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ADVANCED REVIEW

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Transformations for climate change mitigation: A systematic review of terminology, concepts, and characteristics

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Abstract

Deep, broad, and rapid society-wide changes are urgently required to limit global temperature rise in line with the goals of the Paris Agreement. Since 2005, academics and policy makers have increasingly referred to such changes as *transformations*. This recent uptake and rapid diffusion of transformation-related concepts in research on climate change mitigation calls for a systematic and up-to-date analysis. In this article, we address this gap by undertaking a systematic review of articles that use transformation-related terms in the social science literature on climate change mitigation. Drawing on a corpus of 198 articles identified from Scopus, we find a diverse, fragmented research field that strongly focuses on the national, city, and international levels, the energy sector, and high-income countries. Although the use of transformation terminology has increased rapidly, there are few shared definitions, which arguably constitutes a serious challenge to scholarship and evidence-based policy making. To facilitate a more cumulative and impactful approach to research, we propose *transformational climate change mitigation* as a new umbrella term for the varied mitigation-related societal transformations required to meet the goals of the Paris Agreement. We conclude by identifying priorities for future research.

This article is categorized under:

The Carbon Economy and Climate Mitigation > Benefits of Mitigation

KEYWORDS

climate change mitigation, systematic review, transformation, transformational mitigation, transition

1 | INTRODUCTION

Significant and rapid changes in all policy sectors are required to successfully deliver the climate change mitigation needed to meet the Paris Agreement's goals of limiting the rise in global temperatures to less than 2°C and as close to 1.5°C as possible (Intergovernmental Panel on Climate Change, 2018). In the past decade, both academics and policy makers have increasingly referred to such changes as *transformations* (e.g., European Environment Agency, 2019; Fazey, Moug, et al., 2018; Intergovernmental Panel on Climate Change, 2018). In the Scopus database, the number of peer-reviewed articles that focus on climate change mitigation and use transformation-related terms and concepts increased 14-fold between 2005–2009 and 2015–2019 (Figure 1).[1] Between 2007 and 2014, Working Group III of the Intergovernmental Panel on Climate Change (IPCC) increased its use of transformation-related terminology 10-fold (IPCC, 2007; IPCC, 2014b).[2]

These developments arguably constitute a "transformative turn" (Koch et al., 2018, p. 1) in the climate change mitigation literature similar to those identified in other literatures focusing on sustainability (e.g., Clark & Harley, 2020, pp. 355–357; Linnér & Wibeck, 2019), climate change adaptation (e.g., Fedele et al., 2020), and biodiversity conservation (e.g., IPBES, 2019; Massarella et al., 2021). This turn has led to attempts to synthesize existing research on the factors that affect mitigation-related transformations (e.g., Amundsen et al., 2018, p. 25) and to create shared conceptual frameworks and definitions (e.g., Burch et al., 2014). Regarding definitions, Fazey, Moug, et al. (2018, p. 198) have usefully suggested that transformations have three key dimensions: depth ("the intensity or quality of the change"); breadth ("the distribution of change"); and speed ("the timeframe through which a change occurs"). The IPCC has also sought to develop its own shared definitions in its assessment reports, for example, for transformation, societal/social transformation, transformational change, and transformation pathways (Box 1).

Yet despite these and other attempts to develop shared conceptualizations of transformation (Williams et al., 2021), use of the term among academics is varied and, in many cases, ambiguous (e.g., Feola, 2015). Absent a systematic and up-to-date review of the literature, it is difficult to ascertain what the transformational "turn"—and the various attempts to steer it—has actually delivered. In this article, we address this gap by undertaking a systematic review of articles that use transformation-related terms in the social science literature on climate change mitigation. Our analysis identifies 658 articles in Scopus between 1994 and 2019 that focus on climate change mitigation and make use of transformation-related terms and concepts (see Section 2, below). We prioritize 198 articles that mention transformation frequently and/or use it as a central conceptual device. We analyze these prioritized articles in detail to identify their geographical and sectoral focus, the methods and theories they employ, their use of transformation-related terms and concepts, and the triggers, drivers and barriers to transformation they identify. We also employ a bibliometric analysis to explore the extent to which the articles cite each other (direct citation) and how often they cite references in common (bibliographic coupling).

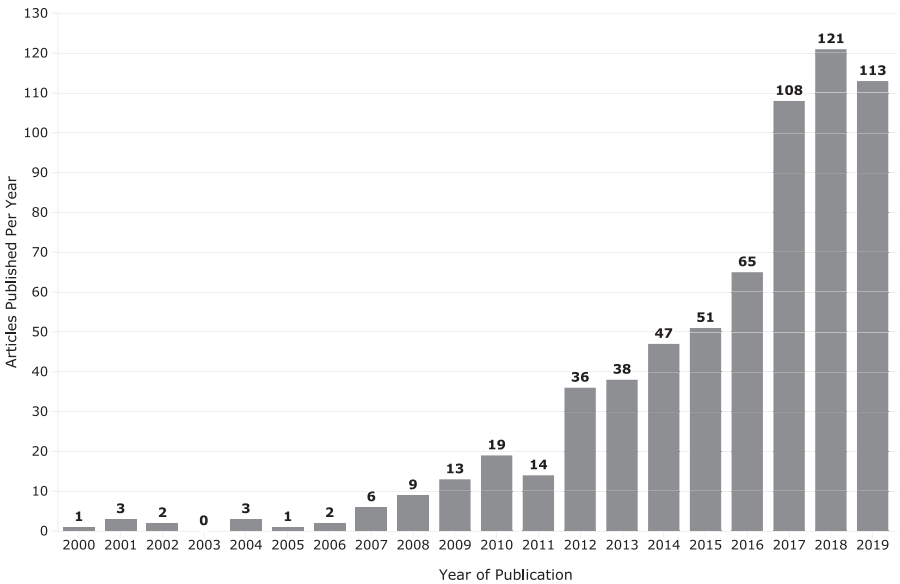

FIGURE 1 Peer-reviewed social science articles in Scopus published between 2000 and 2019 that focus on climate change mitigation and use transformation-related terminology ($n = 652$). See Section 2 for details on search and screening criteria

BOX 1 Transformation concepts in the Intergovernmental Panel on Climate Change reports

The glossary of the 2018 IPCC Special Report on Global Warming of 1.5°C (IPCC, 2018, p. 559) defines four transformation-related concepts associated with climate change mitigation[3]:

Transformation: "A change in the fundamental attributes of natural and human systems."

Transformative change: "A system-wide change that requires more than technological change through consideration of social and economic factors that, with technology, can bring about rapid change at scale."[4]

Societal (social) transformation: "A profound and often deliberate shift initiated by communities toward sustainability, facilitated by changes in individual and collective values and behaviors, and a fairer balance of political, cultural, and institutional power in society."

Transformation pathway: "Trajectories describing consistent sets of possible futures of greenhouse gas (GHG) emissions, atmospheric concentrations, or global mean surface temperatures implied from mitigation and adaptation actions associated with a set of broad and irreversible economic, technological, societal, and behavioral changes."

The remainder of this article is organized as follows. In Section 2, we present the methods we used to identify, select, and analyze the literature. In Section 3, we present the results of our in-depth analysis of the 198 prioritized articles. In Section 4, we discuss our findings and propose *transformational climate change mitigation* as a shorthand term for the varied types of transformation required to limit global temperature rise to 1.5°C. In Section 5, we conclude and identify future directions for research and policy.

2 | METHODS

A systematic review is "a review of a clearly formulated question that uses systematic and explicit methods to identify, select, and critically appraise relevant research" with the aim of consolidating and critically assessing findings on a specific research topic (Cochrane Collaboration, 2003; cited in Siddaway et al., 2019, p. 751). Systematic reviews are increasingly used in social science research on climate change (e.g., Berrang-Ford et al., 2015; Biesbroek et al., 2018; Sherman et al., 2016; Siders, 2019). As the use of transformation-related terminology has expanded, reviews have been conducted in relation to sustainability transformations (e.g., Feola, 2015; Koch et al., 2018) and, more recently, related concepts such as transformational climate change adaptation (e.g., Ajulo et al., 2020; Deubelli & Mechler, 2021). However, to our knowledge, this article is the first systematic review of the use of transformation-related concepts in the literature on climate change mitigation.

