with empirical research. A socio-techno-ecological transitions framework should ideally emerge through the development, testing and validation of conceptual ideas in case studies that cover different technological, industrial and geographical contexts. In particular, it would likely be useful to explore sectors with different relations to nature. For example, slightly different analytical frameworks may be needed when investigating the agri-food sector, which has a direct link to nature, as opposed to the information technology sector, where ecological elements are more peripheral. We look forward to seeing how future research will tackle this and other key questions in the development of a socio-techno-ecological transitions framework.

6. Concluding remarks

This paper set out to contribute to the development of a socio-techno-ecological transitions framework. We have discussed the role of nature in transitions research, argued that there is a need to account better for ecological elements, reviewed adjacent literature that engages with socio-ecological and socio-techno-ecological systems concepts, and discussed emerging topics for future research.

It should be emphasized at this point that a socio-techno-ecological transitions framework should not be developed for its own sake. Instead, the purpose should be to further advance the theoretical and empirical understanding of how transformative change can be accelerated and shaped for the good of society and nature. By developing and applying a socio-techno-ecological system concept, scholars will arguably access a more comprehensive perspective on the dynamics and outcomes of transitions. It remains to be seen what new insights this will result in and whether conventional wisdom will need to be reevaluated as ecological elements are invited to the analysis.

A socio-techno-ecological approach to transitions also raises new empirical questions. Although the role of nature in innovation processes has received scholarly attention in the past, there is much more to learn about how ecological elements shape transitions in different technological, industrial and geographical contexts. Along with this, a socio-techno-ecological transitions framework may lead scholars to investigate new empirical areas with different types of links between social, technological and ecological domains. For example, recent literature on nature-based innovation systems represents a step in this direction, since it focuses on technologies that are inspired by nature and adhere to ecological principles (Dorst et al., 2022; van der Jagt et al., 2020). There is also ample room to expand the empirical scope of transitions research towards ecological restoration (Reynolds, 2021).

In the end, this paper answers to repeated calls for theoretical development at the intersection of socio-ecological and socio-technical systems research (Ahlborg et al., 2019; Olsson et al., 2014; Patterson et al., 2017; Smith and Stirling, 2010; Yap and Truffer, 2021). We have offered a stepping-stone towards a socio-techno-ecological transitions framework, which will hopefully support research that already engages with ecological dimensions of innovation processes and inspire more scholars to explore the role of nature in sustainability transitions.

CRediT authorship contribution statement

John Andersson: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Thomas Taro Lennerfors:** Funding acquisition, Investigation, Project administration, Writing – original draft. **Helena Fornstedt:** Investigation, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The research presented in this paper was conducted within the FINEST center and the authors gratefully acknowledge funding from The Swedish Research Council for Sustainable Development (FORMAS, grant no. 2020-02839). The usual disclaimer applies.

References

Ahlborg, H., Ruiz-mercado, I., Molander, S., Masera, O., 2019. Bringing technology into social-ecological systems research—motivations for a socio-technical-ecological systems approach. Sustainability. https://doi.org/10.3390/su11072009.

Anderies, J.M., 2014. Embedding built environments in social-ecological systems: resilience-based design principles. Build. Res. Inf. 42, 130–142. https://doi.org/10.1080/09613218.2013.857455.

Andersen, A.D., Marìn, A., Simensen, E.O., 2018. Innovation in natural resource-based industries: a pathway to development? Introduction to special issue. Innov. Dev. 8, 1–27. https://doi.org/10.1080/2157930X.2018.1439293.

Andersen, A.D., Wicken, O., 2021. Making sense of how the natural environment shapes innovation, industry dynamics, and sustainability challenges. Innov. Dev. 11, 91–117. https://doi.org/10.1080/2157930X.2020.1770975.

Andersson, E., Borgström, S., Haase, D., Langemeyer, J., Mascarenhas, A., McPhearson, T., Wolff, M., Łaszkiewicz, E., Kronenberg, J., Barton, D.N., Herreros-Cantis, P., 2021a. A context-sensitive systems approach for understanding and enabling ecosystem service realization in cities. Ecol. Soc. 26 https://doi.org/10.5751/ES-12411-260235.

Andersson, E., Borgström, S., Haase, D., Langemeyer, J., Wolff, M., McPhearson, T., 2021b. Urban resilience thinking in practice: ensuring flows of benefit from green and blue infrastructure. Ecol. Soc. 26 https://doi.org/10.5751/ES-12691-260439.

