



Resilience Meets the Water–Energy–Food Nexus: Mapping the Research Landscape

Rick J. Hogeboom^{1,2,3*}, Bas W. Borsje², Mekdelawit M. Deribe², Freek D. van der Meer¹, Seyedabdolhossein Mehvar², Markus A. Meyer⁴, Gül Özerol⁵, Arjen Y. Hoekstra^{2†} and Andy D. Nelson¹

¹Faculty of Geo-Information Science and Earth Observation, University of Twente, Enschede, Netherlands, ²Faculty of Engineering Technology, University of Twente, Enschede, Netherlands, ³Water Footprint Network, Enschede, Netherlands, ⁴Bavarian Environment Agency, Augsburg, Germany, ⁵Faculty of Behavioural, Management and Social Sciences, University of Twente, Enschede, Netherlands

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*Correspondence:

Rick J. Hogeboom
h.j.hogeboom@utwente.nl

[†]Deceased, on 18 Nov 2019

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Resilience thinking is increasingly promoted to address some of the grand challenges of the 21st century: providing water, energy, and food to all, while staying within the limits of the Earth system that is undergoing (climate) change. Concurrently, a partially overlapping body of literature on the water–energy–food (WEF) nexus has emerged through the realization that water, energy, and food systems are intricately linked—and should therefore be understood and managed in conjunction. This paper reviews recent scientific publications at the intersection of both concepts in order to i) examine the status quo on resilience thinking as it is applied in WEF nexus studies; ii) map the research landscape along major research foci and conceptualizations; iii) and propose a research agenda of topics distilled from gaps in the current research landscape. We identify key conceptualizations of both resilience and nexus framings that are used across studies, as we observe pronounced differences regarding the nexus' nature, scope, emphasis and level of integration, and resilience's scope, type, methodological and thematic foci. Promising research avenues include i) improving the understanding of resilience in the WEF nexus across scales, sectors, domains, and disciplines; ii) developing tools and indicators to measure and assess resilience of WEF systems; iii) bridging the implementation gap brought about by (governing) complexity; iv) integrating or reconciling resilience and nexus thinking; v) and considering other development principles and frameworks toward solving WEF challenges beside and beyond resilience, including control, efficiency, sustainability, and equity.

Keywords: water–energy–food nexus, resilience, Sustainable Development Goals, water security, food security, energy security, transformation

INTRODUCTION

Major economic advancements in the 20th century have lifted millions out of poverty and provided water, energy and food to millions more (UNDP, 2016). However, it has become clear that these successes have come and continue to come at a cost to natural capital. In many regions, aquatic and terrestrial ecosystems have degraded beyond repair, resources have been depleted, species are becoming extinct at alarmingly high rates, and vulnerability to shocks has increased (Turner et al., 2003; Vörösmarty et al., 2010; Puma, 2019).

At the same time, millions of people have been left behind in the global development spur. Today still, three in ten people, i.e., 2.1 billion, are lacking access to safe drinking water and six in ten lack safely managed sanitation facilities (UN-WWAP, 2019); nearly one billion people remain deprived of electricity (OECD and IEA, 2018); more than 820 million people have insufficient food, and many more consume unhealthy diets that contribute to premature death and morbidity (Fears et al., 2019; Willett et al., 2019).

Both the negative environmental impacts and insecurity of water, energy and food supply are expected to worsen in the near future, driven by population growth, increasingly resource-intensive lifestyles and vulnerabilities to disruptive shocks including climate change (Hoekstra and Wiedmann, 2014; Steffen et al., 2018). Reaching the UN's Sustainable Development Goals (SDGs), including those on food (SDG 2), water (SDG 6) and energy (SDG 7), require substantial, if not transformative efforts across the actor landscape (FAO et al., 2017; United Nations, 2018; IRENA, 2019). Indeed, one of the major challenges in the Anthropocene epoch is to provide basic human necessities of water, energy and food to all, in an environmentally sustainable, economically viable and socially inclusive manner that is capable to cope with shocks and disasters (Sachs et al., 2019). These challenges call for new ways of thinking on how we manage natural resources (Pingali, 2012; Nyström et al., 2019).

