Received: 8 February 2024 | Revised: 11 June 2024 | Accepted: 12 June 2024

DOI: 10.1002/sd.3101

RESEARCH ARTICLE

Sustainable Development WILEY

Sustainability transition theories: Perpetuating or breaking with the status quo

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Abstract

How scientists frame problems impact the solutions offered. Since the late 1940s development has been equated with modernization, technology adoption, and economic growth. Contrasting to this technocentric view, an ecocentric view has developed since the 1960s. Despite the criticism of technocentric views and increasing evidence that modern human societies are not reaching their environmental and social goals, technocentric views have remained predominant in the sustainable development discourse. Using a Kuhnian lens, the divide between technocentric and ecocentric perspectives can be framed as distinct paradigms within the sustainable development discourse. This paper outlines the continuation of the divide between technocentric and ecocentric worldviews within sustainability transition studies. It shows that the technocentric view remained predominant and that socio-technical transition theory fails to break with technocentric and growth-focused approaches to progress and development. The paper concludes by outlining what could be gained if an ecocentric view became more weight.

KEYWORDS

socio-ecological transition, socio-technological transition, sustainability transition, Thomas Kuhn

1 | INTRODUCTION

The landmark publication by Rockstrom et al. (2009), which has been updated since (Richardson et al., 2023; Steffen et al., 2015), illustrated that nations overshoot several planetary boundaries. In a recent publication, the planetary boundaries concept was expanded to include social indicators, showing that societies neither perform well on those (Rockstrom et al., 2023). To create more sustainable societies, the United Nations developed the Sustainable Development Goals (SDGs), which were adopted in 2015. The SDGs are clustered into 17 overarching goals and contain 169 targets to create sustainable societies. In a recent progress report, it has been highlighted that we are not on track to reach the SDGs by 2030 (United Nations, 2023). The latest IPCC report similarly shows that nations are not on track to reach the Paris Agreement, which requires limiting temperature increase to 1.5°C. The IPCC warns that the window to take action is limited and that urgent and decisive action is needed to sufficiently reduce greenhouse gas emissions, and the correlated negative socio-ecological effects (IPCC, 2023).

To avoid more social and ecological degradation, transitions/transformations to more sustainable systems are required. In this study, we explore and discuss current transition theories, their transformational potential, and their limitations. The goal is to clarify the differences between these theories so that they can guide clear action. Additionally, in this study, we reflect on the role of the scientific discourse and dominant scientific theories in maintaining the unsustainable state of societies. We do so by outlining the connection between the development and the transition studies discourse (Section 2). We argue that the dominant development narrative has been unable to deliver sustainable development. Nevertheless, the dominant transition theory continues to perpetuate this unsuccessful development narrative. Therefore, we suggest that alternative theories and narratives need more attention in society, including from the academic community. To analyze the dynamics between dominant and alternative theories in research, we draw from the work of Kuhn (2012), who outlines how scientific revolutions unfold, arguing that these revolutions are long, slow processes (Section 4). To apply Kuhn's (2012) writing to the transition discourse, one theory needs to dominate the field of transition studies. To establish whether one theory dominates the field, we conducted a quantitative literature study (Sections 5 and 6). We conclude by outlining the need and potential benefits of using an alternative theory (Section 7).

2 | THE RESISTANCE OF THE GROWTH-DRIVEN DEVELOPMENT NARRATIVE

In 2015 the Millennium Development Goals (MDGs) were followed by the Sustainable Development Goals (SDGs). The MDGs were mostly meant to be followed *by Developing Countries* (United Nations, 2015, p. 5f). Thus, with the adoption of the SDGs, the quest to reach *development* goals was expanded to the *Global North*. The concept of development put forward by these frameworks continues to be based on *Western* ideas of progress (Schöneberg & Häckl, 2020). Accordingly, what this *progress* entails and how to measure it, is likewise based on *Western* ideas. The development pathway includes modernization and the use of novel technologies, the installation of liberal market economies, and continuous annual GDP growth (Schmelzer, 2017). A famous framework that captures this development pathway is Rostow's (1969) *Stages of Economic Growth* (Foster-Carter, 1976). In his book, Rostow (1969) discussed the development steps starting from a traditional society and culminating in a society coined by high mass consumption. Rostow (1969) proposed that development and progress are achieved through industrialization, thus technological advancement (Mokyr, 2005) and economic growth (Schmelzer, 2015). Despite the criticism of Rostow's work, his ideas and the notion of modernization as the path towards development and progress have not lost relevance (Solivetti, 2005).

The economic growth narrative is intricately linked to the development narrative (Schmelzer, 2017). Development and progress are not only linked to the notion of economic growth but also to the adoption of novel technology and continuous investment in technologies (Rosenberg, 1974). As Mokyr (2005) puts it: "Technology is knowledge. Knowledge […] is at the core of modern economic growth, […]." Within the current economic system, continuous economic growth is facilitated through capital accumulation and technological change. Economic growth is understood to be a necessary prerequisite to achieve prosperity and alleviate poverty (Common & Stagl, 2005, chapter 6). Further, through technological progress, resource constraints can be overcome and thus continuous economic growth can be maintained (Common & Stagl, 2005, chapter 7). Thus, the nexus between economic growth and technology creates a virtuous cycle. In terms of *development*, it was technologies and modernization that freed up workforce (from agricultural activities) and made industrialization possible. Thus, questioning economic growth means questioning progress and well-being. Likewise, questioning technology means questioning progress and well-being.

Despite the success of the *Western* path to progress, in the 1960s, negative side-effects of this *development* path became apparent. Rogers' (1983) book on the *Diffusion of Innovation* reflects on a discourse that started as a response to the negative side effects of industrialization. Rogers (1983) argues that a paradigm shift is needed. He criticizes the Eurocentric perspective on *development* as well as the blind focus on economic growth. Economic growth criticism started in the late 1960s. A key publication representing the environmental movement of the 1960s was *Silent Spring* (Epstein, 2014; Lear, 1993), which uncovered the devastating side effects of insecticide use. A few years later, Boulding (1966) published his paper about the planet Earth as a spaceship criticizing people's, but especially economists', inability to adjust to the fact that humans have to get by a limited amount of resources. Another landmark publication was the *Limits to Growth* report published in 1972 (Meadows, 2010), which warned of the negative impacts of overshooting resource extraction thresholds. A few years later, the publication *Small Is Beautiful: A Study of Economics As If People Mattered* (Schumacher, 1919), criticized the development path of growthism. Schumacher put forward an alternative economic system based on small structures and sufficiency. These publications discussed the shortcomings of the prevalent development narrative. The publications also fostered civil society environmental movements (Rome, 2003; Rootes, 2008) that aimed at a paradigm shift. In response to the increased social and ecological well-being concerns, some environmental protection laws were enacted, that called, for example, for the development and production of cleaner technologies (e.g., pesticides in response to Carson's book [Epstein, 2014], the Gothenburg Protocol to reduce acid rain [Menz & Seip, 2004]). Nevertheless, the growth-based development narrative remained dominant across the world.