Andersson, J., 2020. Shape it until you make it: A conceptual foundation for efforts to analyze and shape technological innovation. Doctoral thesis. Department of Technology Management and Economics, Chalmers University of Technology in Gothenburg, Sweden.

Andersson, J., Hellsmark, H., Sandén, B.A., 2021. The outcomes of directionality: towards a morphology of sociotechnical systems. Environ. Innov. Soc. Transit. 40, 108–131. https://doi.org/10.1016/j.eist.2021.06.008.

Andersson, J., Hellsmark, H., Sandén, B.A., 2018. Shaping factors in the emergence of technological innovations: the case of tidal kite technology. Technol. Forecast. Soc. Change 132, 191–208. https://doi.org/10.1016/j.techfore.2018.01.034.

Andersson, J., Hojcková, K., Sandén, B.A., 2023. On the functional and structural scope of technological innovation systems—A literature review with conceptual suggestions. Environ. Innov. Soc. Transit. 49, 100786 https://doi.org/10.1016/j.eist.2023.100786.

Andersson, J., Plummer, P., Lennerfors, T., Hedberg, C., 2024. Socio-techno-ecological transition dynamics in the re-territorialization of food production: the case of wild berries in Sweden. Sustain. Sci. https://doi.org/10.1007/s11625-023-01461-7.

Arora, S., Hofman, N.B., Koshti, V., Ciarli, T., 2013. Cultivating compliance: governance of north Indian organic basmati smallholders in a global value chain. Environ. Plan A 45, 1912–1928. https://doi.org/10.1068/a45421.

Arthur, B.W., 2009. The Nature of Technology: What It Is and How It Evolves. Free Press, New York.

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., Truffer, B., 2015. Technological innovation systems in contexts: conceptualizing contextual structures and interaction dynamics. Environ. Innov. Soc. Transit. 16, 51–64. https://doi.org/10.1016/j.eist.2015.07.003.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008a. Analyzing the functional dynamics of technological innovation systems: a scheme of analysis. Res. Policy 37, 407–429. https://doi.org/10.1016/j.respol.2007.12.003.

Bergek, A., Jacobsson, S., Sandén, B.A., 2008b. 'Legitimation' and 'development of positive externalities': two key processes in the formation phase of technological innovation systems. Technol. Anal. Strateg. Manag. 20, 575–592. https://doi.org/10.1080/09537320802292768.

Berkes, F., Colding, J., Folke, C., 2003. Navigating Social-Ecological Systems: Building Resilience for Complexity and Change. Cambridge University Press.

Berkes, F., Folke, C., 1998. Linking Social and Ecological systems: Management Practices and Social Mechanisms For Building Resilience. Cambridge University Press, Cambridge, UK.