One such contemporary paradigm is the 'nexus approach'. Originating in public debates on environmental policy, nexus thinking advocates that water, energy and food systems should be viewed collectively and holistically in order to reach water, energy and food (WEF) security (WEF, 2011; Bleischwitz et al., 2018; Liu et al., 2018). Nexus thinking emphasizes the need to consider interlinkages between WEF systems and integrate their management, in order to reduce trade-offs and build synergies across these key sectors, thus presenting a contrasting framework to traditional sectoral approaches (Al-Saidi and Elagib, 2017; Hoff et al., 2019).

Concurrently, 'resilience thinking' emerged in scientific debates (Holling, 1973). Evolving from the field of ecology, resilience thinking is strongly anchored in sustainability science and global change research (Folke et al., 2010; Scheffer et al., 2012; Anderies, 2015). In an uncertain and complex world, unforeseen shocks and disasters can proliferate across scales and systems in unexpected ways, reducing system performance (Nyström et al., 2019). Resilience thinking, therefore, emphasizes the need to design, develop and manage systems for resilience such that they can sustain their function when facing inevitable disturbances, be it sudden disturbances such as a pandemic or those of longer duration such as climate change (World Bank, 2013; Hall et al., 2014; UNDP, 2014; Grafton et al., 2019).

Both nexus and resilience framings find increasingly fertile ground in science as well as policy arenas, where each is backed and cultivated by a growing community of advocates. However, it remains unclear to what extent they are capable to deliver on their promise and materially contribute to WEF security goals. Both framings have been criticized for, among others, their

epistemological agility, their conceptual dissonance (both within and across disciplines), and—perhaps as a consequence—their lack of practical merit toward solving major global challenges (Olsson et al., 2015; Cairns and Krzywoszynska, 2016; Folke, 2016; Gillard, 2016). While the general notion of resilience as 'the capacity of a system to cope with shocks' is widely shared, the specific conceptualizations of the shocks, tools, methods and approaches underlying it vary greatly across literature (Grafton et al., 2016; Allen et al., 2019). Likewise for the nexus, the plurality of typologies yields a spectrum that ranges from simply acknowledging that connections exist between water, food and energy systems, to proposing advanced analytical frameworks for integrated WEF policy development (Scott et al., 2011; Leck et al., 2015; Albrecht et al., 2018). At the same time, there is an occasional overlap in the aims and concepts in both framings, which led several scholars to attempt to integrate the two schools of thought (Guillaume et al., 2015; de Grenade et al., 2016; Stringer et al., 2018).

Given the growing prominence of both nexus and resilience framings in recent literature, as well as expressed concerns over their merit and conceptual clarity, we set out to review recent scientific publications that conflate the two schools of thought. Specifically, the aim of this paper is to:

- i) examine the status quo of resilience thinking as it is applied in WEF nexus studies, by reviewing recent scientific publications at the intersection of both concepts;
- ii) map the research landscape, by identifying key research foci and conceptualizations of nexus and resilience framings;
- iii) propose a research agenda, by distilling recommendations and knowledge gaps from the reviewed publications.

The body of research on both resilience and nexus thinking is substantial and extends over various research domains. This paper does not attempt to resolve all semantic dissonances or fundamental critiques surrounding both framings, nor does it aspire to provide a full coverage of resilience and nexus literature. Rather, it tries to help those interested in (applying) resilience and WEF nexus thinking understand the state of affairs in this growing body of literature and identify future avenues of research.