New technologies, which are means to sustain and increase economic growth, continue to be perceived as capable of offsetting problems related to environmental degradation (European Commission, 2019). The Environmental Kuznets (EK) curve supports the idea of decoupling environmental burdens from economic activity, whereas decoupling is facilitated through innovation, such as clean technology. However, neither an EK curve pattern (Kaya Kanlı & Küçükefe, 2022) nor absolute decoupling could be attested (Haberl et al., 2020; Hickel & Kallis, 2019). Despite this evidence, trust in technology to facilitate sustainable development seems not to diminish (European Commission, 2019; The White House, 2023).

Thus, the discourse that started in the 1960s is an ongoing one. It is a discourse between technocentric and ecocentric worldviews (Marletto et al., 2016). It is the discourse about weak and strong sustainability (Beckerman, 1995; Biely et al., 2018; Daly, 1995), between environmental and ecological economists (Beder, 2011). It is about discount rates, the incommensurability of values, the ways to measure and define well-being, or the monetarization of nature (Biely, 2014). It is about keeping the current economic system or replacing it with another one. It is about moving to a post-growth society or remaining stuck in a system that is based on unlimited (green) growth facilitated by technological advancements. These divergent perspectives persist, but, given the fact that we are not achieving the SDGs and that we are continuing to overshoot planetary boundaries, it can be argued that the scientific fields dealing with sustainable development and sustainability transitions (including economics) need a paradigm shift just as much as our societies need such a shift. Breaking with how scientists frame sustainability problems could help to stop perpetuating narratives that are part of the problem.

2.1 | Development and transition theories

Transition studies provide frameworks to understand past transitions and to hypothesize about how future transitions could unfold (Asquith et al., 2018; Schlaile & Urmetzer, 2021; Scoones et al., 2020; Sovacool & Hess, 2017). There are many different conceptions, such as socio-technical transition theory (Geels, 2002a), socio-ecological transition theory (Gunderson & Holling, 2002), socio-institutional (Loorbach et al., 2017) or socio-economic transition theory (Kemp et al., 2022), transition pathways (Pathways, 2021), and the three horizons (Sharpe et al., 2016). Many transition concepts have developed since the beginning of the 21st century. However, transition thinking predates the 21st century and can be connected to the sustainable development discourse (Escobar, 2015; Schlaile & Urmetzer, 2021).

The connection between the (sustainable) development debate and transition studies is illustrated by the history of the SDGs and its founding document. The resolution that enacted the SDGs is titled *Transforming our world: the 2030 Agenda for Sustainable Development*. The notion of transformation is thus central to the SDGs. Understandably so, some projects exploring transitions use the SDGs as a starting point (Pathways, 2021).

Mapping out different approaches to sustainable development, Marletto et al. (2016) distinguished between status quo and transformative approaches, whereat technocentric ones belong to the former and ecocentric ones to the latter. Similar to the development discourse, one can identify a technocentric and an ecocentric approach within transition studies. These two are represented by socio-technical and socio-ecological transition theory.

The work of Thomas Kuhn provides insights into paradigm changes within science. Socio-technical and socio-ecological transition theory can be understood as two transition theories based on different paradigms. To expand on this, the next section introduces the work of Thomas Kuhn. Further, the division into two different paradigms, marked by the institutionalization of the respective research streams, is outlined. Thereafter the dominance of one of the research streams within sustainability transition literature is illustrated. The next section explores how the two research streams break or continue with the dominant paradigm.

3 | SOCIO-TECHNICAL AND SOCIO-ECOLOGICAL TRANSITION THEORY

3.1 | Socio-technical transition theory

Socio-technical transition theory gained momentum through the work of Frank Geels (Geels, 2002b).[1] His dissertation is titled: *Understanding the Dynamics of Technological Transitions: A Co-evolutionary and Socio-technical Analysis*. His first scientific paper capturing his Ph.D. thesis is titled: *Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study* (Geels, 2002a). The headings indicate that Geels approaches processes of social change through a technological lens. That technology lens is also emphasized in the abstract of his 2002 paper: "This paper addresses the question of how technological transition (TT) comes about?" The social sphere is added to understand technological change, as he outlines that the mainstreaming of technology requires "changes in user practices, regulations, industrial networks infrastructure, and symbolic meaning or culture" (Geels, 2002a). Thus, Geels' work falls in the sociological tradition of diffusion of innovation research investigating the connection between technological innovations and society (Rogers, 1983, p. 50).[2]

Socio-technical transition theory understands technological change in connection to social systems. A technological transition takes place when a new technology is successfully upscaled and thus integrated into the social system. Socio-technical transition theory is illustrated through the Multi-level perspective (MLP) framework, which theorizes about past (Geels, 2002a, 2005), ongoing (Derwort et al., 2022) and future transitions (Geels et al., 2020). The MLP provides a framework to understand transition processes on three different levels (micro, meso, and macro). Process-wise it is hypothesized that a technological innovation starts from a niche, which is, over time, scaled up and integrated into the market (and thus society). The niche is the micro-level. The regime, which denotes the dominant socio-technical system, is the meso-level. Global and long-term developments are captured by the landscape (macro-level). Since its introduction the MLP has been refined and developed further and combined with other frameworks (Derwort et al., 2022; Kanger, 2021).

Although socio-technical transition theory might be framed as sustainability transition theory, it has been developed to understand technological transitions (e.g., from sailing ships to steamships [Geels, 2002a], from horse-drawn carriages to automobiles [Geels, 2005]). Arguably the societal aspects of technological transitions have been further explored since the 2002 paper. Using insights from sociology, Geels (2004) outlined in more detail how technological changes are connected to society. The MLP has also been combined with behavioral science (Keller et al., 2022), research on power

(Avelino, 2017; Geels, 2014), or agency (Geels, 2020). Some have also extended the MLP to integrate the role of individuals (Geels, 2020; Göpel, 2016).

Socio-technical transition theory has found wide applications such as for the green economy (Gibbs & O'Neill, 2014), the circular economy (Mathur et al., 2023), the protein transition (Bulah et al., 2023), or the energy transition (Prados et al., 2022).

3.2 | Socio-ecological transition theory

Socio-ecological transition theory focuses on human-nature interactions (Olmos-Martínez & Ortega-Rubio, 2020). A prominent representative of socio-ecological thinking is Elena Ostrom, who provided insights into managing human-nature systems (Ostrom, 2009). Prevalent approaches connected to socio-ecological thinking are material flow analysis (Helmut et al., 2006), social metabolism (Haberl et al., 2019), the ecological footprint (Halpern et al., 2022) or the planetary boundaries concept (Richardson et al., 2023). In terms of transitions, the book *Panarchy by* Gunderson and Holling (2002) outlines the phases of change captured by the adaptive cycle. "Panarchy is a conceptual model that describes the ways in which complex systems of people and nature are dynamically organized and structured across scales of space and time" (Allen et al., 2014, p. 578). Additionally, the Panarchy framework provides insights regarding scale (Berkes & Ross, 2016). While it is beyond the scope of this paper to explain in detail transition models, it is important to highlight that Panarchy as conceptual model describes transitions in adaptive and continuous cycles that affect both smaller scales and larger scales, specifically emphasizing the cross-scale linkages whereby processes at one scale affect those at other scales to influence the overall dynamics of the system (i.e., concept of nested adaptive cycles). These cycles are characterized by "[…] inherent dynamics of living systems: that is, living systems are complex, adaptive, and undergo stages of growth, conservation, release, and reorganization […]" (Garmestani et al., 2020, p. 576).