In this review, we address three research questions in relation to the social science literature on climate change mitigation:

1. How are transformation-related terms and concepts used and defined, and what is their relationship to the concept of "transition"?
2. What are the sectoral, scalar and geographical foci of articles that use transformation-related terminology and what theoretical and methodological approaches do they employ?
3. What characteristics of transformations do they observe, including their triggers, barriers, drivers, and outcomes?

2.1 | Identification, screening, and eligibility procedures

Our systematic review approach consisted of three stages, following Moher et al. (2009): identification, screening, and eligibility (Figure 2). In the initial identification stage, we searched the titles, abstracts, and keywords of peer-reviewed articles in the Scopus academic database for the search term "transform" with a Boolean wildcard operator (i.e., transform*) and at least one of the following mitigation-related terms, which we identified through a review of the existing literature: climat*, global warming, carbon, greenhouse, mitigation, and decarb*. We also considered including

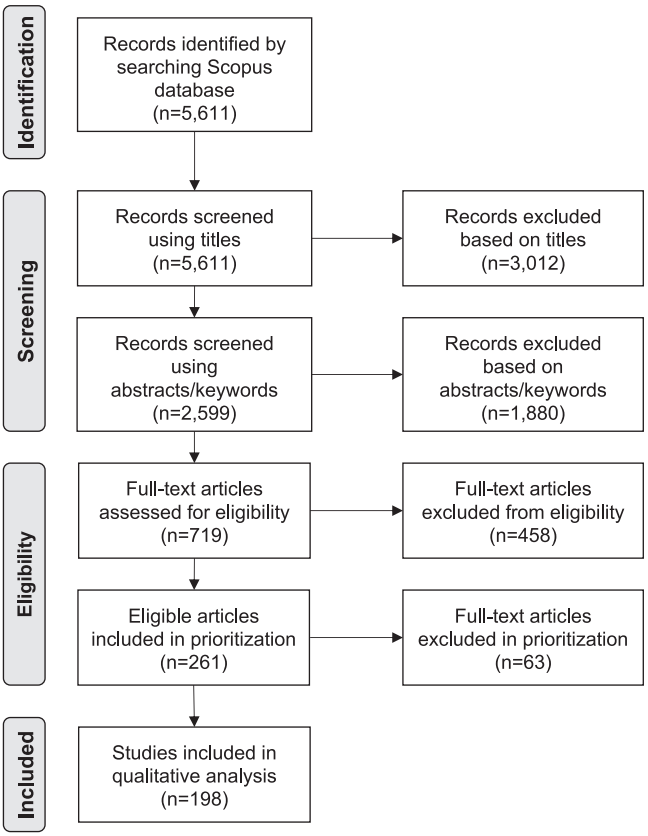

FIGURE 2 Search and screening procedure, adapted from the PRISMA flow chart (Moher et al., 2009)

search terms related to energy and sustainability (sustainab*), but the resulting number of articles was too large to analyze given our resource constraints.[5] The search was limited to articles written in English published in and before 2019, given that at the time of our review, Scopus' coverage of articles published in 2020 was still incomplete.

Initially, we limited our search to journals in Scopus's Social Science theme in order to exclude journals focusing on the natural sciences, engineering, and so on. This first search was carried out on 31st January 2021 and new results were added weekly until 11th May 2021; together, these searches returned 3195 results. From 23rd to 31st July 2021, we also searched 22 additional journals that are not included in the Scopus Social Science theme, but which are either prominent interdisciplinary journals (e.g., *Science*, *Nature*) or had a high proportion of social science articles (e.g., *Climate Policy*, *Journal of Environmental Policy*, *and Planning*).[6] This search returned a further 2206 results. We identified a further 210 articles by starting with the articles which we initially deemed eligible for our review (see eligibility stage, below) and analyzing their reference lists (backward reference checking) and the documents which cited them (forward reference checking; see Biesbroek et al., 2018, p. 4). Overall, 5611 articles met our search criteria.

At the screening stage, we analyzed these 5611 articles to find those that focused on deliberate transformation(s) and climate change mitigation. To do so, we developed five exclusion criteria:

- The article does not mention "climate change" (or related terms including "global warming");
- The article is focused on climate change adaptation;
- The article mentions climate change mitigation, but does not focus on the topic;
- Transformation is mentioned, but it is not deliberate (e.g., demographic transformation);
- Transformation is deliberate, but is it not related to climate change mitigation (e.g., land use transformation).

We conducted an initial screening of the article titles to exclude those that did not address climate change mitigation (ambiguous titles, such as those that referenced sustainability, were retained for further analysis). This title-based screening stage resulted in the exclusion of 54% of the initial results, leaving 2599 articles. We then screened the abstracts and keywords of these remaining articles to examine whether they addressed deliberate

mitigation-related transformations using the exclusion criteria above. This screening resulted in the exclusion of a further 34% of the initial results (1880 articles), leaving 719 articles (13% of the original search results).

At the beginning of the eligibility stage, a further 61 articles were excluded based on an analysis of the full text, leaving 658 articles. In order to further prioritize, we surveyed the full text of each article according to two criteria. The first criterion was based on the number of times that transformation-related terminology was used in an article. The second criterion focused on how the terminology was used, contrasting articles that used terms in a generic, contextual manner with those that used them in a concrete way, for example, as a defined analytical concept. Combining these criteria, each article was classified as exhibiting low, medium, or high engagement with transformation terminology. Low-engagement articles either mentioned transformation-related terminology infrequently (an average of six times) or used that terminology in a broad, generic manner. As an example, 35 low-engagement articles mentioned transformation-related terms only once and limited their use to the title, abstract, or keywords. Medium-engagement articles mentioned transformation terminology more frequently (an average of 14 times) and/or used that terminology more concretely than low-engagement articles (e.g., as an analytical concept). High-engagement articles mentioned transformation terminology frequently (an average of 44 times) and/or had a strong focus on transformation-related concepts. We identified 397 low-engagement articles (60%), 106 medium-engagement articles (16%), and 155 high-engagement articles (24%). The low-engagement articles were excluded from further analysis, leaving 261 medium-engagement and high-engagement articles.

In the final prioritization substage, we selected 198 articles (i.e., 76% of the total of 261) for in-depth qualitative coding (a list of these prioritized articles is available in Table S1). Our prioritization proceeded in two stages. In the first stage, we included all medium-engagement and high-engagement articles identified from Social Science theme journals ($n = 173$). In the second stage, we prioritized an additional 29 high-engagement articles from the 22 journals not included in the Social Science theme. These articles were prioritized if they met at least one of two criteria: greater than 40 transformation occurrences in the text ($n = 22$) or more than 50 citations to the article in Scopus ($n = 8$).[7]

2.2 | Analysis of prioritized articles

In total we prioritized 205 articles, seven of which were excluded in later stages for meeting the exclusion criteria. The remaining 198 articles were analyzed using the qualitative coding schema outlined in Table 1. The coding schema was made up of 14 coding categories related to our three research questions: the first on transformation and transition terms and concepts (transformation terms, transition terms), the second on foci, methods, and theories (sector/system, scale, geography, methods, and theories), and the third on transformation characteristics (triggers, drivers, barriers, outcomes, speed of transformation, actors, and co-benefits).

In addition to analyzing the 198 articles according to the categories in Table 1, we aimed to map the broad contours of the literature reviewed and explore whether the articles cited each other or had references in common (see Section 3.4). To do so, we carried out two bibliographic network analyses using Scopus data on the reference lists of 197 articles of the articles we analyzed (99%).[9] We used the Table 2Net software tool (Jacomy, 2013) to create the network files and Gephi (Bastian et al., 2009) to visualize and analyze them. We used two approaches: a bibliographic coupling approach and a direct citation approach (Boyack & Klavans, 2010). In the bibliographic coupling approach, two articles were connected to each other when they shared at least one reference in common. In the direct citation approach, two articles were connected when the first article cited the second article directly.

3 | RESULTS

The 198 articles that we analyzed were published in 97 academic journals. Only eight journals published five or more of these articles: *Current Opinion in Environmental Sustainability* (19), *Energy Research and Social Science* (18), *Sustainability* (11), *Global Environmental Change* (9), *Wiley Interdisciplinary Reviews: Climate Change* (5), *Technological Forecasting and Social Change* (5), *Futures* (5), and *Environment and Planning C* (5). Although the 198 articles were published over a 19-year time period (2001–2019), nearly 70% were published from 2015 onwards, with half published in just the final 3 years of the period studied (2017–2019). In other words, the corpus of articles is relatively widely spread across journals and is relatively recent.