Branny, A., Møller, M.S., Korpilo, S., McPhearson, T., Gulsrud, N., Olafsson, A.S., Raymond, C.M., Andersson, E., 2022. Smarter greener cities through a social-ecological-technological systems approach. Curr. Opin. Environ. Sustain. https://doi.org/10.1016/j.cosust.2022.101168.
Chaffin, B.C., Gosnell, H., Cosens, B.A., 2014. A decade of adaptive governance scholarship: synthesis and future directions. Ecol. Soc. 19 https://doi.org/10.5751/ES-06824-190356.
Chang, H., Pallathadka, A., Sauer, J., Grimm, N.B., Zimmerman, R., Cheng, C., Iwaniec, D.M., Kim, Y., Lloyd, R., McPhearson, T., Rosenzweig, B., Troxler, T., Welty, C., Brenner, R., Herreros-Cantis, P., 2021. Assessment of urban flood vulnerability using the social-ecological-technological systems framework in six US cities. Sustain. Cities Soc. 68 https://doi.org/10.1016/j.scs.2021.102786.
Chang, H., Yu, D.J., Markolf, S.A., Hong, C.yu, Eom, S., Song, W., Bae, D., 2020. Understanding urban flood resilience in the anthropocene: a social–ecological–technological systems (SETS) learning framework. Ann. Am. Assoc. Geogr. 111, 837–857. https://doi.org/10.1080/24694452.2020.1850230.
Colding, J., Barthel, S., 2019. Exploring the social-ecological systems discourse 20 years later. Ecol. Soc. 24 https://doi.org/10.5751/ES-10598-240102.
Cosens, B., Ruhl, J.B., Soininen, N., Gunderson, L., Belinskij, A., Blenckner, T., Camacho, A.E., Chaffin, B.C., Craig, R.K., Doremus, H., Glicksman, R., Heiskanen, A.S., Larson, R., Similä, J., 2021. Governing complexity: integrating science, governance, and law to manage accelerating change in the globalized commons. Proc Natl Acad Sci USA. https://doi.org/10.1073/pnas.2102798118.
Depietri, Y., McPhearson, T., 2017. Integrating the grey, green, and blue in cities: nature-based solutions for climate change adaptation and risk reduction. In: Kabisch, N., Korn, H., Stadler, J., Bonn, A. (Eds.), Theory and Practice of Urban Sustainability Transitions Nature-Based Solutions to Climate Change Adaptation in Urban Areas. Springer.
Dorst, H., van der Jagt, A., Toxopeus, H., Tozer, L., Raven, R., Runhaar, H., 2022. What's behind the barriers? Uncovering structural conditions working against urban nature-based solutions. Landsc. Urban Plan. 220, 104335 https://doi.org/10.1016/j.landurbplan.2021.104335.
Edmondson, D.L., Kern, F., Rogge, K.S., 2018. The co-evolution of policy mixes and socio-technical systems: towards a conceptual framework of policy mix feedback in sustainability transitions. Res. Policy 1–14. https://doi.org/10.1016/j.respol.2018.03.010.
el Bilali, H., 2019. Research on agro-food sustainability transitions: a systematic review of research themes and an analysis of research gaps. J. Clean. Prod. 221, 353–364. https://doi.org/10.1016/j.jclepro.2019.02.232.
Elzinga, R., Janssen, M.J., Wesseling, J., Negro, S.O., Hekkert, M.P., 2023. Assessing mission-specific innovation systems: towards an analytical framework. Environ. Innov. Soc. Transit. 48 https://doi.org/10.1016/j.eist.2023.100745.
Farla, J., Markard, J., Raven, R., Coenen, L., 2012. Sustainability transitions in the making: a closer look at actors, strategies and resources. Technol. Forecast. Soc. Change 79, 991–998. https://doi.org/10.1016/j.techfore.2012.02.001.
Feenberg, A., 2005. Critical theory of technology: an overview. Tailoring Biotechnol. 1, 47–64.
Folke, C., 2006. Resilience: the emergence of a perspective for social-ecological systems analyses. Glob. Environ. Change 16, 253–267. https://doi.org/10.1016/j.gloenvcha.2006.04.002.
Folke, C., Carpenter, S.R., Walker, B., Scheffer, M., Chapin, T., Rockström, J., 2010. Resilience thinking: integrating resilience, adaptability and transformability. Ecol. Soc. 15 (4), 20.
Folke, C., Hahn, T., Olsson, P., Norberg, J., 2005. Adaptive governance of social-ecological systems. Annu. Rev. Environ. Resour. https://doi.org/10.1146/annurev.energy.30.050504.144511.
Foxon, T.J., Reed, M.S., Stringer, L.C., 2009. Governing long-term social-ecological change: what can the adaptive management and transition management approaches learn from each other? Environ. Policy Gov. 19, 3–20. https://doi.org/10.1002/eet.496.
Galaz, V., 2012. Geo-engineering, governance, and social-ecological systems: critical issues and joint research needs. Ecol. Soc. 17 https://doi.org/10.5751/ES-04677-170124.