An example of the application of the adaptive cycle and the Panarchy concept is the paper by Kuhmonen and Kuhmonen (2023). They analyzed the transformation of the Finnish agri-food system identifying six distinct system states. The states are identified by the system's respective metabolism and trade orientation. Each of these states collapsed as the system matured and became overly rigid. Respective systems became locked into a certain development path, which, in the long run, reduced adaption options (e.g., actors' ability to react differently). In the event of a big external shock, the systems collapsed, which allowed a new system to emerge. The Panarchy concept has not only been used to explore ecological challenges such as forest management (Qiao et al., 2024). It has also been used to understand community resilience (Berkes & Ross, 2016), sustainable supply chain management (Madonna et al., 2024), and adaptive governance (Chaffin & Gunderson, 2016).

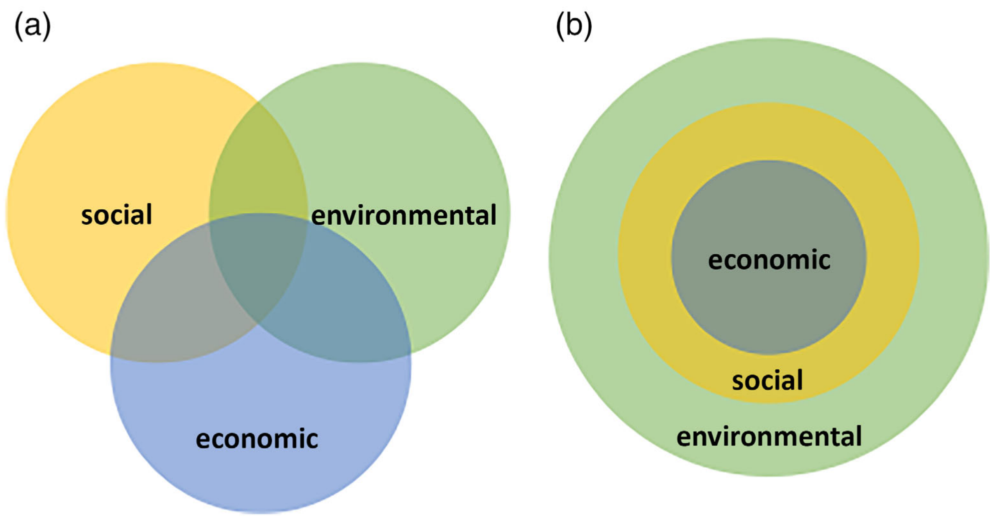
The next section (Section 3.3) presents more in-depth the main points of differences between these frameworks. Nevertheless, we highlight here a crucial difference between socio-ecological and socio-technical thinking is that the former frames the system as socio-**ecological**, rather than socio-**technical** (Andersson et al., 2024). In *Panarchy*, technologies are presented as relevant factors within transition processes as well (Gunderson & Holling, 2002; Kuhmonen & Kuhmonen, 2023). However, instead of framing technology as the solution to sustainability issues, the downsides of technology are highlighted too. The downsides relate to the notion of socio-technical landscapes used in socio-technical transition theory (Geels & Schot, 2007). The lock-ins created by technologies stem from human's inability to fully understand the world's complexity (Panarchy). Thus, solutions only address a current problem without taking account of (or ignoring) side effects across scales (time and space). That has the effect that humans are trapped in a vicious cycle where they constantly have to solve the problem created by the solution they have applied to another problem (Béné, 2022).

3.3 | Incommensurability of socio-technical and socio-ecological transition theory

There are many similarities between the socio-ecological transition theory (the adaptive cycle) and the socio-technical transition theory (using the MLP). For example, both work on different scales, whereas each scale has certain characteristics (e.g., stability). Both discuss the problem of lock-ins created by the rigidity of the current system. Socio-technical theory uses the notion of the socio-technical landscape. A similar approach can be found in resilience theory, where resilience is explained using the topography of a landscape (Walker et al., 2004). Socio-ecological transition theory uses resilience thinking as well as the notion of lock-ins. However, resilience is not only determined by technological artifacts but by the natural system as well. Other similarities are that both refer to Schumpeter's idea of creative destruction, both look at the role of technology[3] in change processes and both use the concept of complex adaptive systems.

Despite these similarities, we argue that the different transition theories cannot be combined. Even if one might be tempted to see how they can be integrated (Geels, 2010; Nilsen, 2010). They cannot be combined because they developed out of different worldviews, one that understands nature to be an external factor and one that does not. In line with Kuhn's (2012) argumentation, one could say that if socio-technical and socio-ecological transition theories were the same, they would not need different institutions. One could easily integrate publications focusing on human-nature interactions within journals that frame the world as a socio-technical system. The split between socio-technical and socio-ecological transition theory is similar to the split between environmental economics and ecological economics[4] (Beder, 2011; Biely, 2014; Munda, 1997). These two follow different pre-analytical visions, as Daly (1996) calls it. The different pre-analytical visions are famously illustrated by the weak and strong sustainability illustrations (see Figure 1). And it is reflected by ecological economists taking the economic system out of its vacuum and placing it within the natural environment (Costanza et al., 2009).

FIGURE 1 (a) Weak sustainability, (b) strong sustainability. Weak sustainability depicts sustainability as the overlap between social, economic, and environmental spheres. Strong sustainability depicts the economy embedded within the social system, which is embedded in the natural system. For a discussion of these two concepts see, for example, Chakori (2022), Biely (2020) or Lozano (2008).



These two interpretations of sustainability are also reflected in the frames that socio-technical and socio-ecological literature use. The potential to separate humans from the environment is proposed by socio-technical literature. Instead of framing the social as part of the **biotope** it is argued that humans live in a **technotope** (Geels & Schot, 2007). The description of the landscape within the MLP frames the environment as an external factor,[5] Thus, the MLP frame has parallels to neoliberal views, where environmental factors are external too (Costanza et al., 1998). As Boulding (1966) discussed in 1966, the exclusion of the environment leads to environmental degradation. Externalizing the environment allows to neglect the material reality of technology.

4 | KUHN'S SCIENTIFIC REVOLUTIONS

The discourse within transition studies can be understood as the struggle between a dominant and an alternative paradigm. The work of Kuhn (2012) about *The Structure of Scientific Revolutions* sheds light on paradigm changes within a scientific field. He does not only outline how such shifts come about but also why they are lengthy and difficult processes.

Kuhn (2012) described scientific activities as puzzle-solving. This puzzle-solving activity is called normal science. Puzzle-solving does not aim to discover real novelty. That is since the result of the puzzle is predetermined by the paradigm. One could say that the paradigm is the picture on the box of the puzzle. If scientists encounter anomalies, the paradigm is not automatically scrutinized, but the anomalies are made to fit the paradigm. That is why paradigm changes within science take a long time. There are mechanisms that protect a discipline from a paradigm change. These are institutional and psychological mechanisms. For example, Kuhn (2012) referred to confirmation bias. Examples are scientists who, being confronted with an anomaly, rather question their experimental setup than the paradigm. Or they search for logical explanations that are in line with the paradigm, rather than questioning the paradigm. Furthermore, Kuhn (2012) referred to power structures. As indicated by Rogers (1983), scientists are part of an ingroup (see below), which is following a specific paradigm. The group tries to protect its existence by protecting the paradigm. Examples are journals reluctant to publish research that challenges the paradigm the journal represents.