TABLE 1 Coding categories used in the qualitative analysis of prioritized articles focused on climate change mitigation and utilizing transformation-related terms and concepts ($n = 198$)

Coding category	Definition	Percentage of prioritized articles (n = 198) coded using the coding category (left-hand column)
Transformation terminology		
Transformation terms	Reference to distinct term(s) that include transform*.	100%
Definition	Definition given for transformation term(s).	53%
Operationalization	Usage of transformation terminology to (a) provide context to study (contextual), (b) describe a normative aim/goal (normative), and/or (c) underpin a historical analysis of a past transformation related to climate change mitigation (historical).	100%
Transition terminology		
Occurrences	The number of occurrences of the term transition(s).	89% (at least one transition occurrence)
Relationship to transformation	The relationship between transformation and transition (equated, distinct, and ambiguous).	89%
Sector/system	Economic/emissions sectors (e.g., energy, food/diet) or broader systems (society, economy).	84%
Scale	The scale of focus (e.g., individual, city, national, and international).	89%
Geography	Regional/national focus.	76%
Method	Research methods employed (e.g., interviews and document analysis).	64%
Theory	Theoretical approaches employed (e.g., socio-technical transitions and policy diffusion).	53%
Triggers	Factors that trigger transformation.	31%
Drivers	Factors that make it easier to plan and implement a mitigation-related transformation or that enable options to do so (Modified from IPCC, 2014a, p. 1758).[8]	71%
Barriers	Factors that make it harder to plan and implement a mitigation-related transformation or that restrict options to do so (Modified from IPCC, 2014a, p. 1758).	68%
Outcomes	The outcome of a transformation process (actual or planned).	57%
Speed	The speed at which transformation occurs.	32%
Actors	The government, business, civil society, other groups, and individuals which participate in transformation processes.	70%
Co-benefits	The positive effects that a transformation has on other objectives, thereby increasing the total benefits for society or the environment (Modified from IPCC, 2018, p. 546).	70%

3.1 | Transformations and transitions

3.1.1 | Transformation-related terminology

We identified 6937 occurrences of transformation terminology in the 198 articles. Within each article, we distinguished between distinct transformation terms, identifying 1584 terms. As an illustration, we found 60 instances of transformation-related terminology in Schmitz (2015), which were used to refer to three distinct ideas: green transformations, low carbon transformations, and transformative alliances. Articles used an average of eight distinct transformation-related terms. However, this conceals wide variation. Four articles employed only one term

(e.g., transformational change in Chia et al., 2019), while four others employed more than 25 distinct terms (Amundsen et al., 2018; Fazey, Moug, et al., 2018; O'Brien, 2018; Tàbara et al., 2019). We organized these terms into 62 categories (see Table 2). A single term could be placed in multiple categories. For example, Maassen's (2012, p. 441) concept of urban infrastructural transformation was included in the urban and infrastructure categories in Table 2.

Across this wide range of terminology, specific definitions were rare. We were able to identify explicit definitions for only 213 of the 1584 transformation-related terms (13%). On average, articles defined 15% of the terms that they used, with 47% of articles not explicitly defining any terms. As illustrations, 59% of the uses of the general concept of transformation were defined (e.g., Ellis & Tschakert, 2019), 67% of deliberate transformation (67%, see O'Brien, 2012), 36% of green transformation (e.g., Schmitz, 2017; citing Scoones et al., 2015), and 39% of transformational capacity (e.g., Hölscher, Frantzeskaki, & Loorbach, 2019, p. 796). Reference to the IPCC's definitions of the terms presented in Box 1 (see Section 1) were conspicuously rare. For example, only 4 out of the 19 definitions of "transformation" referenced the IPCC's definition of the concept (e.g., Boodoo et al., 2018, p. 674).

Measured by the percentage of articles in which they occurred, common categories included energy (49% of articles), governance (36%), social/societal (34%), and technological (20%) transformations. It was also common for articles to mention transformational/transformative change (35%), processes (22%), actions (18%), pathways (16%), and potential (14%). Other articles described the depth (33%, e.g., fundamental), breadth (17%, e.g., broad) and speed (11%, e.g., rapid) of transformations.

Given the sheer breadth of the categories we identified, it is beyond the scope of this review to examine each of them in detail. However, below, we provide an overview of the usage of the concepts of transformation, energy transformation, governance transformation, transformational/transformative change, and transformation pathway. The generic concept of transformation was among the most frequently defined. Four articles refer to the IPCC's (2018), p. 559) definition, namely: "a change in the fundamental attributes of natural and human systems" (e.g., Boodoo et al., 2018, p. 674; Tàbara et al., 2019, p. 808). Similarly, some articles included new transformation definitions that mirrored but did not completely replicate the IPCC's general emphasis (see Box 1). Fazey, Schäpke, et al. (2018), pp. 55–56) defined transformation as "a process leading to marked and qualitative change and processes that lead to fundamentally different forms of thinking, actions, systems, and structures." Ellis and Tschakert (2019, p. 168) defined it as "a process of social change that challenges, and ultimately replaces, dominant development trajectories toward desirable low-carbon, climate-resilient futures." Drawing on Brown et al. (2013), Korhonen-Kurki et al. (2017, p. 62) defined transformation as "a profound, substantial, and irreversible change". Notably, these definitions emphasize the depth of change as a key aspect of transformation.

Although energy transformations were the most common category (13% of all occurrences, mentioned in 49% of the articles), these terms were rarely defined (just 12 out of 200 occurrences). In a notable exception, Rogelj et al. (2015, p. 522) define the global energy transformation as the "rapid and fundamental decarbonization of the global energy system". Similarly, Bernstein and Hoffmann (2018), p. 191) define transformational decarbonization as "a phase change whereby fossil energy [...] is not just lessened, but a new trajectory toward replacement or zero use of carbon-based energy is generated."

We identified terms related to transformational/transformative change 104 times, appearing in 35% of the articles, of which only 18% included definitions. Four articles that focused on forest-related mitigation and the REDD+ program (e.g., Brockhaus et al., 2014) used a shared definition of transformational change from the gray literature, namely: a "shift in discourse, attitudes, power relations, and deliberate policy and protest action that leads policy formulation and implementation away from business-as-usual policy approaches that directly or indirectly support deforestation and forest degradation" (Brockhaus & Angelsen, 2012, p. 17). In their review of how transformational change is conceptualized by international funding agencies, Boodoo et al. (2018, p. 674) discussed several definitions of transformational change with reference to the IPCC and the United Nations Framework Convention on Climate Change (UNFCCC), but argued that "a universal definition of [transformational change] contrasts with principles of sovereignty within the UNFCCC." Like transformational change, governance, policy, and political transformations (36% of articles) were rarely defined (12 out of 118 occurrences). One illustrative definition in this category was provided by Hölscher, Frantzeskaki, and Loorbach (2019), p. 792), who defined transformational climate governance as "the processes of interaction and decision-making by which multiple actors seek to address climate change mitigation and adaptation while purposefully steering societies towards low-carbon, resilient and sustainable objectives" (see also Hölscher, Frantzeskaki, McPhearson, & Loorbach, 2019).

The concept of "transformation pathways" is prominent in the IPCC and the wider academic literature (IPCC, 2014b; Rosenbloom, 2017). However, the concept was defined differently in the articles we examined.