Geels, F.W., 2022. Causality and explanation in socio-technical transitions research: mobilising epistemological insights from the wider social sciences. Res. Policy 51, 104537. https://doi.org/10.1016/j.respol.2022.104537.
Geels, F.W., 2010. Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective. Res. Policy 39, 495–510. https://doi.org/10.1016/j.respol.2010.01.022.
Geels, F.W., 2005. The dynamics of transitions in socio-technical systems: a multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930). Technol. Anal. Strateg. Manag. 17, 445–476. https://doi.org/10.1080/09537320500357319.
Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory. Res. Policy 33, 897–920. https://doi.org/10.1016/j.respol.2004.01.015.
Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res. Policy 31, 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8.
Geels, F.W., Kemp, R., 2007. Dynamics in socio-technical systems: typology of change processes and contrasting case studies. Technol. Soc. 29, 441–455. https://doi.org/10.1016/j.techsoc.2007.08.009.
Ghazinoory, S., Nasri, S., Ameri, F., Montazer, G.A., Shayan, A., 2020. Why do we need 'problem-oriented innovation system (PIS)' for solving macro-level societal problems? Technol. Forecast. Soc. Change 150, 119749. https://doi.org/10.1016/j.techfore.2019.119749.
Gong, H., Andersen, A.D., 2024. The role of material resources for rapid technology diffusion in net-zero transitions: insights from EV lithium-ion battery technological innovation system in China. Technol. Forecast. Soc. Change 200, 123141. https://doi.org/10.1016/j.techfore.2023.123141.
Grubler, A., 1998. Technology and Global Change. Cambridge University Press, Cambridge, UK.
Gulsrud, N.M., Raymond, C.M., Rutt, R.L., Olafsson, A.S., Plieninger, T., Sandberg, M., Beery, T.H., Jönsson, K.I., 2018. Rage against the machine'? The opportunities and risks concerning the automation of urban green infrastructure. Landsc. Urban Plan. 180, 85–92. https://doi.org/10.1016/j.landurbplan.2018.08.012.
Gunderson, L.H., Holling, C.S., 2002. Panarchy : Understanding Transformations in Human and Natural Systems. Island Press, Washington.
Hamborg, S., Meya, J.N., Eisenack, K., Raabe, T., 2020. Rethinking resilience: a cross-epistemic resilience framework for interdisciplinary energy research. Energy Res. Soc. Sci. 59 https://doi.org/10.1016/j.erss.2019.101285.
Hansen, T., Coenen, L., 2015. The geography of sustainability transitions: review, synthesis and reflections on an emergent research field. Environ. Innov. Soc. Transit. 17, 92–109. https://doi.org/10.1016/j.eist.2014.11.001.
Hekkert, M.P., Janssen, M.J., Wesseling, J.H., Negro, S.O., 2020. Mission-oriented innovation systems. Environ. Innov. Soc. Transit. 34, 76–79.
Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: a new approach for analysing technological change. Technol. Forecast. Soc. Change 74, 413–432. https://doi.org/10.1016/j.techfore.2006.03.002.
Hellin, J., Fisher, E., Loboguerrero, A.M., 2021. Reflections on enhancing the impact of climate risk management through transformative adaptation. Front. Clim. 3 https://doi.org/10.3389/fclim.2021.751691.
Hojcková, K., Ahlborg, H., Morrison, G.M., Sandén, B.A., 2020. Entrepreneurial use of contexts in technological innovation systems: the case of blockchain-based peer-to-peer electricity trading. Res. Policy 49, 104046. https://doi.org/10.1016/j.respol.2020.104046.
Holling, C.S., 1973. Resilience and stability of ecological systems. Annu. Rev. Ecol. Syst. 4, 1–23.
Hughes, T.P., 1987. The evolution of large technological systems. In: Bijker, W.E., Hughes, T.P., Pinch, T.J. (Eds.), The Social Construction of Technological Systems. MIT Press, Cambridge.
IPBES, 2019. Global Assessment Report on Biodiversity and Ecosystem Services.
IPCC, 2018. Global warming of 1.5 °C. An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Intergovernmental Panel on Climate Change, Geneva.
Isaksen, K.R., 2018. Without foundation or neutral standpoint: using immanent critique to guide a literature review. J. Crit. Realism. 17, 97–117. https://doi.org/10.1080/14767430.2018.1427180.
Jacobsson, S., Karltorp, K., 2012. Formation of competences to realize the potential of offshore wind power in the European Union. Energy Policy 44, 374–384. https://doi.org/10.1016/j.enpol.2012.01.069.