Despite these protective mechanisms at some point, paradigms change. That happens when too many anomalies have been found and a new paradigm is better at explaining these anomalies. Kuhn (2012) described different phases as well as the characteristics of these phases. For example, a prevalent paradigm is usually institutionalized. The paradigm is represented by journals, scientific groups, and curricula. Evolving new paradigms strive for this institutionalization as well. Proponents of an alternative paradigm need to establish their own institutions because they are not heard in the institutions representing the dominant paradigm. Thus, new journals, books, and new groups can be an indication of alternative paradigms forming. Books often help build the foundation when scientific papers do not provide enough space to lay out new paradigms, or to reframe existing ones.

4.1 | Paradigm changes in the field of development studies

The discussion about paradigm changes related to sustainable development and sustainability transition discourse is not new. Already Rogers (1983), who wrote about *The Diffusion of Innovation*, reflected on the resonance of the diffusion discourse with the development paradigm and the echo chambers within scientific disciplines. Pertaining to the latter, he referred to the insights of Thomas Kuhn.

> During the past twenty years or so, diffusion research has grown to be widely recognized, applied, and admired, but it has also been subjected to constructive and destructive criticism. This criticism is due in large part to the stereotyped and limited ways in which most diffusion scholars have come to define the scope and

> method of their field of study. Once diffusion researchers came to represent an "invisible college,"* they began to limit unnecessarily the ways in which they went about studying the diffusion of innovations. Such standardization of approaches has, especially in the past decade, begun to constrain the intellectual progress of diffusion research (Rogers, 1983, p. xvii).

In the footnote (marked by the asterisk), Rogers referred to the work of Kuhn, explaining that the "invisible college is an informal network of researchers who form around an intellectual paradigm […]" (Rogers, 1983). In fact, Rogers dedicated a whole section to the topic of paradigms and the invisible colleges (Rogers, 1983, p. 42ff). Connected to this discussion about paradigms is Rogers' reflection on the diffusion studies' contribution to the at the time prevalent development paradigm. Rogers concluded that the elements of the development paradigm fit the classical diffusion model quite well. These elements, among others, are a focus on economic growth, industrialization, and technology. As pointed out above, Rogers called for a paradigm shift. A shift away from growthism, trickle-down rhetoric, and Eurocentric development views (Rogers, 1983, p. 120ff).

Others have used Kuhn's work as well to discuss paradigm changes in the context of the sustainable development discourse.[6] Foster-Carter (1976) used Kuhn's ideas to discuss conflicting paradigms within development studies. He used it to confront the prevalent development paradigm, based on Rostow's (1969) *Stages of Economic Growth*, with neo-Marxian ideas of development. Williams and McNeill (2005) used Kuhn's work to describe the paradigm shift within economics and its relation to development thought. Thus, a shift from growth-centered, technocentric development towards an ecocentric perspective. As illustrated in Section 2.1, the development and the transition discourse are connected. Thus, applying Kuhn's writing to the transition discourse seems promising.

5 | METHOD

To better understand which transition theory dominates the sustainability transition literature a systematic quantitative literature study was conducted on the 19th of September 2023. To analyze sustainability transition literature, we performed a keyword search on Scopus using the search string "sustainability transition" OR "sustainability transformation" limited to title, abstract, and keywords. This rendered 3102 scientific publications. No additional filters were applied, thus all types of scientific publications (e.g., book chapters, reviews, and books), all languages (e.g., English, German, and Spanish), and all years (here from 1997 to 2023) were included in the subsequent analysis. The complete list of publications was exported as a CSV file and analyzed with Excel and R. To explore this body of literature, we focused on the keywords of the downloaded publication data. We used the author keywords and not the index keywords, as they referred to transition theory or concepts. The keyword list was limited to the first five author keywords of each publication listed in the data set. To analyze the keywords, the list of keywords was cleaned up. For example, all keywords were changed to American English (labour → labor), the singular version (systems → system), or the hyphenated version (agrifood → agri-food) of the respective keyword. That reduced the initial number of keywords from 6286 to 6023.

We also analyzed the timeline, authors, and journals. The timeline provides an overview of the evolution of the field. For this, the keywords were clustered in socio-technical, multi-level perspective, transition management,[7] and socio-ecological. The clusters are described in Figure 2. The journals and authors within the data set were analyzed with Excel and R. We identified the dominant journals and authors with Excel. The connections between clusters of keywords, journals, and authors were analyzed with a network analysis in R using the igraph package. Detailed information can be found in the Supplementary Information.

6 | RESULTS

Table 1 provides an overview of the 20 most used keywords (sustainability transition and sustainability transformation were removed). Six of these keywords relate to transition theories or concepts: Multi-level perspective, Socio-technical transition, Transition management, and Socio-ecological system. The dominance of the Multi-level perspective within sustainability transition literature is indicated by the count value in Table 1.

Among the 20 most used keywords, only socio-technical transition theory and transition management can be found (see Table 1). Concepts that focus on other aspects of sustainability transitions or frame systems in different ways could be found in ranks 29 and 33 (resilience and socio-ecological). Other keywords related to socio-ecological framings were ranked even further down the list. This illustrates the dominance of socio-technical transition theory within sustainability transition literature. It shows that the main analytical frame for sustainability transitions is the MLP and that systems are predominantly framed as socio-technical.

To further analyze the transition theories, all relevant keywords were filtered from the dataset and analyzed as a cluster (see Figure 2). The dominance of the Multi-level perspective is maintained with 158 counts. The socio-technical transition cluster catches up considerably with 142 counts. The socio-ecological and transition management clusters lag behind with 52 and 45 counts respectively.

We have also tested for cluster co-occurrence. Although the MLP has been developed within the socio-technical transition theory, there are only 21 overlaps between the two clusters across publications within the dataset. Due to this limited co-occurrence, the two clusters are treated separately. The MLP cluster co-occurs twice with the transition management cluster and not once with the socio-ecological cluster.

Figure 3 illustrates the connection between authors within the dataset and the clustered author keywords. Most authors are connected to the Multi-level cluster (407), followed by the Socio-technical cluster (378) and the socio-ecology cluster (179). The