TABLE 2 Transformation-related terms identified in 198 prioritized articles (total occurrences, number of articles in which they are mentioned, and the number with definitions of terms)

Category of transformation-related term	Occurrences (number and percentage of total terms [$n = 1584$])	Articles that mention at least one term from the category (number and percentage of total articles [$n = 198$])	Definitions of terms (number of terms defined and percentage of occurrences)
Transformation (no modifiers)	31 (2%)	31 (16%)	19 (61%)
Subject of transformation (i.e., what is being transformed?)			
Energy	200 (13%)	98 (49%)	12 (6%)
Society (social/societal)	144 (9%)	68 (34%)	8 (6%)
Governance/policy/politics	118 (7%)	71 (36%)	12 (10%)
Urban/suburban	80 (5%)	33 (17%)	7 (9%)
Economy	51 (3%)	36 (18%)	1 (2%)
Technology	47 (3%)	39 (20%)	4 (9%)
Ideas/narratives	36 (2%)	29 (15%)	6 (17%)
Market	34 (2%)	16 (8%)	6 (18%)
Infrastructure	30 (2%)	18 (9%)	2 (7%)
Research/science	29 (2%)	19 (10%)	5 (17%)
Global	27 (2%)	23 (12%)	0 (0%)
System (systemic)	26 (2%)	21 (11%)	2 (8%)
Business/corporate/industrial	22 (1%)	18 (9%)	3 (14%)
Diet/food/agriculture	22 (1%)	13 (7%)	0 (0%)
Socio-technical system	18 (1%)	16 (8%)	1 (6%)
Transportation/mobility	18 (1%)	13 (7%)	0 (0%)
Behaviors/practices	16 (1%)	13 (7%)	0 (0%)
Development	16 (1%)	13 (7%)	0 (0%)
Regime	16 (1%)	10 (5%)	0 (0%)
Beliefs/preferences/attitudes	15 (1%)	13 (7%)	0 (%)
Built environment/infrastructure	13 (1%)	9 (5%)	1 (8%)
Capitalism	8 (1%)	5 (3%)	1 (13%)
Community	8 (1%)	8 (4%)	0 (0%)
Consumption	8 (1%)	8 (4%)	1 (13%)
Socio-ecological system	8 (1%)	8 (4%)	0 (0%)
Paradigm/worldview	7 (0.4%)	6 (3%)	3 (43%)
Culture	5 (0.3%)	5 (3%)	0 (0%)
Heating/cooling	5 (0.3%)	2 (1%)	1 (20%)
Nation	4 (0.3%)	4 (2%)	0 (0%)
Waste	4 (0.3%)	2 (1%)	0 (0%)
Transformational/transformative...			
Change	104 (7%)	70 (35%)	19 (18%)
Action/initiative/solution	55 (3%)	36 (18%)	7 (13%)
Process/dynamics	51 (3%)	43 (22%)	3 (6%)
Pathway	41 (3%)	32 (16%)	7 (17%)
Future/scenario/vision	34 (2%)	25 (13%)	4 (12%)
Potential	34 (2%)	27 (14%)	7 (21%)

TABLE 2 (Continued)

Category of transformation-related term	Occurrences (number and percentage of total terms [$n = 1584$])	Articles that mention at least one term from the category (number and percentage of total articles [$n = 198$])	Definitions of terms (number of terms defined and percentage of occurrences)
Capacity	24 (2%)	19 (10%)	9 (38%)
Elements/factors	22 (1%)	17 (9%)	8 (36%)
Effects/impacts/outcomes	21 (1%)	16 (8%)	0 (0%)
Innovation/experimentation	17 (1%)	11 (6%)	4 (24%)
Adaptation/resilience	13 (1%)	11 (6%)	6 (46%)
Actors/agents	12 (1%)	11 (6%)	3 (25%)
Learning	12 (1%)	6 (3%)	6 (50%)
Alliances/networks	7 (0.4%)	6 (3%)	2 (29%)
Practices	5 (0.3%)	5 (3%)	1 (20%)
Moments/windows of opportunity	4 (0.3%)	4 (2%)	2 (50%)
Descriptive terms/types of transformation			
Depth of transformation (e.g., deep, fundamental, radical)	96 (6%)	65 (33%)	9 (9%)
Low carbon/mitigation	86 (5%)	57 (29%)	5 (6%)
Sustainability	62 (4%)	47 (24%)	4 (6%)
Breadth of transformation (e.g., broad, wide, large-scale)	43 (3%)	33 (17%)	2 (5%)
Speed of transformation (e.g., rapid, gradual)	27 (2%)	21 (11%)	3 (11%)
Structural	22 (1%)	19 (10%)	1 (5%)
Green	14 (1%)	14 (7%)	5 (36%)
Justice	10 (1%)	7 (4%)	0 (0%)
Deliberate	9 (1%)	8 (4%)	6 (67%)
Deliberative	9 (1%)	5 (3%)	0 (0%)
Drivers of transformation	6 (0%)	5 (3%)	0 (0%)
Personal	5 (0.3%)	5 (3%)	0 (0%)
Carbon neutral	5 (0.3%)	3 (2%)	1 (20%)
Barriers to transformation	3 (0.2%)	3 (2%)	0 (0%)
Other/miscellaneous terminology	99 (6%)	70 (35%)	20 (20%)

The IPCC (2014b), p. 1273) defined a transformation pathway as "the trajectory taken over time to meet different goals for greenhouse gas (GHG) emissions, atmospheric concentrations, or global mean surface temperature change that implies a set of economic, technological, and behavioral changes," a definition which is alluded to by, for example, Isley et al. (2015), p. 147). In contrast, articles drawing on the sustainability transitions literature defined a transformation pathway as a specific type of transition, "characterized by external pressure (from the landscape level or outsider social groups) and gradual adjustment and reorientation of existing regimes" (Verbong & Geels, 2010, p. 1216; Yadav et al., 2019).

3.1.2 | Transformations and transitions

A number of authors have discussed the relationship between transformations and transitions (Hjerpe et al., 2017; Hölscher et al., 2018). To further explore this issue, we counted the occurrences of transition-related terminology in our sample of articles: 89% mentioned the term transition at least once. Overall, although our systematic review was designed to identify transformation-related articles, 30% of the articles we examined mentioned transitions more

frequently than transformations. We also examined how the relationship between transition and transformation was defined. We found 39 articles (20%) that appeared to equate the two terms (e.g., Horan, 2019) and 57 (29%) that left the relationship between the two terms ambiguous (e.g., Aylett, 2013). Finally, 72 articles (36%) treated transition and transformation as distinct concepts. Among them, some defined a transition as a more incremental form of change than a transformation (e.g., Krellenberg et al., 2016, p. 53), while others treated a transformation as a subtype of transition that involved incumbent industries changing ("transforming") instead of being replaced (e.g., Geels et al., 2016; Luederitz et al., 2017).

3.2 | Focus areas, theories, and methods

3.2.1 | Sectors, scales, and geographical focus

Of the articles we reviewed, 167 (84%) focused on at least one sector or system (Table 3). The most common sectoral foci were energy (53%; e.g., Rogelj et al., 2015; Geels et al., 2016), transportation and mobility (11%; e.g., Hussaini & Scholz, 2017), buildings and infrastructure (10%, e.g., Pauliuk et al., 2013), heating and cooling (8%; e.g., Büttner & Rink, 2019), diet/food/agriculture (7%; e.g., Campbell et al., 2018), industry (4%; e.g., Busch et al., 2018), personal consumption (3%; e.g., Büchs et al., 2015), forestry (3%, e.g., Brockhaus et al., 2014), and waste (2%; e.g., Silver, 2017). Broader systems were also afforded attention, especially society (20%; e.g., O'Brien, 2016) and the economy (10%; e.g., Kirby, 2013). Although 71% of the articles examined only one sector or system, the remainder analyzed two or more. Some sectors, such as energy and forestry, were more often the only ones named in the articles (e.g., Brockhaus et al., 2014; Rogelj et al., 2015). In contrast, consumption was not the sole focus of a single article.

Of those examined, 177 (89%) of the articles focused on at least one scale of analysis. The most common were the national (27%; e.g., Canzler & Wittowsky, 2016), urban (22%; e.g., Castán Broto, 2017), international (21%; e.g., Boodoo et al., 2018), community (15%; e.g., Burch et al., 2014), and regional scales (9%; e.g., Weller, 2012). Analysis at the level of organizations, households and individuals was more limited, with 11% of articles mentioning at least one of these three (e.g., Büchs et al., 2015 examined the household and individual levels).

Articles on diet/food/agriculture and mobility, tended to focus on the international and national levels (54% of diet/food articles), with comparatively little focus on households and individuals; only one article, equivalent to 7% of the total, focused on individuals (Alexander et al., 2017). The picture was different for articles on heating and cooling, which focused more on the community (27%) and household levels (20%), and articles on consumption which focused more on the community (50%) and individual levels (33%). Unsurprisingly, 68% of articles looking at buildings and infrastructure had cities as a primary focus.

Geographically, Europe was the most-studied region; it was a focus of 38% of the 198 articles. Fully 29% of the articles looked solely at Europe. Other regions of the world received far less attention: North America (13%), Asia (13%), Africa (8%), Oceania (7%), and South America (4%). The most frequently studied countries were the United Kingdom (15%), the United States (11%), Germany (7%), Australia (6%), Sweden (5%), and China (5%). The United Kingdom was the focus of more articles (30) than every geographical region except Europe (the closest region was North America, covered by 26 articles). Our results show that high-income countries as defined by the World Bank[10] (World Bank, 2020) were overrepresented: they constituted 74% of countries specifically mentioned. Among articles that focused on upper middle-income and lower middle-income countries (25% of the total), approximately 53% analyzed the BRICS group of major economies (Brazil, Russia, India, China, and South Africa, although Russia was not a focus of any article). We identified only two articles that studied a low-income country: a case study of Mbale, Uganda (Silver, 2017) and another that included Mozambique (Power et al., 2016).