METHODS

A quick key word search in major scientific databases reveals the vast body of literature on resilience, with over 100,000 hits across all disciplines, of which more than 22,000 are in disciplines relevant to sustainability science. The WEF nexus literature, in turn, boasts over 1,000 peer-reviewed publications. While we provide a short overview on both concepts in "Characterizing the WEF Nexus" and "Characterizing Resilience" sections reviewing all resilience and nexus studies that have a bearing on water, energy, and food is beyond our scope. For our formal review of scientific publications, we

confined ourselves to those that explicitly conflate both domains. That is, we specifically examined the status quo on resilience thinking as it is applied in WEF nexus studies and selected only those scientific publications for review that explicitly make mention of both resilience and nexus concepts. The following criteria were used to define our pool of publications to be reviewed:

- The publication is included in the Web of Science or Scopus database;
- The publication is peer-reviewed (e.g., research articles, review papers, conference proceedings, books, and book chapters). Gray literature, although substantial, is excluded;
- The title, keywords or abstract of the publication include terms that relate to the WEF nexus, viz. “nexus” in combination with “water”, “food” or “agriculture”, and “energy” or “electricity”;
- The title, keywords or abstract of the publication include terms that relate to resilience thinking, viz. “resilient” or “transformative”;
- The publication is published between 2011 and 2020 (as the nexus was first coined in 2011 Hoff, 2011).

While this procedure, which was carried out in February 2020, results in a base set of publications, it may exclude other relevant ones. For example, adaptive capacity, robustness, and vulnerability are concepts often used in resilience thinking, but if not explicitly mentioned alongside resilience, these references are not captured in our search criteria. The same goes for bordering concepts from e.g., urban metabolism studies, sustainability science, systems thinking and political ecology (Dalla Fontana and Boas, 2019). Furthermore, because of this paper’s focus on water, energy and food, publications that include other nexus facets, such as climate (Chirisa and Bandaiko, 2015), soil (Hatfield et al., 2017), health (Mabhaudhi et al., 2016), and trade (Pastor et al., 2019), are not necessarily captured by the search. To at least partly overcome these shortcomings, the authors—who have a background in either a WEF domain or resilience discourse—cross-checked the list and supplemented where necessary from their own expertise. Hence, while we do not hold to the illusion that we are complete in reviewing all there is to say about resilience and the WEF nexus, we believe have included a substantial and representative proportion of the scientific literature.

The dataset thus obtained contained 166 publications. After an initial round of review, several publications were found to merely refer to resilience or the nexus in passing or as a general (buzz) word, rather than to the approach or the school of thought that these terms represent. Such publications were excluded from further scrutiny, so that the definitive set of publications that forms the basis for mapping the research landscape constitutes 43 documents (**Supplementary Material** provides an overview).

Given the conceptual dissonance around both approaches, we hypothesized that the research landscape would be highly divergent and heterogeneous. We therefore characterized the research landscape in order to structure our mapping exercise and provide clarity. Hereto, several key dimensions or

conceptualizations of both resilience and nexus concepts were distilled from a generic literature review on both schools of thought (see “**Characterizing the WEF Nexus**”, “**Characterizing Resilience**”, “**Spatial Scale and Case Study**” sections). Next, we developed a spreadsheet for data analysis to classify and map the selected publications accordingly (section “**Mapping the Research Landscape**”).

The analysis of the results of the mapping exercise led to a preliminary research agenda. Complemented by recommendations for further research mentioned in the reviewed publications themselves, we synthesized these findings and converged the long list of potential research avenues into five broad categories of further research opportunities.