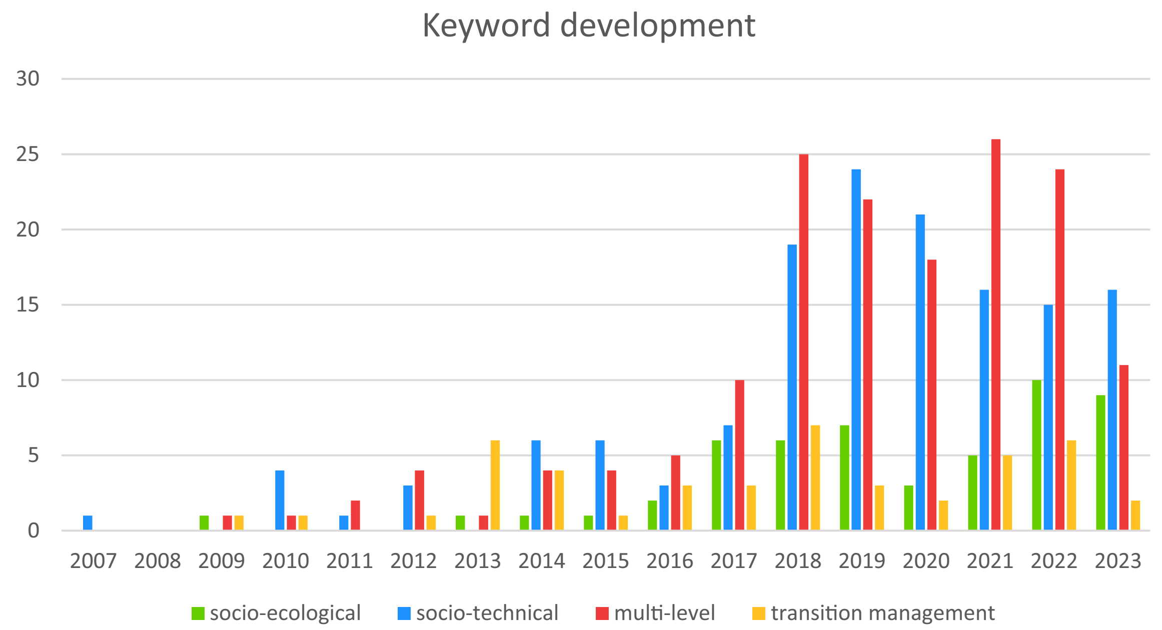


FIGURE 2 Evolution of keyword use. **Socio-technical** is the sum (142) of the following keywords: Socio-technical transition, Socio-technical system, Socio-technical regime, Socio-technical change, Socio-technical imaginaries, Socio-technical, Socio-technical analysis, Socio-technical niche, Socio-technical transition theory, Socio-technical experiments, Socio-technical innovation, Socio-technical system analysis, Socio-technological system, Socio-technical transition research, Socio-technical landscape, Socio-technical configurations, Multi-level socio-technical transition theory, Long-term socio-technical analysis, Socio-technical pathways, Multi-level perspective on socio-technical transition, Socio-technical configuration analysis, Governance for socio-technical transition, Socio-technical scenario. **Multi-level perspective** is the sum (158) of the following keywords: Multi-level perspective, Multi-level governance, Multi-level perspective on socio-technical transition, Multi-level barrier and driver analysis, Multi-level perspective on system innovation, Multi-level policy mix, Multi-level analysis, Multi-level perspective of sustainability transition, Multi-level growth model, Multi-level perspective on sustainability transition, Multi-level of action, Multi-level perspective theory, Multi-level organizational assessment procedure, Multi-level socio-technical transition theory, Multi-level transition, Multi-level-growth model, Multi-level, Multi-level perspective modeling, **Transition management** is the sum (45) of the following keywords: adaptive transition management, Sustainability transition management, Sustainable business model sustainability transition management, Transition management. **Socio-ecological** is the sum (52) of the following keywords: Socio-ecological system, Socio-ecological transformation, Socio-ecological conflicts, Long-term socio-ecological research, Socio-ecological approach, Socio-ecological regime, Socio-ecological network, Socio-ecological crises, Socio-ecological relations, Socio-ecological resilience, Marine socio-ecological system, Socio-ecological tipping points (SETPs), Socio-ecological transition, Socio-ecological history, Desiderata of socio-ecological transformation theories, Socio-ecological integration.

smallest cluster in terms of connections to authors is the transition management cluster (135). The gray dots in Figure 3 capture authors that are connected to two or more clusters. A list of these authors can be found in the SI. However, Figure 3 shows that most connections are between the socio-technical and the multi-level cluster. Note that the network is more connected than the data in the tables, as the network shows the first five authors of each publication. The tables only show the publication and the connected keywords.

Following Kuhn's (2012) work, there are clear indicators for the formation of distinct research avenues that are based on distinct paradigms. These indicators are related to the institutionalization of distinct research avenues. Socio-ecological and socio-technical approaches to sustainability transition are represented in distinct groups (Sustainability Transitions Research Network [STRN] and Future Earth), different conferences (International Sustainability Transitions Conference [IST] and Transformations) as well as different books providing the basic foundations of the respective paradigm (e.g., Grin et al. (2010) and Gunderson and Holling (2002)).

Apart from research groups and conferences, journals represent another form of institutionalization. Table 2 provides insights about the main publication outlets for each keyword cluster. *Environmental Innovation and Societal Transitions* (EIST) is a relevant outlet for the multi-level, socio-technical, and transition management clusters. Generally, these three clusters greatly overlap in journal outlets. Apart from the journal *Local Environment* all other journals appear in these three clusters. *Sustainability (Switzerland)* is the only journal that is a relevant outlet for all four clusters. The most prominent journal outlets for each of the clusters thus indicate that researchers using specific keywords target different audiences. As EIST seems to be the main outlet for the first three keyword clusters, but not for the socio-ecology cluster we added another keyword search (on 21.09.23). The connections between journals and the clustered keywords are illustrated in Figure 4.

Limited to EIST only nine articles can be found for the socio-ecology,[8] and for "socio-tech*"[9] 144. Searching for concepts within socio-ecology, using "panarchy" as search string renders no results.

TABLE 1 Keyword frequency.

Rank	Keyword	Count
1	Sustainability	244
2	**Multi-level perspective**	134
3	Energy transition	99
4	Climate change	91
5	Circular economy	90
6	Governance	88
7	Transition	85
8	Innovation	63
9	Transdisciplinary	60
10	Sustainable development	59
11	Transformation	57
12	**Socio-technical transition**	51
13	Agency	48
14	Food system	43
15	**Transition management**	41
15	Renewable energy	41
15	Agroecology	41
16	Cities	40
17	**Socio-technical system**	37
18	SDGs	34
19	**Socio-ecological system**	31
19	**Strategic niche management**	31
20	Resilience	30
20	Energy policy	30

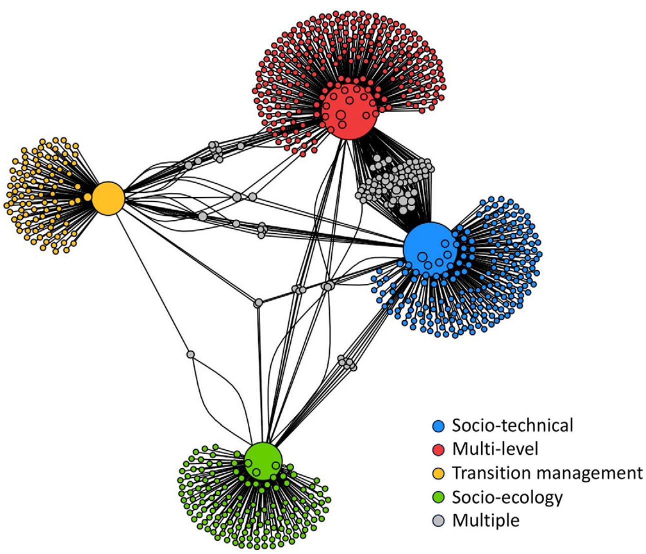


FIGURE 3 Authors connected to clustered author keywords.