3.2.2 | Theory and methods

Overall, we identified a theoretical approach in 105 articles (53% of the total, see Table 4). We categorized the most common group of theories (20% of articles) as "critical theories" because they critiqued the underlying structure of society (e.g., capitalism), argued for its dominant role in causing climate change, and called for society-wide change towards a more just social and economic system. Critical theories included energy democracy (e.g., Allen et al., 2019), governmentality (e.g., Castán Broto, 2017), political economy (e.g., Chia et al., 2019), and social practice theory

TABLE 3 Sector/system, scale, and geographical focus of the 198 articles reviewed

Sector/system	Articles mentioning sector/system (number and percentage [$n = 198$])
Energy	104 (53%)
Society	39 (20%)
Transportation/mobility	22 (11%)
Built environment/infrastructure	19 (10%)
Economy	19 (10%)
Heating/cooling	15 (8%)
Diet/food/agriculture	13 (7%)
Industry	7 (4%)
Consumption	6 (3%)
Forestry	6 (3%)
Waste	3 (2%)
All sectors	*167 (84%)*
Scale	Articles mentioning scale (number and percentage [$n = 198$])
National	53 (27%)
City	44 (22%)
International	41 (21%)
Community	29 (15%)
Regional	18 (9%)
European Union	11 (6%)
Organizational	10 (5%)
Individual	8 (4%)
Household	5 (3%)
All levels of analysis	*177 (89%)*
Geographical region	Articles mentioning region (number and percentage [$n = 198$])
Europe	75 (38%)
North America	26 (13%)
Asia	25 (13%)
Global	19 (10%)
Africa	15 (8%)
Oceania	14 (7%)
South America	8 (4%)
All regions	*150 (76%)*
Country (top 10 most mentioned)	Articles mentioning country (number and percentage [$n = 198$])
United Kingdom	30 (15%)
United States	21 (11%)
Germany	14 (7%)
Australia	12 (6%)
Sweden	10 (5%)
China	9 (5%)
Brazil	7 (4%)
Canada	7 (4%)
India	7 (4%)
South Africa	6 (3%)

(Continues)

TABLE 3 (Continued)

World Bank country income categories	Mentions of countries in articles (total mentions [$n = 224$])[a]
High income	166 (74%)
Upper middle income	35 (16%)
Lower middle income	22 (10%)
Low income	2 (0.5%)

[a]The number of countries mentioned is higher than the number of articles because it was common for articles to mention multiple countries.

TABLE 4 Theories employed by the 198 articles reviewed

Theory category	Articles mentioning theory (number and percentage [$n = 198$])	Examples
Critical theories	39 (20%)	Energy Democracy; Governmentality; Political Economy; Social Practice Theory
Transitions	35 (18%)	Multilevel Perspective; Strategic Niche Management; Transition Management
Political science	17 (9%)	Multilevel Governance; Policy Diffusion
Transformation	15 (8%)	Market Transformation; Transformational Climate Governance; Transformational Leadership
Futures/visioning/scenarios/modeling	12 (6%)	Sociotechnical Imaginaries; Economic Modeling
Other	11 (6%)	Behavior Change; Education for Sustainable Development
All theory categories	*105 (53%)*	

(e.g., Shove, 2010). Another prominent group of theories was related to socio-technical transitions (18%), including the multilevel perspective (e.g., Geels et al., 2016) and strategic niche management (e.g., Seyfang & Haxeltine, 2012). These theories stem from the technological innovation literature and focus on the broad economic and social dynamics of change. Other categories included theories of political science and public policy/administration (e.g., multilevel governance in Schroeder et al., 2013), as well as futures and visioning (e.g., sociotechnical imaginaries in F. Engels & Münch, 2015). We identified methods in 127 articles (64% of the total). Of the articles that explicitly mentioned the methods used, the most frequent were interviews (27%), document analysis (19%), literature reviews (16%), case studies (12%), modeling (8%), deliberative/participatory techniques (6%), surveys (5%), and participant observation (3%). We identified both a theory and a method in 70 articles (35%). In 36 articles (18%), we were not able to identify either a theory or a method.

3.3 | Characteristics of transformation

3.3.1 | Triggers, drivers, barriers, and outcomes

An important component of our review was to identify the characteristics of mitigation-related transformations. Some of the most important characteristics were related to triggers, drivers, and barriers. Among these, drivers (71%), and barriers (68%) were much more likely to be mentioned than triggers (34%) (see Section 2 for definitions). We classified triggers, drivers, and barriers into 14 categories (Table 5; see Eisenack et al., 2014, p. 868). Factors related to governance, policy, and institutions were the most commonly cited triggers (19%), drivers (42%), and barriers (57%). Common governance-related triggers were international legal commitments such as the Paris Agreement and the 1.5°C target (e.g., Grandin et al., 2018), and national and/or local policy commitments (e.g., F. Engels & Münch, 2015). Governance-related drivers included well-designed and sufficiently well-resourced policy and governance processes, as well as financial incentives (e.g., Markantoni, 2016). Governance-related barriers included vested interests, such as in the energy

TABLE 5 Transformation-related triggers, drivers, and barriers identified in the 198 articles reviewed

	Articles mentioning...		
Category	**Triggers**	**Drivers**	**Barriers**
Attitudinal/behavioral	1 (1%)	35 (18%)	30 (15%)
Economic/financial/market	9 (5%)	50 (25%)	69 (35%)
Environmental goals/impacts	20 (10%)	17 (9%)	1 (1%)
Governance/policy/institutional	38 (19%)	83 (42%)	113 (57%)
Inequality	4 (2%)	-	9 (5%)
Infrastructure	-	19 (10%)	27 (14%)
Knowledge	3 (2%)	30 (15%)	24 (12%)
Non-state actors	10 (5%)	23 (12%)	3 (2%)
Skills and capacities	1 (1%)	12 (6%)	9 (5%)
Social structures, systems, and practices	4 (2%)	43 (22%)	14 (7%)
Socio-cultural	1 (1%)	7 (4%)	5 (3%)
Technological	6 (3%)	28 (14%)	29 (15%)
Uncertainty	1 (1%)	1 (1%)	7 (4%)
All categories	*68 (34%)*	*141 (71%)*	*135 (68%)*

sector (e.g., Stirling, 2014), the absence of mitigation policies (e.g., Brockhaus et al., 2014), and inertia created by existing policies and institutions (e.g., Burch et al., 2014). Another group of commonly cited barriers was a lack of policy/governance coordination and cooperation between state and non-state actors (e.g., Moloney & Horne, 2015; Schroeder et al., 2013).

Technological factors were mentioned as both a trigger and a driver (e.g., Jacobsson et al., 2017), while a lack of sufficient technology and innovation was also cited as a barrier (e.g., Loftus et al., 2015). Within the financial/economic category, costs were both a barrier—for example, high costs of renewable technology or lack of funds to support its development (e.g., Barkenbus, 2009)—and a driver, for instance, when costs fell (e.g., Riahi et al., 2015). The articles also discussed key components of carbon lock-in related to infrastructures such as existing buildings and energy systems (e.g., Tozer, 2019). Similarly, another category of barriers were high-carbon paradigms, beliefs, and behaviors such as consumerism, throw-away culture, and public opposition (e.g., Canzler & Wittowsky, 2016; Marsden & Rucinska, 2019).

Another important characteristic of a transformation is its realized or planned outcomes. Transformation outcomes were mentioned in 57% of the articles. Outcomes were often high-level, future goals, such as limiting atmospheric CO_2 concentrations to 450 ppm GHG equivalent (e.g., Riahi et al., 2015), the 1.5°C target (e.g., Gordon & Johnson, 2018), or (more qualitatively) creating a low-carbon economy (e.g., Delman, 2011). The outcomes of historical transformations were generally more narrowly framed, often drawing on specific case studies. These included increases in solar energy in specific regions, such as Portland, Oregon (Aylett, 2013) and the creation of a solar co-operative in Mumbai (Schroeder et al., 2013).