Jenkins, L.D., 2022. Power, politics, and culture of marine conservation technology in fisheries. Conserv. Biol. 36 https://doi.org/10.1111/cobi.13855.
Kaae, B.C., Holm, J., Caspersen, O.H., Gulsrud, N.M., 2019. Nature Park Amager–examining the transition from urban wasteland to a rewilded ecotourism destination. J. Ecotourism 18, 348–367. https://doi.org/10.1080/14724049.2019.1601729.
Kanger, L., Schot, J., 2018. Deep transitions: theorizing the long-term patterns of socio-technical change. Environ. Innov. Soc. Transit. 0–1. https://doi.org/10.1016/j.eist.2018.07.006.
Karltorp, K., 2016. Challenges in mobilising financial resources for renewable energy—The cases of biomass gasification and offshore wind power. Environ. Innov. Soc. Transit. 19, 96–110. https://doi.org/10.1016/j.eist.2015.10.002.
Karltorp, K., Guo, S., Sandén, B.A., 2017. Handling financial resource mobilisation in technological innovation systems—The case of Chinese wind power. J. Clean. Prod. 142, 3872–3882. https://doi.org/10.1016/j.jclepro.2016.10.075.
Kemp, R., Schot, J., Hoogma, R., 1998. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. Technol. Anal. Strateg. Manag. 10, 175–195.
Kivimaa, P., Kern, F., 2016. Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. Res. Policy 45, 205–217. https://doi.org/10.1016/j.respol.2015.09.008.
Köhler, J., Geels, F.W., Kern, F., Köhler, J., Geels, F.W., Kern, F., Markard, J., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., Mcmeekin, A., Susan, M., Nykvist, B., Onsongo, E., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., A, B.T., B, D.W., Mühlemeier, M.S., Nykvist, B., Onsongo, E., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., Turnheim, B., Welch, D., Wells, P., Köhler, J., Geels, F.W., Kern, F., Markard, J., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., Mcmeekin, A., Susan, M., Nykvist, B., Onsongo, E., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., A, B.T., B, D.W., 2019. An agenda for sustainability transitions research: state of the art and future directions. Environ. Innov. Soc. Transit. 31, 1–32. https://doi.org/10.1016/j.eist.2019.01.004.
Krueger, E.H., McPhearson, T., Levin, S.A., 2022. Integrated assessment of urban water supply security and resilience: towards a streamlined approach. Environ. Res. Lett. 17 https://doi.org/10.1088/1748-9326/ac78f4.
Loorbach, D., 2010. Transition management for sustainable development: a prescriptive, complexity-based governance framework. Governance 23, 161–183. https://doi.org/10.1111/j.1468-0491.2009.01471.x.
Low, S., Baum, C.M., Sovacool, B.K., 2022. Rethinking net-zero systems, spaces, and societies: "Hard" versus "soft" alternatives for nature-based and engineered carbon removal. Glob. Environ. Change 75, 102530. https://doi.org/10.1016/j.gloenvcha.2022.102530.
Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: an emerging field of research and its prospects. Res. Policy 41, 955–967. https://doi.org/10.1016/j.respol.2012.02.013.
Markard, J., Truffer, B., 2008. Technological innovation systems and the multi-level perspective: towards an integrated framework. Res. Policy 37, 596–615. https://doi.org/10.1016/j.respol.2008.01.004.
Markolf, S.A., Chester, M.V., Eisenberg, D.A., Iwaniec, D.M., Davidson, C.I., Zimmerman, R., Miller, T.R., Ruddell, B.L., Chang, H., 2018. Interdependent infrastructure as linked social, ecological, and technological systems (SETSs) to address lock-in and enhance resilience. Earths Future 6, 1638–1659. https://doi.org/10.1029/2018EF000926.
Maxwell, J.A., 2012. A Realist Approach for Qualitative Research. Sage Publications, Thousand Oaks, CA.
McGinnis, M.D., Ostrom, E., 2014. Social-ecological system framework: initial changes and continuing challenges. Ecol. Soc. 19 https://doi.org/10.5751/ES-06387-190230.
McPhearson, T., Cook, E.M., Berbés-Blázquez, M., Cheng, C., Grimm, N.B., Andersson, E., Barbosa, O., Chandler, D.G., Chang, H., Chester, M.V., Childers, D.L., Elser, S.R., Frantzeskaki, N., Grabowski, Z., Groffman, P., Hale, R.L., Iwaniec, D.M., Kabisch, N., Kennedy, C., Markolf, S.A., Matsler, A.M., McPhillips, L.E., Miller, T.R., Muñoz-Erickson, T.A., Rosi, E., Troxler, T.G., 2022. A social-ecological-technological systems framework for urban ecosystem services. One Earth. https://doi.org/10.1016/j.oneear.2022.04.007.
McPhearson, T., Haase, D., Kabisch, N., Gren, Å., 2016a. Advancing understanding of the complex nature of urban systems. Ecol. Indic. 70, 566–573. https://doi.org/10.1016/j.ecolind.2016.03.054.