For the search string "adaptive cycle" one result is found (Pearson & Bardsley, 2022). In contrast, the MLP,[10] a concept developed within socio-technical transition theory, renders 58 results. This pattern indicates what Kuhn (2012) discussed in terms of a journal's potential reluctance to publish ideas that challenge the paradigm represented by the respective journal.

TABLE 2 Main journals associated with the keyword cluster.

Key word: Multi-level	
Journal name	**Number of mentions**
Environmental Innovation and Societal Transitions	18
Sustainability (Switzerland)	17
Journal of Cleaner Production	10
Research Policy	9
Energy Research and Social Science	8
Technological Forecasting and Social Change	8
Key word: socio-technical	
Journal name	**Number of mentions**
Environmental Innovation and Societal Transitions	22
Energy Research and Social Science	14
Technological Forecasting and Social Change	11
Sustainability (Switzerland)	9
Research Policy	7
Key word: transition management	
Journal	**Number of mentions**
Sustainability (Switzerland)	7
Journal of Cleaner Production	4
Environmental Innovation and Societal Transitions	3
Global Environmental Change	2
Local Environment	2
Energy Policy	2
Technological Forecasting and Social Change	2
Key word: socio-ecological	
Journal	**Number of mentions**
Sustainability (Switzerland)	8
Sustainability Science	3
Agricultural Systems	3
Ecological Economics	3
Landscape Ecology	2
Ecology and Society	2

7 | DISCUSSION

7.1 | Agency: The role of scientists

Scientists acting as change agents, play an important role in transitions. The way we frame problems and the solutions we offer make a

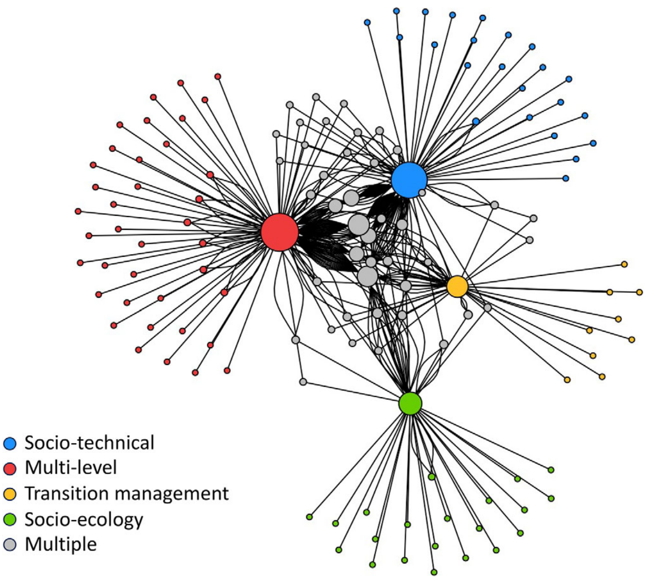


FIGURE 4 Journals connected to clustered author keywords. Gray nodes indicate that journals are connected to more than one clustered author keyword.

difference and contribute to change or stagnancy (Ely, 2021, p. 38). Scientific knowledge enters society in many ways, such as consultancy, education (Halbe et al., 2015; Lozano et al., 2013), or policymaking (Blythe et al., 2018; Pregernig, 2014; Schlüter et al., 2022). Thus, the way scientists frame problems and the solutions that scientists suggest influence societies (Blythe et al., 2018; Pregernig, 2014). As we presented above, over the years, the socio-technical transition theory has become the dominant sustainability transition theory (see Figure 2). The dominance of the socio-technical transition theory might reflect the general dominance of this worldview among scientists dealing with sustainability transition questions. An example are the scenarios in the IPCC reports, which rely on technological progress to achieve the needed greenhouse gas reductions (Keysser & Lenzen, 2021). Similarly, in a review of transition theories, Markard et al. (2012) only include theories related to technological change. The main theories mentioned are Technological Innovation Systems, Multi-Level Perspective, Strategic Niche Management, and Transition Management. The less well-versed reader might get the impression that socio-technical transition theory is indeed THE transition theory, which is, of course, a misrepresentation, as there are many transition theories (Asquith et al., 2018; Schlaile & Urmetzer, 2021). Arguably, socio-technical transition theory provides a good analytical framework for understanding technological change (Geels, 2006) and lock-ins (Ford & Newell, 2021). However, the question is whether it should implicitly be framed as THE sustainability transition theory and whether it should be used for transitions that are not about technology (see e.g., Vandeventer et al., 2019). A *dark side of transformations* (Blythe et al., 2018) is another example of academic discourse perpetuating the status quo by using a new or different terminology without introducing a substantial change. A prominent example is green growth[11] or the green economy (Blythe et al., 2018; Hamilton & Ramcilovic-Suominen, 2023; Wanner, 2015). The perpetuation of the status quo by scientists is also discussed by Leach et al. (2010), who highlight the aspect of dominance (see also Hamilton & Ramcilovic-Suominen, 2023).

Kuhn (2012) refers to education and the provision of literature as a means to maintain and perpetuate established paradigms. Not only is education a means to recruit new scientists to follow the taught paradigm. It is also a means to connect science with the real world. Students, that might become the future workforce (e.g., politicians, employers/companies directors, and employees), are taught a specific worldview (Jickling, 2016; Spash, 2020). Without a diversity of theories, and critical thinking, provided to them, they might blindly take over the paradigm they were taught.

Scientists are not detached from society but take active roles (Kurzman & Owens, 2002). "Researchers play an important role in framing sustainability transformations, and this calls for reflexivity, given the power they hold as actors within them" (Ely, 2021, p. 41). Transition literature suggests that scientists should seek an even more active role in transformative processes (Wittmayer & Schapke, 2014). Leach et al. (2010, p. 5) indicate that dominant players are able to create "motorways" that support and consequentially ossify certain narratives, while pushing alternative narratives in the background. The formation of powerful academic interest groups who only support one specific paradigm connects to Rogers' (1983, p. xvii) concepts of the "invisible college," discussed above (see Section 4).

Analog to the views of scientific pluralism (Ludwig & Ruphy, 2021) it can be stated that scientific inquiry and knowledge production profit from diversity. A diversity of concepts, theories, or approaches allows scientists to reflect and thus further develop the field (Bernard & Cooperdock, 2018; Kuhn, 2012). A lack of diversity may create an ontological and epistemological lock-in, where scientists get trapped in an echo chamber (Chappin & Ligtvoet, 2014; Unerman, 2020), or an invisible college, as Rogers (1983) called it. A diversity of transition approaches can "safeguard against the appropriation of the term [transition or transformation] by any single framing or perspective" (Blythe et al., 2018). And as Ely (2021, p. 41) states: "Working across and beyond different disciplines alerts us to the fact that sustainability is subject to very different and conflicting understandings."