3.3.2 | Actors

In total, 70% of the 198 articles discussed the role of actors in transformations (Figure 3). The most common actor categories were government (57%), business (49%), individuals (32%, variously framed as citizens, consumers, communities and publics), non-governmental organizations (23%), and academic institutions (12%). In some cases, governments were presented as enabling transformations (e.g., J. Williams, 2016) while in others they impeded them (e.g., Biggs, 2016). Fossil fuel industries were often cited as impeding transformations (e.g., Stirling, 2014) while those in renewable energy companies and non-governmental organizations were generally identified as enablers (Aylett, 2013). Publics and individuals were seen as both impeding (e.g., Engels et al., 2013) but also enabling change, either mobilizing directly of their own volition or because of engagement mechanisms such as participatory processes (e.g., Mikkola & Risku-

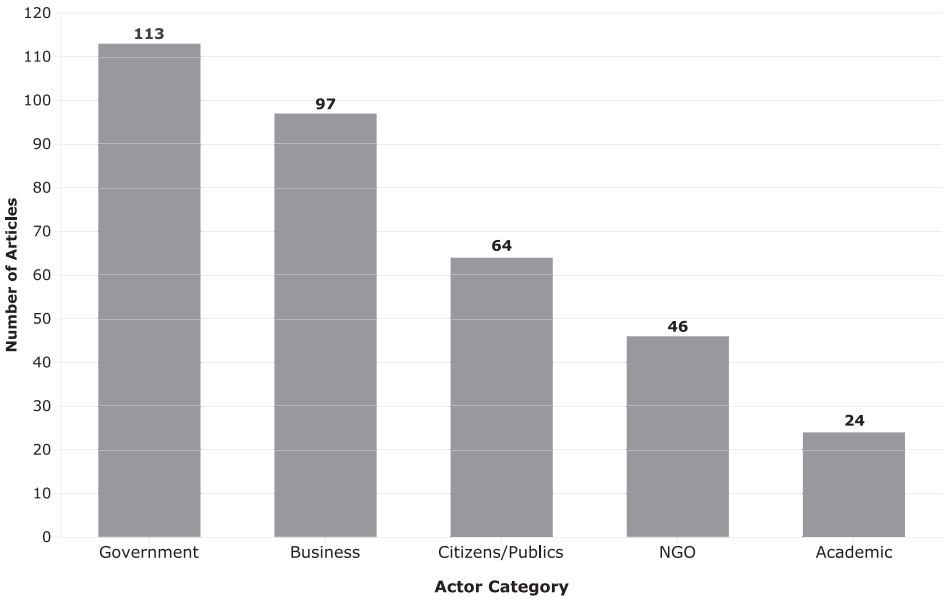

FIGURE 3 Actor categories identified as being involved in transformations in the 198 articles reviewed

Norja, 2014). Finally, academic institutions and research organizations were also mentioned as transformation-related actors, often working in partnership with other actors (e.g., Tonn, 2007).

3.3.3 | Speed of change

Our review also focused on the speed of transformations. Given that the aspiration of the Paris Agreement is to achieve rapid and deep decarbonization, it was notable that only 63 articles (32%) explicitly addressed the speed and timing of change. Transformations were defined as taking place over various timeframes. A number of authors explicitly referred to transformation as a rapid process (e.g., Grandin et al., 2018). On the other hand, Newell (2019, p. 44) argued that transformations can "take decades or often centuries". Urpelainen (2013) emphasized the role of gradualist, incremental policy strategies to trigger transformations. Some articles mentioned different speeds and timescales occurring concurrently: for example, a process of slowly instigating changes in beliefs/paradigms while also achieving rapid technological change (Messner, 2015, p. 262).

3.3.4 | Co-benefits and adverse side effects

A co-benefits framing is often deemed to be especially relevant to the challenge of initiating and delivering transformations at scale and speed. It has also been widely employed by the IPCC. We therefore examined the extent to which the articles focused on the co-benefits of mitigation, such as improved air quality, health, and economic benefits (Table 6; see Deng et al., 2017; Hamilton et al., 2021). Just under a third of the articles (28%) referred to co-benefits. The majority of co-benefits mentioned were classified as economic (20% of articles), followed by distributional (12%), ecosystem (6%), health, and air pollution (4% each). Economic co-benefits included the creation of jobs, businesses, and general economic growth (e.g., Tozer & Klenk, 2018). Some articles referred to co-benefits that strengthen social and environmental justice (e.g., Healy & Debski, 2017). Co-benefits for biodiversity were also mentioned, for example as a result of reducing deforestation (e.g., Fischer et al., 2016). Health co-benefits, such as improved health from better air quality, were a key impact of closing coal-fired power plants (e.g., Grandin et al., 2018; Horan, 2019).

On the other hand, because transformations bring rapid change and potential disruption, they may also cause adverse side effects, such as economic damage or greater social injustice (IPCC, 2014b, p. 5; Blythe et al., 2018). We did not systematically code for adverse side effects, but we did find some examples: Silver (2017, p. 1490), for example,

TABLE 6 Co-benefits (the categories of transformational mitigation co-benefits addressed in the 198 articles reviewed)

Category	Articles mentioning co-benefit (number and percentage of all articles)
Economic	39 (20%)
Distributional	24 (12%)
Ecosystem	11 (6%)
Health	8 (4%)
Air pollution	8 (4%)
Energy security	5 (3%)
Resource efficiency	4 (2%)
Food security	2 (1%)
Other	8 (4%)
All co-benefit categories	*55 (28%)*

Note: Categories modified from Deng et al. (2017).

argued that low-carbon societal transformation had excluded waste pickers who were already marginalized in Ugandan society.

3.4 | Bibliographic network analysis

We adopted two approaches to our bibliographic network analysis of the 197 articles for which Scopus included reference list data (see Section 2). The bibliographic coupling approach examined the extent to which articles shared references with each other. It revealed that the articles with the highest number of shared references were largely literature reviews or offered broad theoretical treatments of the subject (e.g., Geels et al., 2018; Gillard et al., 2016; Moore et al., 2018; Rosenbloom, 2017). Overall, out of 19,306 possible article pairs sharing one or more citations, only 19% were found in the network analysis.[11] Among the articles that shared references, the average number was 2 common references; the highest was 70 common references (Hölscher, Frantzeskaki, & Loorbach, 2019; Hölscher, Frantzeskaki, McPhearson, & Loorbach, 2019). At the other extreme, 11 articles did not share any common references with the other 196 articles. The extent to which articles shared references varied by journal: articles published in *Environment and Planning C* shared at least one reference with 70% of the other articles in the journal, followed by *Current Opinion in Environmental Sustainability* (49%). At the other end of the spectrum, only 13% of articles in *Sustainability* had at least one reference in common with each other.

Other subsets of the literature showed greater than average shared references, including those focusing on the city level (43%, more than twice the average) and communities (31%). Articles that used transitions theories were highly interconnected (61% of possible connections, three times the average), as were articles that used transition terms more often than transformation terms (47%). Of the most heavily cited 109 references by the articles that we analyzed, about a third were transition-related, including eight of the 10 most-cited articles (e.g., Geels, 2002; Geels & Schot, 2007; Smith et al., 2005). In what is a highly fragmented literature, articles employing transitions-oriented theories and concepts, therefore, stood out for their level of interconnection.

In our second approach, we created a direct citation network, where two articles are connected when the first article cites the second article (see Figure 4). Direct citations between the 197 articles were rare. Only 115 articles (58%) were the source or recipient of a direct citation, with only 171 inter-article citations (1.2% of 14,428 total references). Five articles received 28% of all inter-article citations (Burch et al., 2014, 12 citations; Gillard et al., 2016, 10 citations; Rogelj et al., 2015, 9 citations; Seyfang & Haxeltine, 2012, 8 citations; O'Brien, 2016, 8 citations). Within this subset, the number of citations that were related to transformation varied greatly (the average for these five articles was 47% transformation-related citations). For example, 67% of citations to Burch et al. (2014) were transformation-related, for example, related to the concept of development-path transformations (Moore et al., 2018, p. 13) or in reference to factors affecting urban transformation (Amundsen et al., 2018, p. 25). On the other hand, none of the citations to Seyfang and Haxeltine (2012) focused on transformation, instead focusing on topics such as community energy innovation (Geels et al., 2018, p. 27).