McPhearson, T., Pickett, S.T.A., Grimm, N.B., Niemelä, J., Alberti, M., Elmqvist, T., Weber, C., Haase, D., Breuste, J., Qureshi, S., 2016b. Advancing urban ecology toward a science of cities. Bioscience 66, 198–212. https://doi.org/10.1093/biosci/biw002.
Mehvar, S., Wijnberg, K., Borsje, B., Kerle, N., Maarten Schraagen, J., Vinke-De Kruijf, J., Geurs, K., Hartmann, A., Hogeboom, R., Hulscher, S., 2021. Review article: towards resilient vital infrastructure systems-challenges, opportunities, and future research agenda. Nat. Hazards Earth Syst. Sci. 21, 1383–1407. https://doi.org/10.5194/nhess-21-1383-2021.
Moore, M.L., Tjornbo, O., Enfors, E., Knapp, C., Hodbod, J., Baggio, J.A., Norström, A., Olsson, P., Biggs, D., 2014. Studying the complexity of change: toward an analytical framework for understanding deliberate social-ecological transformations. Ecol. Soc. 19 https://doi.org/10.5751/ES-06966-190454.
Muñoz-Erickson, T.A., Meerow, S., Hobbins, R., Cook, E., Iwaniec, D.M., Berbés-Blázquez, M., Grimm, N.B., Barnett, A., Cordero, J., Gim, C., Miller, T.R., Tandazo-Bustamante, F., Robles-Morua, A., 2021. Beyond bouncing back? Comparing and contesting urban resilience frames in US and Latin American contexts. Landsc. Urban Plan. 214 https://doi.org/10.1016/j.landurbplan.2021.104173.
Musiolik, J., Markard, J., Hekkert, M., 2012. Networks and network resources in technological innovation systems: towards a conceptual framework for system building. Technol. Forecast. Soc. Change 79, 1032–1048. https://doi.org/10.1016/j.techfore.2012.01.003.
Musiolik, J., Markard, J., Hekkert, M.P., Furrer, B., 2018. Creating innovation systems : how resource constellations affect the strategies of system builders. Technol. Forecast. Soc. Change 153. https://doi.org/10.1016/j.techfore.2018.02.002.
Nilsson, A.E., Avango, D., Rosqvist, G., 2021. Social-ecological-technological systems consequences of mining: an analytical framework for more holistic impact assessments. Extr. Ind. Soc. 8 https://doi.org/10.1016/j.exis.2021.101011.
Nogueira, L.A., Wigger, K.A., Jolly, S., 2021. Common-pool resources and governance in sustainability transitions. Environ. Innov. Soc. Transit. 41, 35–38. https://doi.org/10.1016/j.eist.2021.10.004.
Ollivier, G., Magda, D., Mazé, A., Plumecocq, G., Lamine, C., 2018. Agroecological transitions: what can sustainability transition frameworks teach us? An ontological and empirical analysis. Ecol. Soc. 23 https://doi.org/10.5751/ES-09952-230205.
Olsson, P., Galaz, V., Boonstra, W.J., 2014. Sustainability transformations: a resilience perspective. Ecol. Soc. 19 https://doi.org/10.5751/ES-06799-190401.
Ostrom, E., 2009. A general framework for analyzing sustainability of social-ecological systems. Science 325 (1979), 419–422.
Ostrom, E., 2007. A diagnostic approach for going beyond panaceas. Proc. Natl. Acad. Sci. 104 (39), 15181–15187.
Pahl-Wostl, C., 2007. Transitions towards adaptive management of water facing climate and global change. Water Resources Management, pp. 49–62. https://doi.org/10.1007/s11269-006-9040-4.
Partelow, S., 2018. A review of the social-ecological systems framework: applications, methods, modifications, and challenges. Ecol. Soc. https://doi.org/10.5751/ES-10594-230436.
Patterson, J., Schulz, K., Vervoort, J., van der Hel, S., Widerberg, O., Adler, C., Hurlbert, M., Anderton, K., Sethi, M., Barau, A., 2017. Exploring the governance and politics of transformations towards sustainability. Environ. Innov. Soc. Transit. 24, 1–16. https://doi.org/10.1016/j.eist.2016.09.001.
Pigford, A.A.E., Hickey, G.M., Klerkx, L., 2018. Beyond agricultural innovation systems? Exploring an agricultural innovation ecosystems approach for niche design and development in sustainability transitions. Agric. Syst. 164, 116–121. https://doi.org/10.1016/j.agsy.2018.04.007.
Pinch, T.J., Bijker, W.E., 1987. The social construction of facts and artifacts: or how the sociology of science and the sociology of technology might benefit each other. In: Bijker, W.E., Hughes, T.P., Pinch, T.J. (Eds.), The Social Construction of Technological Systems. MIT Press, Cambridge.
Pineda-Pinto, M., Herreros-Cantis, P., McPhearson, T., Frantzeskaki, N., Wang, J., Zhou, W., 2021. Examining ecological justice within the social-ecological-technological system of New York City, USA. Landsc. Urban Plan. 215 https://doi.org/10.1016/j.landurbplan.2021.104228.
Plummer, P., Andersson, J., Lennerfors, T., 2024. Foraging for development: an analysis of the Swedish innovation system for wild berries. Agric. Syst. 216, 103901. https://doi.org/10.1016/j.agsy.2024.103901.