7.2 | Shortcomings of technocentric views

In the face of worrying trends regarding increased food security, climate change, deforestation, biodiversity loss, and inequality—just to name some socio-ecological negative trends caused by unsustainability of the growth-driven system, (Casse & Jensen, 2009; Hoang & Kanemoto, 2021; Otero et al., 2020; Vos & Bellù, 2019), proponents of growthism and technocentric views continue to provide explanations that make the anomalies (deterioration of socio-ecological conditions) fit the paradigm. The idea of weak sustainability is the pushback of capitalist/neoclassical economists showing that the anomalies do not invalidate their assumptions (Hamilton, 1995; Solow, 1974). Thus, the concept of weak sustainability needed to be invented to integrate the anomalies within the economic growth paradigm. Increasing inequality has been matched with the Kuznets curve and trickle-down rhetoric. Or the blame was put on government mismanagement rather than the capitalist market mechanism (Raffer & Singer, 2001) and its market failures (e.g., externalities). Environmental problems have been matched with the Environmental Kuznets curve and ideas of relative decoupling (Özcan & Öztürk, 2019). Relative decoupling discourses are put forward by hopes of technological advances able to tackle "externalities." Focusing on technological change (and its connections to society) does not address the underlying problems that caused the sustainability challenges humanity is facing (Ruggeri & Garrido, 2021). For example, an energy transition that is merely based on switching to renewables without considering energy use patterns created by the economic system in place, or resource limitations that will exacerbate socio-ecological problems (Watari et al., 2019). A transition towards a sustainable fashion industry might be inhibited in a system that requires economic growth (Dzhengiz et al., 2023). However, it can be questioned whether technological innovation per se leads to sustainable societies. Technological innovations do not address questions of resource access, or the distribution of burden and benefit.

The role of technology advancement is key to defending and continuing the current growth-driven economic system and it is central to the mainstream sustainability transition discourse. The growth-driven economy was (re)named green, circular, or bio. All facets of the same economic system, in which the role of technology to make this change happen is central (Giurca & Befort, 2023; Ziegler et al., 2023). Though, these changes do not address the fundamental problems of our current economic system: infinite economic expansion on a finite planet is, probably, impossible (Haberl et al., 2020; Hickel & Kallis, 2019; Kaya Kanlı & Küçükefe, 2022). Research indicates that a circular, bioeconomy needs to acknowledge planetary boundaries and, therefore, the need for sufficiency and not only efficiency (Desing et al., 2020; Holden et al., 2023; Ramcilovic-Suominen et al., 2022). Moreover, for these concepts to be truly transformative, they need to change the power and wealth dynamics (Zell-Ziegler et al., 2021).

As long as suggested transformations focus on technology and capitalist market mechanisms they will fall short of solving underlying problems (Pungas, 2023). Using practical examples, Leach et al. (2010) illustrated how closed-down technocratic worldviews equate to the application of a reductionist frame that brings forth ill-suited *solutions*. Chakori et al. (2022) provide an example from food packaging use. They point out that interventions to reduce packaging only tackle symptoms of the problem and that a reduction of packaging requires a deeper change of the growth-driven (food) economy. Similarly, Leeuwis et al. (2021) showed how interventions in the food system do not change the fundamental problems within that system. They argued that the interventions fail to address issues of inequality because they do not challenge but rather align with the current paradigm. To tackle inequality, they suggested reverting to alternative approaches that challenge the dominant paradigm. Specifically, they refer to approaches that "[…] start from ecological principles of community and environmental sustainability" (Leeuwis et al., 2021).

Analyzing transformations in food systems Béné (2022) stated that one problem with technology-based transitions is that they rely on market forces. A primary condition for a technology to survive and to be mainstreamed is the technology's "economic viability not its potential future societal benefits" (Béné, 2022). He reflected on an article by Herrero et al. (2020), who selected 75 innovations that could transform the food system. Béné (2022) highlighted that these 75 innovations are a wish list, but that due to the complexity of the transition process, it cannot be assured that these technologies really succeed. "Symbolistically, they [scientists] replace the 'invisible hand' by a visible one in an attempt to steer innovations towards sustainability. But the market, left alone, is blind to sustainability" (Béné, 2022). Arguably, the same is true for technologies and innovations in other sectors. Technologies are blind to sustainability. With every technology, we are faced with burden and benefit questions, with questions about sustainable scales, and so forth. To consider these questions, we not only have to understand the social dynamics permitting or blocking technology mainstreaming. We not only have to understand the positive and negative consequences of technology upscaling on the social system. We also must understand that the social system sits within an ecosphere. Thus, the solutions we apply and how we apply them depend on our worldview.

Accordingly, many argue that a sustainability transition requires addressing worldviews and paradigms (such as economic growth) (Abson et al., 2017; Davelaar, 2021; Fischer & Riechers, 2019; Woiwode et al., 2021). Some have used the MLP to explore a worldview shift. Göpel's (2016) work on *The Great Mindshift*, used the MLP to illustrate the worldview shift within the transition process. Similarly, Naberhaus et al. (2011) theorized about worldview changes using the MLP. Thus, the MLP might be a tool that can be used to challenge the current development narrative. Though these authors mostly seem to use the MLP because of its ability to illustrate different scales. The MLP is then no longer used to investigate technological innovation. The detachment between the MLP and socio-technical frame is also indicated by our literature review with only 21 co-occurrences between the two keyword clusters. Nevertheless, one remains to wonder what the vehicle of change in these examples might be. The MLP builds on market forces. It is difficult to imagine how market forces lead to a mindset change (though enlightening books are exchanged within the market system). The idea of market forces being the vehicle of change resembles the idea of a Trojan horse, where the current is destroyed from within.

7.3 | What socio-ecological views could add

As noted, socio-ecological views do not neglect the role of technology. However, they also discuss the downsides of technology myopia. An example is Gunderson and Holling's (2002) discussion of the resilience concept. They differentiate between two different approaches to resilience. One focuses on efficiency, the other on sustenance. The former is the technocentric approach to resilience where one wants to increase control, thus reducing variability. The other focuses on diversity. This is based on an ecological understanding of resilience where diversity and redundancies play a crucial role in facilitating the adaptive capacity of a system.[12] Diversity and redundancies create options a system can fall back onto in the event of disturbances (Lin, 2011; Olmos-Martínez & Ortega-Rubio, 2020). Hence, a diversity of options creates buffers for a system. Thus, following socio-ecological thinking, systems should maintain, rather than upscale niches. Thus, socio-ecological thinking represents a break with traditional development thinking.

> Modern development has tried to muscle out environmental disturbances by literally hardening the environment. Dams, canals, barriers of all sorts, straight lines that are predictable, all of these features of the 'developed' landscape are meant to ensure the gable of uniformity (Tănăsescu, 2022, p. 73).

The importance of maintaining the niche is illustrated by the energy transition. As in many instances, one technology and energy source will not be sufficient to meet the demand, the energy transition will require nations and regions to adopt a portfolio of options (solar, wind, hydrological, tidal, etc.) that fit the respective biophysical circumstances (availability of solar radiation, wind, water bodies, etc.) (Hoggett, 2014; Leach et al., 2010). To stabilize supply, the future energy system should focus on resilience, adaptability, and flexibility (Hoggett, 2014). In agriculture, (genetic) crop diversity is important to reduce the risk of disease (Drenth & Kema, 2021; Lin, 2011). The natural genetic variety of crops supports their adaptive capacity, which could be vital for food security when conditions are changing due to climate change (Mercer & Perales, 2010). Crop diversity might reduce the need to apply pesticides (Lin, 2011) or increase income stability (Harkness et al., 2021). Hence, diversity also translates to economic benefits (Banerjee & Banerjee, 2015; Lin, 2011). The lack of or the neglect of alternatives can lead to lock-ins and make adaptations more difficult (Haberl et al., 2004). For example, cities that prioritized car-based mobility might have to completely overhaul the infrastructure to make space for public transport, pedestrians, and bike infrastructure (Driscoll, 2014). Thus, a socio-ecological approach calls for maintaining the niche to create more adaptable and thus more resilient systems. It does not want to upscale the niche as this would rid the system of necessary buffer capacity. This is tough contrary to the logic of the current socio-economic system that favors larger scales as they allow for harnessing economic scale effects (Bossink et al., 2023; Wilson, 2012).