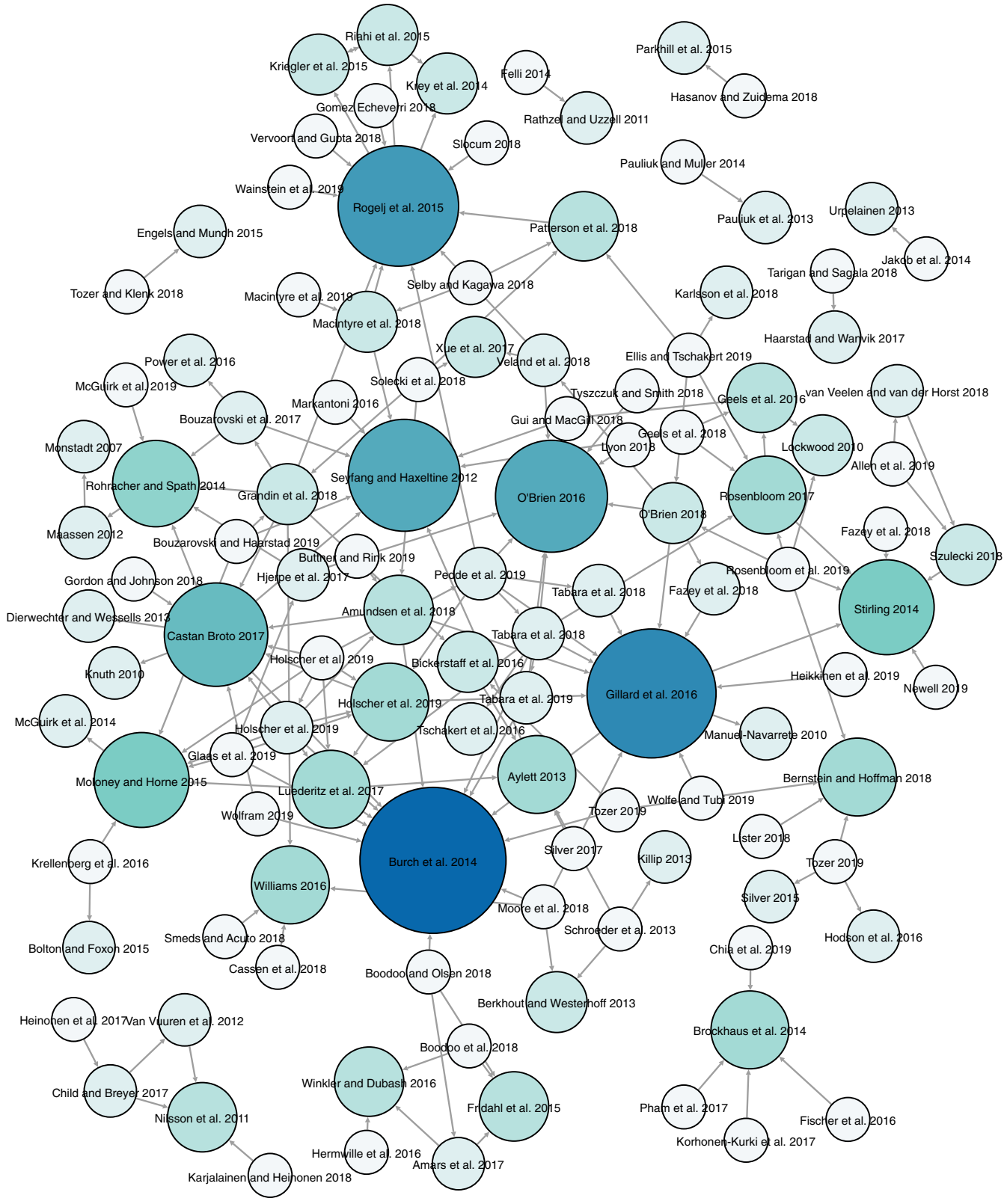

FIGURE 4 Direct citation network of the 197 transformation-related articles (the 115 articles with at least one incoming or outgoing reference to another article in the corpus are shown). The size and color of individual nodes indicates an article's *in-degree*, that is, the total number of times it was cited by other articles in the corpus

4 | DISCUSSION

Our main objective in this article was to understand how transformation-related terms and concepts are used in the social science literature on climate change mitigation, and to extract key insights about when, where and how transformation occurs. Below, we draw out key findings from our review and make some suggestions for future research.

4.1 | Conceptual ambiguity

As noted in the Introduction, there is a lively debate around the conceptual meaning of transformation. Previous reviews of the use of transformation-related terminology have suggested that "social science understandings of transformation are diverse, fragmented, and contested" (Brown et al., 2013, p. 100; see also Fazey, Moug, et al., 2018, p. 198; Feola, 2015). Our systematic review has confirmed that there are indeed widespread examples of an emerging transformation *terminology*. Terms related to energy transformations, transformational change, and governance/policy transformations were each used in at least a third of the articles that we studied. However, the "transformational turn" in the literature has not yet translated into common *definitions*, with less than 15% of terms being defined and an even smaller proportion of articles drawing on shared definitions. In some cases, the sheer number of distinct terms used in individual articles made it difficult to distinguish the relationship between them. We also found disagreement and widespread ambiguity about the relationship between transformations and transitions. Despite our focus on transformation-related articles, our findings confirm the full range of transformation/transition relationships identified by previous research (Hjerpe et al., 2017, p. 26; Hölscher et al., 2018). Diverging definitions of the transformation/transition relationship have continued to persist in more recent research on climate change mitigation and other sustainability issues that fell outside the scope of our review (cf. Clark & Harley, 2020, p. 355; Linnér & Wibeck, 2020, p. 222).

Some of this conceptual ambiguity arises as a result of the adoption of similar terms (albeit with different meanings) across relatively discrete theoretical and disciplinary literatures; differences that are magnified when they are used across such a wide variety of scales, sectors, and geographical regions. A degree of "constructive ambiguity" (Boodoo et al., 2018, p. 674) is perfectly understandable—it is arguably indicative of the deeply contested nature and extent of the transformations deemed necessary to limit warming to 1.5°C (see Section 1). But the sheer number of terms, concepts and definitions also constitutes a serious challenge to scholarship as well as knowledge-based climate action and policy making because it complicates the already daunting challenge of decarbonizing society (Newig & Rose, 2020, pp. 671–673).[12] Achieving the scale and pace of emissions reductions required is made that much more difficult if these issues are not collaboratively addressed.

4.2 | Toward shared terms and concepts

In this review, we have made an important next step towards cumulative knowledge building by undertaking a broad-based review of how transformation-related terms and concepts have been used thus far in the literature on climate change mitigation (see, e.g., Berrang-Ford et al., 2015, pp. 755–756; Newig & Rose, 2020, pp. 673–675). An even more difficult next step is to move towards common definitions of key terms and concepts. As several authors have noted, the relevant breadth, depth, and speed of mitigation that can be considered to be "transformational" is dependent on factors such as the sectoral focus and national context (Brown et al., 2013; Fazey, Moug, et al., 2018). Therefore, we propose the concept of *transformational climate change mitigation* as an umbrella term that encompasses the multiple mitigation-related transformations—operating across diverse sectors, levels and geographical scales—that together constitute global climate change mitigation. We define *transformational climate change mitigation* as that which is sufficiently broad, deep, and rapid to contribute to fulfilling the goals of the Paris Agreement and which involves a fundamental shift in the trajectory of societal change away from patterns of development that normalize high-carbon ways of living (Box 2).

Our proposed definition share similarities with Bernstein and Hoffmann's (2018), p. 191) concept of "transformational decarbonization" (which is focused on energy transformations) and Hurlimann et al.'s (2021) concept of "climate change transformations" (which incorporates both climate change mitigation and adaptation). Our definition also draws on Fazey, Moug, et al.'s (2018), p. 198) three dimensions of transformation: depth ("the intensity or quality of the change"); breadth ("the distribution of change"); and speed ("the timeframe through which a change occurs"). Many of

BOX 2 Transformational climate change mitigation

In order to facilitate discussion and move toward clearer shared understandings of transformations for climate change mitigation, we propose the umbrella term of *transformational climate change mitigation*.

Transformational climate change mitigation: Climate change mitigation that is sufficiently broad, deep, and rapid to contribute to fulfilling the goals of the Paris Agreement and which involves a fundamental shift in the trajectory of societal change away from patterns of development that normalize high-carbon ways of living.

the definitions reviewed here rightly emphasize the depth aspect. However, less attention is paid to the speed or breadth of transformations. These additional dimensions are expected to be important. For example, whether the decarbonization of the electricity system in high-income countries occurs by 2030, 2050, or 2100 will have a crucial influence on the world's chances of meeting the Paris Agreement's goals (Rogelj et al., 2015).