Raven, R., Schot, J., Berkhout, F., 2012. Space and scale in socio-technical transitions. Environ. Innov. Soc. Transit. 4, 63–78. https://doi.org/10.1016/j.eist.2012.08.001.

Razzaghi Asl, S., 2022. Re-powering the nature-intensive systems: insights from linking nature-based solutions and energy transition. Front. Sustain. Cities. https://doi.org/10.3389/frsc.2022.860914.

Reyers, B., Moore, M.L., Haider, L.J., Schlüter, M., 2022. The contributions of resilience to reshaping sustainable development. Nat. Sustain. https://doi.org/10.1038/s41893-022-00889-6.

Reynolds, J.L., 2021. Earth system interventions as technologies of the Anthropocene. Environ. Innov. Soc. Transit. 40, 132–146. https://doi.org/10.1016/j.eist.2021.06.010.

Rip, A., Kemp, R., 1998. Technological change. In: Rayner, S., Malone, E.L. (Eds.), Human Choice and Climate Change. Battelle Press, Columbus, OH, pp. 327–399. https://doi.org/10.1007/BF02887432.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., et al., 2009. A safe operating space for humanity. Nature 461, 472–475. https://doi.org/10.1038/461472a pmid:19779433.

Rosenberg, N., 1994. Exploring the Black Box: Technology, Economics and History. Cambridge University Press, Cambridge.

Rotmans, J., Kemp, R., van Asselt, M., 2001. More evolution than revolution: transition management in public policy. Foresight 3, 15–31. https://doi.org/10.1108/14636690710816471.

Sandén, B.A., Hillman, K.M., 2011. A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden. Res. Policy 40, 403–414. https://doi.org/10.1016/j.respol.2010.12.005.

Sandén, B.A., Jonasson, K.M., 2005. Variety Creation, Growth and Selection Dynamics in the Early Phases of a Technological Transition. Chalmers University of Technology, Gothenburg, Sweden. ESA-report 2005:13.

Selin, H., Selin, N.E., 2022. The human–technical–environmental systems framework for sustainability analysis. Sustain. Sci. https://doi.org/10.1007/s11625-022-01177-0.

Smith, A., Stirling, A., 2010. The politics of social-ecological resilience and sustainable socio-technical transitions. Ecol. Soc. 15 https://doi.org/10.5751/ES-03218-150111.

Smith, A., Stirling, A., Berkhout, F., 2005. The governance of sustainable socio-technical transitions. Res. Policy 34, 1491–1510. https://doi.org/10.1016/j.respol.2005.07.005.

Smith, A., Voß, J.P., Grin, J., 2010. Innovation studies and sustainability transitions: the allure of the multi-level perspective and its challenges. Res. Policy. https://doi.org/10.1016/j.respol.2010.01.023.

Sorge, S., Mann, C., Schleyer, C., Loft, L., Spacek, M., Hernández-Morcillo, M., Kluvankova, T., 2022. Understanding dynamics of forest ecosystem services governance: a socio-ecological-technical-analytical framework. Ecosyst. Serv. 55 https://doi.org/10.1016/j.ecoser.2022.101427.

Sovacool, B.K., Axsen, J., Sorrell, S., 2018. Promoting novelty, rigor, and style in energy social science: towards codes of practice for appropriate methods and research design. Energy Res. Soc. Sci. https://doi.org/10.1016/j.erss.2018.07.007.

Steffen, W., Crutzen, P.J., McNeill, J.R., 2007. The anthropocene: are humans now overwhelming the great forces of nature? Ambio 36, 614–621. https://doi.org/10.1579/0044-7447(2007)36 [614:TAAHNO]2.0.CO;2.

Steffen, W., Noone, K., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., De Wit, C.A., Hughes, T., Van Der Leeuw, S., Rodhe, H., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J., 2009. Planetary boundaries: exploring the safe operating space for humanity. Ecol. Soc. 14 (2), 32.

Stirling, A., 2011. Pluralising progress: from integrative transitions to transformative diversity. Environ. Innov. Soc. Transit. 1, 82–88. https://doi.org/10.1016/j.eist.2011.03.005.

Susur, E., Karakaya, E., 2021. A reflexive perspective for sustainability assumptions in transition studies. Environ. Innov. Soc. Transit. 39, 34–54. https://doi.org/10.1016/j.eist.2021.02.001.

Suurs, R.A., Hekkert, M.P., 2009. Cumulative causation in the formation of a technological innovation system: the case of biofuels in the Netherlands. Technol. Forecast. Soc. Change 76, 1003–1020. https://doi.org/10.1016/j.techfore.2009.03.002.