RESILIENCE AND THE WEF NEXUS

Both resilience and nexus framings have a long pedigree and an active backing from scholarly communities. According to Al-Saidi and Elagib (2017), nexus thinking finds its origins in environmental policy studies and public debate on natural resources management, while resilience has precursors in science debates on sustainability and systems thinking. Nexus thinking was first conceived at the WEF (2011), and most authors identify the flagship publication by Holling (1973) as the onset of resilience thinking insofar it became relevant in a WEF nexus context. Where the essence of the nexus is the about interconnections between water, energy and food systems, resilience is about the capacity of a system to respond to threats and retain its ability to deliver benefits (Lawford et al., 2013; Grafton et al., 2016). Given the many excellent expositions that have been written on each concept already, we will refrain from repeating their findings here, and instead refer the reader to comprehensive and recent reviews on either the nexus by Ringler et al. (2013); Al-Saidi and Elagib (2017); Albrecht et al. (2018); Liu et al. (2018); Bleischwitz et al. (2018) or on resilience by Carpenter et al. (2001); Walker et al. (2006); Hollnagel et al. (2006); Folke et al. (2010); Béné and Doyen (2018); Moser et al. (2019). The next sections, rather, expound on distilling general characteristics that are shared or accepted within different (sub)fields or arenas of nexus and resilience research, respectively. They are summarized in **Table 1**.

Characterizing the WEF Nexus Scope of the Nexus

The first major dichotomy in nexus literature pertains to the interpretation, or scope, of the term nexus itself. The nexus can either be perceived (i.e., scoped) as a descriptive account of interactions and interdependencies between different natural resources *systems*; or it can be scoped as an *approach* that enables and supports transition across sectors and stakeholders in these systems (Howells et al., 2013; Howarth and Monasterolo, 2016).

The notion of the nexus as linked *systems* is found in Bleischwitz et al. (2018) and Dalla Fontana and Boas (2019), for example, who present the nexus as a term referring to context-

TABLE 1 | Characteristics of the WEF nexus and resilience literature, which are used to map the research landscape.

Concept	Dimension	Operationalisation
Nexus	Scope of the nexus Emphasis on nexus components Level of nexus integration	Approach, system Water, energy, food, equal WEF Incorporation, cross-linking, assimilation
Resilience	Scope of resilience Type of resilience Methodological focus Thematic domain Disturbance source Disturbance phase	Engineering resilience (ER), social-ecological systems (SES) resilience, transformation Specified, general Theorizing, building, measuring, modeling Infrastructure, policy, governance, social capital, investment, technology Internal, external Foresee, cope, recover
Both	Spatial scale Case study	Local, national, regional, global Yes, No

specific interlinkages between different natural resource systems, including water, energy and food. Stringer et al. (2018) elaborate this perspective as follows: “To explain the nexus in its simplest form, water is needed to generate energy, energy is needed to supply water, energy is needed to produce food, food can be used to produce energy, water is needed to grow food, while food transports (virtual) water, often using energy”. Note that we use the term *systems* to cover several more specific interpretations, such as the resources themselves, resource sectors, systems, or securities of resources. While we attempted to define the nexus scope at this higher level of granularity, we found that many studies fail to expound on their system interpretation or have ambiguous interpretations. In our scoring procedure, reviewed studies that scope the nexus as a *system* are thus taken to reflect all these underlying interpretations.

The notion of the nexus as an *approach*, in contrast, postulates that the nexus “identifies tradeoffs and synergies of water, energy and foods systems, internalizes social and environmental impacts, and guides development of cross-sectoral policies” (Albrecht et al., 2018). This nexus-as-approach notion is advocated as an advancement over current and often sector-specific governance of natural resources bridging the sectoral divides, or siloes, in mainly environmental policy integration (Hoff et al., 2019). Scoping the nexus as an approach thus not only acknowledges interlinkages that exist between WEF systems, but also includes systems thinking, considers different scales for problem solving, embraces complexity, and promotes participation in management and governance. It is this latter scoping that gave rise to the nexus as a frame for sustainability science, more than the former.