The Panarchy concept also allows to analyze how changes on a smaller scale trigger changes on the macro scale and vice versa. For example, it allows to understand how the diversity on the smaller scales (e.g., genetic diversity, diversity of banks) contributes to the resilience of larger systems (e.g., ecosystem, financial system) (Haldane & May, 2011). Thus, it does not externalize the macro scale (landscape in MLP).

An ecological worldview leads to completely different problem framings and thus the solutions one would suggest are different (Tănăsescu, 2022). A socio-ecological view does not neglect the role of technology, but it places technology within a socio-ecological context. Acknowledging biophysical limits is not understood as limiting the prosperity of societies but as a stimulus for innovation and creativity (Richardson et al., 2023). Taking a global perspective highlights that (e.g., geographic) problem-shifting does not provide solutions (Dorninger et al., 2021; Sharif et al., 2022). Thus, biophysical limits are recognized and social dynamics, such as rebound effects, that counterbalance efficiency gains are acknowledged (Haberl et al., 2019). Emphasizing that increasing efficiencies and simultaneously increasing consumption does lead to a zero-sum game at best, highlights the need to consider alternative economic models that do not focus on economic growth (Haberl et al., 2020).

Additionally, the notion of maintaining the niche would turn economic thinking on its head asking for where we need to create redundancies (thus *inefficiency*) to increase the resilience and thus the adaptability of the system. Hence socio-ecological thinking would call for breaking with the currently dominant growth paradigm and technocentric views. Socio-ecology, framing the world differently, provides alternative solutions for the anomalies we have been observing since the 1960s. To achieve sustainability we need to generate better understanding of socio-ecological systems and how insights from ecology, such as adaptive capacities, can help to create thriving social systems (Spangenberg, 2011). Similarly to Wiedmann et al. (2020), we thus call for strengthening research avenues that focus on human-nature relationships, alternative economic systems, and alternative concepts of development. Furthermore, we advocate for a greater diversity of lenses applied to sustainability transitions.

As we discussed in this study, socio-technical transition theory is coined by the notion of upscaling (technological) innovations. However, as indicated above, this might strip systems of their adaptability and resilience. Therefore, how can we build societies that embrace plurality (maintaining the niche) rather than one-fits-all solutions? Many possible future research avenues need to be explored. For example, future research could expand alternative notions of transition theories (e.g., the pluriverse—defined as historical and existing initiatives, practices, and worldviews that diverge from dominant development discourses [Kaul et al., 2022]). Moreover, applying a socio-ecological lens to tackle the current socio-ecological crisis might help explore changes to our socio-economic system, which implies that the transformation process cannot be limited to (ecomodernist) market-based mechanisms. If so, what other vehicles of change exist and how can these be fostered? Moving beyond reductionist transformational processes will entail re-politicizing sustainability, transitions, and more broadly science and its related practices. Additionally, changing the economic system requires influencing worldviews and power dynamics. Therefore, more research needs, for example, to delve into power shifts able to catalyze transformational processes and agency. How can we use insights from socio-ecology to theorize such a deep transition? We believe that this theoretical framework offers important lenses to understand the dynamics of transitions and transformations. Future studies might also need to explore more in-depth the translation of these frameworks into practice. This type of research could reveal successful applications in real-world situations or the limits of these frameworks.

8 | CONCLUSION

As scientists, we play an important role in influencing development narratives, and their repercussions. Despite the high dominance, and resistance, of the technocentric, growth-focused, development narrative, there is a promising body of work advancing scientific pluralism. Given that modern societies are struggling to reach sustainability it might be required to focus on alternative scientific paradigms. One alternative paradigm is socio-ecology, which understands human societies to be embedded in nature; our planet that has finite resources (i.e., planetary boundaries). We have argued that applying an alternative lens, such as socio-ecology, helps to understand problems from different vantage points, which then helps to identify alternative solutions.

ACKNOWLEDGMENTS

The authors would like to thank the audience of the International Sustainability Transitions Conference 2023 (IST 23), for their valuable feedback. At IST 23, a preliminary version of this manuscript was presented.

CONFLICT OF INTEREST STATEMENT

All authors have no conflicts of interest.

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ENDNOTES

[1] The multi-level perspective as well as socio-technical transition were already earlier discussed by René Kemp, Arie Rip, or Johan Schott. The latter two were Frank Geels PhD promotors.

[2] At the time Rogers' wrote his book, economics was only categorized as a minor tradition of diffusion of technology studies. Given the significance of market mechanism within socio-technical transition theory and the fact that it is based on evolutionary economics, socio-technical transition theory is also part of the economic tradition.

[3] This is obvious for socio-technical transition theory. But socio-ecological theory too looks at the role of technology. For Gunderson and Holling (2002) the use of technology is one of four factors that explains differences between the natural and the social system and why socio-ecological systems can change faster than natural systems. These factors can also explain why systems become maladaptive and hence to not change.

[4] The journal *Ecological Economics* is among the top five outlets for the socio-ecological keyword cluster.

[5] Without discussing this further it might also give the impression that humans might not have the ability to do something about climate change. Therefore, it limits the agency of humans for problems human societies have created.

[6] For an account about the limitations of Kuhn's work in context of social sciences see Foster-Carter (1976).

[7] Adjacent to socio-technical theory is transition management, which suggests employing a strategic approach to steer future developments of socio-technical systems (Kemp et al., 2007). Transition management is a governance approach for complex challenges that require adopting a long-term perspective (Loorbach, 2010).

[8] Exact search string: TITLE-ABS-KEY ("socio-ecol*" OR "social-ecol*" OR "socioecol*" OR "socialecol*").

[9] Exact search string: (TITLE-ABS-KEY "socio-tech*").

[10] Exact search string: TITLE-ABS-KEY ("multi-level perspective").

[11] An economic concept that postulates that infinite economic growth on a finite planet is possible through technological innovation. Thus the green economy concept builds on the assumption that absolute decoupling is possible (Hickel & Kallis, 2019).

[12] Within socio-ecological literature there are different notions of resilience. For example Olmos-Martínez and Ortega-Rubio (2020, p. 6) differentiate between three different approaches: "[…] (1) centered in equilibrium (recovering after a disturbance), (2) multiple equilibrium status (absorbing disturbances while maintaining its essential functions and relationships), and (3) adaptive change (having the capacity of adaptively organizing itself to preserve its essential attributes after a disturbance) […]."

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Biely, K., & Chakori, S. (2024). Sustainability transition theories: Perpetuating or breaking with the status quo. *Sustainable Development*, 1–17. https://doi.org/10.1002/sd.3101