Svensson, O., Nikoleris, A., 2018. Structure reconsidered: towards new foundations of explanatory transitions theory. Res. Policy 47, 462–473. https://doi.org/10.1016/j.respol.2017.12.007.

Truffer, B., Rohracher, H., Kivimaa, P., Raven, R., Alkemade, F., Carvalho, L., Feola, G., 2022. A perspective on the future of sustainability transitions research. Environ. Innov. Soc. Transit. 42, 331–339. https://doi.org/10.1016/j.eist.2022.01.006.

Turnheim, B., Geels, F.W., 2013. The destabilisation of existing regimes: confronting a multi-dimensional framework with a case study of the British coal industry (1913–1967). Res. Policy 42, 1749–1767. https://doi.org/10.1016/j.respol.2013.04.009.

Van Den Bergh, J.C.J.M., Truffer, B., Kallis, G., 2011. Environmental innovation and societal transitions: introduction and overview. Environ. Innov. Soc. Transit. 1, 1–23. https://doi.org/10.1016/j.eist.2011.04.010.

Van Der Brugge, R., Van Raak, R., 2007. Facing the adaptive management challenge: insights from transition management. Ecol. Soc. 12 (2), 33.

van der Jagt, A.P.N., Raven, R., Dorst, H., Runhaar, H., Van Der Jagt, A.P.N., Raven, R., Dorst, H., Runhaar, H., van der Jagt, A.P.N., Raven, R., Dorst, H., Runhaar, H., 2020. Nature-based innovation systems. Environ. Innov. Soc. Transit. 35, 202–216. https://doi.org/10.1016/j.eist.2019.09.005.

van der Leer, J., van Timmeren, A., Wandl, A., 2018. Social-ecological-technical systems in urban planning for a circular economy: an opportunity for horizontal integration. Archit. Sci. Rev. 61, 298–304. https://doi.org/10.1080/00038628.2018.1505598.

van Driel, H., Schot, J., 2005. Radical innovation as a multilevel process: introducing floating grain elevators in the port of Rotterdam. Technol. Cult. 46, 51–76.

Vermunt, D.A., Negro, S.O., Van Laerhoven, F.S.J., Verweij, P.A., Hekkert, M.P., 2020. Sustainability transitions in the agri-food sector: how ecology affects transition dynamics. Environ. Innov. Soc. Transit. 36, 236–249. https://doi.org/10.1016/j.eist.2020.06.003.

Ville, S., Wicken, O., 2013. The dynamics of resource-based economic development: evidence from Australia and Norway. Ind. Corp. Change 22, 1341–1371. https://doi.org/10.1093/icc/dts040.

Walker, B., Holling, C.S., Carpenter, S.R., Kinzig, A., 2004. Resilience, adaptability and transformability in social-ecological systems. Ecol. Soc. 9 (2), 5.

Waters, C.N., Zalasiewicz, J., Summerhayes, C., Barnosky, A.D., Poirier, C., Gałuszka, A., Cearreta, A., Edgeworth, M., Ellis, E.C., Ellis, M., Jeandel, C., Leinfelder, R., McNeill, J.R., Richter, D.D.B., Steffen, W., Syvitski, J., Vidas, D., Wagreich, M., Williams, M., Zhisheng, A., Grinevald, J., Odada, E., Oreskes, N., Wolfe, A.P., 2016. The Anthropocene is functionally and stratigraphically distinct from the Holocene. Science 1979, 351. https://doi.org/10.1126/science.aad2622.

Wesseling, J., Meijerhof, N., 2023. Towards a mission-oriented innovation systems (MIS) approach, application for Dutch sustainable maritime shipping. PLOS Sustain. Transform. 2, e0000075 https://doi.org/10.1371/journal.pstr.0000075.

Wieczorek, A.J., Hekkert, M.P., 2012. Systemic instruments for systemic innovation problems: a framework for policy makers and innovation scholars. Sci. Public Policy 39, 74–87. https://doi.org/10.1093/scipol/scr008.

Wirth, S., Markard, J., 2011. Context matters: how existing sectors and competing technologies affect the prospects of the Swiss Bio-SNG innovation system. Technol. Forecast. Soc. Change 78, 635–649. https://doi.org/10.1016/j.techfore.2011.01.001.

Yap, X., Truffer, B., 2021. Opportunities and challenges of the rising Space sector : contours of a research agenda for sustainability transitions. In: Proceedings of the International Sustainability Transitions Conference 2021.