4.3 | Characteristics of transformation

A key theme that emerges from our review of the existing literature is that deliberate societal transformation requires the active participation of non-governmental organizations, business actors, and citizens to reconfigure societal systems. This points to the need to exploit synergies between different elements of policy (Jordan & Moore, 2020), perhaps using a co-benefits framing, and also to expand the opportunities for non-state actors to participate in policy making and to empower publics so they can actively engage in transformation (Blythe et al., 2018, pp. 1217–1218). Economic and social co-benefits of climate action may help mobilize these groups by aligning climate goals with other goals of importance (cf. IPCC, 2014b).

However, our systematic review also identified several challenges for this vibrant subfield which go well beyond addressing conceptual ambiguity. For example, we could not identify clear theoretical or methodological approaches in nearly one-fifth of the articles. Nearly 70% did not discuss issues related to the speed of transformation and it was uncommon to discuss concrete transformation outcomes aside from the fulfillment of broad, future goals. These omissions—if left unaddressed—will make it more difficult to recognize when a transformation has occurred, when it ends and what the eventual outcomes are.

Nevertheless, we have identified several empirical commonalities related to triggers, drivers, and barriers of transformation around which a more cumulative research program could be built. For example, policy/governance factors were identified as the most common driver and barrier of transformation and policy makers were the most commonly identified group of actors—although this may in part be due to our focus on "deliberate" (i.e., directed) change. Economic factors, such as incentives, were also seen as critical, followed by social, behavioral, and technological factors. These findings are consistent with relevant theoretical literatures (Geels, 2002; O'Brien, 2012).

5 | CONCLUSIONS AND NEW RESEARCH DIRECTIONS

In this article, we have reported the findings of a novel systematic review of the social science literature on transformations for climate change mitigation, published between 1994 and 2019. We have employed a transparent, reproducible approach to survey a vibrant and rapidly expanding field addressing topics of potentially enormous policy relevance. In all, our review identified 658 articles that engage with transformation-related terminology. This constitutes a potentially important reservoir of policy-relevant knowledge.

Our systematic review also confirmed the extent of conceptual heterogeneity in the existing literature. We have sought to contribute to this debate by identifying and defining the concept of *transformational climate change mitigation*: climate mitigation that is sufficiently broad, deep, and rapid to contribute to fulfilling the goals of the Paris Agreement. However, our systematic review also revealed that attempts to make greater use of defined transformation terminology, for example, by the IPCC, has only partly been reciprocated within the academic literature. For example, our analysis found that the IPCC's definitions—of transformation, of transformative change, and of social/societal

transformation (see Box 1)—are not widely cited in the literature we surveyed, which is curious given that IPCC reports summarize the academic state of the art and are mostly authored by academics. We identified several empirical themes (e.g., with respect to triggers, drivers, and barriers of transformation) around which a more cumulative research program could and should be built.

Based on our experience of undertaking this systematic review, we propose several areas for further research. First, there is significant scope for further reviews of the existing empirical and conceptual literature on transformations and climate change mitigation. By design, this review has a broad focus and we have deliberately presented our findings at a similarly general level. Future research could examine explanations for the patterns found here as well as the scope for shared transformation frameworks, concepts, and cumulative knowledge syntheses for specific areas and/or topics, such as the energy sector or cities. Similarly, systematic reviews of transformational climate change adaptation are emerging (Ajulo et al., 2020). Research that synthesizes findings from research on transformations for both climate change mitigation and adaptation could deliver broader lessons for climate governance more generally (Hurlimann et al., 2021). We analyzed the relationship between transitions and transformations in our prioritized corpus of articles, but we selected these articles based on their use of transformation terminology. A fuller understanding of how these two terms are used likely necessitates a review that also examines the wider transitions literature. Transformational language is also increasingly prominent in the policy literature (European Environment Agency, 2019; IPCC, 2018). It would be useful to review documentation generated by the IPCC, IPBES, the UNFCCC, the European Environment Agency, and other policy-oriented institutions (similar to Boodoo et al., 2018) to determine whether practitioners use transformation terms and concepts differently than academics and where the points of connection and commonality lie, with a view to opening up new spaces for conversation and knowledge exchange.

Second, there is a need for new empirical research. For example, most of the articles examined here focused on higher-income economies, which may have greater resources for transformations but may also be more "locked-in" to high-carbon development pathways. There is undoubtedly a need for new research that explores transformation(s) in lower-income economies from the perspective of different disciplines and scales, although this review may have missed articles focusing on these topics if they were not written in English.

Third, another topic which is ripe for new empirical research is the growing attention to the transformation of difficult-to-mitigate sectors such as food, material consumption, transportation, and the heating and cooling of buildings. Our review confirms that these receive relatively little attention in the existing literature. As the energy sector decarbonizes, these sectors will account for a greater share of overall emissions but thus far have proven stubbornly resistant to mitigation efforts (Capstick et al., 2014; United Nations Environment Programme, 2020). In other words, they constitute sectors to which the concept of transformation appears highly relevant. And indeed, they are beginning to attract more scholarly attention, in literature that was published recently and falls outside the scope of this review (see: Frank et al., 2020 on heating; Jacobson et al., 2020 on aviation).

Finally, our focus on "deliberate" transformation likely highlighted more "top-down" or policy-led forms of transformation. Yet transformation also originates from the grassroots level. It is therefore important to ensure that future research and reviews attend to society-led forms of transformation (of which we found several in our corpus, e.g., Seyfang & Haxeltine, 2012), exploring how they may be characterized, if they may be upscaled, and what the role government policy plays therein (cf. Geels, 2002). Our review indicates that a systematic analysis of the trade-offs and co-benefits associated with mitigation at such levels may help identify additional barriers to transformation. Linking with emerging work from other areas would also build opportunities for greater exchange with knowledge users, and eventually offer practical insights into accelerating climate change mitigation transformations.

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CONFLICT OF INTEREST

The authors have declared no conflicting interests.

AUTHOR CONTRIBUTIONS

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DATA AVAILABILITY STATEMENT

Data on the articles reviewed for this systematic review are included in supplementary material.

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ENDNOTES

[1] We identified 31 peer-reviewed articles between 2005–2009 and 458 articles between 2015–2019. See Section 2 for details.

[2] We identified 47 uses of transformation-related terminology in the Fourth Assessment Report Working Group III Technical Report (IPCC, 2007) and 520 uses in the Fifth Assessment Report Working Group III Technical Report (IPCC, 2014b).

[3] In addition, the IPCC Special Report refers to the concept of transformational climate change adaptation (p. 542).

[4] The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) also defines transformative change: "a fundamental, system-wide reorganization across technological, economic and social factors, including paradigms, goals and values" (IPBES, 2019, p. 14).

[5] A Scopus search on 23 April 2021 of Social Science theme journals returned 3155 articles using the climate change mitigation search terms used in this systematic review, 5551 using "sustainab*," and 2182 using "energy," for a total of 9184 results. The mitigation-only search returned 800 (14%) of the articles from the "sustainab*" search and 562 (26%) of the articles from the "energy" search.

[6] Annual Review of Environment and Resources; Carbon Management; Climate Policy; Climatic Change; Ecological Economics; Ecology and Society; Energies; Energy Policy; Environmental Values; Joule; Journal of Cleaner Production; Journal of Environmental Management; Journal of Environmental Planning and Management; Journal of Environmental Policy and Planning; Nature; Nature Communications; Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences; Proceedings of the National Academy of Sciences of the United States of America; Regional Environmental Change; Renewable and Sustainable Energy Reviews; Research Policy; Science; Technological Forecasting and Social Change.

[7] One article met both criteria (Burch et al., 2014).

[8] Modified from "adaptation constraint," as defined in the Working Group II Glossary of the IPCC Fifth Assessment Report (IPCC, 2014a, p. 1758). See also: Linnér and Wibeck (2021) on drivers of sustainability transformations.

[9] Scopus did not include reference data for one article (Goodman, 2009).

[10] Based on the 2021 fiscal year, the World Bank categorizes high-income economies as those with a Gross National Income (GNI) per capita of $12,536 or more, upper middle-income economies between $4046 and $12,535, lower

middle-income economies between $1036 and $4045, and low-income economies with $1035 or less of GNI per capita (World Bank, 2020).

[11] Graph density of 0.192 calculated in Gephi.

[12] We thank an anonymous reviewer for making us aware of this research.

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