Emphasis on Nexus Components

While the WEF (2011) presented the nexus as an integrative framework for achieving WEF security, studies tend to emphasize either water, energy or food within the broader WEF nexus. For example, the early study by Hoff (2011) revolved mainly around water security, Villamor et al. (2020) emphasize the role of the energy system within the WEF nexus, and Ringler et al. (2013) food (as a resource and sector). Since nexus thinking has emerged from the water domain, it is often presented as a logical evolution from water-centric Integrated Water Resources Management (Allouche et al., 2015; Allouche, 2016). We therefore hypothesize that the water

component is particularly emphasized in the WEF nexus research landscape, despite its intended integrative scope (cf. Benson et al., 2015; de Loe and Patterson, 2017). Note that in studies that scope the nexus as linked systems, nexus components may refer to inputs (water, energy, or food resources as input to achieve some other goal), as output (e.g., WEF security) or both. Since this focus is often implicit or ambiguous, reviewed studies that emphasize nexus components are taken to reflect any of these foci in our scoring procedure.

Level of Nexus Integration

A third nexus dimension identified in literature is the level at which components of the WEF nexus are integrated. While nexus studies often mention the importance of integrating water, energy and food systems, there is no consensus on what integration means. Al-Saidi and Elagib (2017) distinguish three levels of integration: *incorporation* is the most holistic view on the nexus that tries to describe and quantify as many interactions between the three resources as possible. Since incorporation implies an equal importance of the water, energy, and food concerns in the nexus, it is expected to be found in macro-level studies (e.g., high-level policy formulation, resource allocation and strategic investments). *Cross-linking* focuses on capturing specific interlinkages, mostly between two nexus components faced with major or priority issues. Examples include trade-off analyses between food and energy issues. Finally, *assimilation* implies looking at the nexus from the perspective of one specific sector while considering the links to other sectors. Assimilation tends to purport the view of sectoral or operational managers attempting to include other WEF components' concerns in their strategies.

Another way to understand the level of integration is presented by Gragg et al. (2018), where WEF systems are either unconnected or siloed; interconnected or linked; or interdependent and nested. The interconnected and interdependent systems categories seem to overlap with the cross-linking and incorporation levels postulated by Al-Saidi and Elagib (2017), respectively.

Characterizing Resilience

Key characteristics of resilience framings distilled from literature include its scope, type, methodological focus, thematic domain, and the source and phase of perceived disturbances.

Scope of Resilience

More than on the nexus, resilience literature sketches an image of a magic word with a wide spectrum of interpretations and diverse formulations across disciplines (Moser et al., 2019). While this conceptual dissonance allows for multiple valid characterizations, the first major dimension we identify here is the differentiation in scoping resilience.

Early resilience literature often uses the metaphor of a stability landscape, where resilience is a measure of the persistence of a system and of its ability to absorb change and disturbance while it remains in its basin of attraction (Holling, 1973). Cumulative disturbances may at some point move the system over a threshold of the current basin of attraction, thus bringing it into another, possibly undesirable domain (Gunderson and Holling, 2002). Resilience of the system, then, depends on the maximum amount of change tolerable within the basin of attraction (known as latitude), the ease of changing (resistance), the closeness of system thresholds (precariousness), and cross-scale interactions (panarchy) (Walker et al., 2004). While resilience encompasses the whole stability landscape, different fields emphasized different stability aspects. Specifically, when the behavior of the system in the neighborhood of an attractor within a given domain of attraction is of interest, resilience is understood as engineering resilience; when changes in the state of the system between different domains of attraction, but within the stability landscape of the system are of interest, we speak of social-ecological systems (SES) resilience; and when changes of the stability landscape are of interest, resilience is scoped as transformation (Gallopin, 2006).

Engineering resilience focusses on the speed of return to an equilibrium state after a disturbance, maintaining efficiency in the face of change, and resisting shocks to conserve system functioning (Holling, 1996; Walker et al., 2004; Folke, 2006). It is the most practical scoping of resilience that, as the name implies, is prevalent in the engineering sciences. Note that engineering resilience, while easily confused, is not the same as resilience engineering. Resilience engineering is a related concept that refers to a specific sub-field of safety research on failures in complex (engineered) systems, and aims to maintain system functioning while preventing harm to persons (Hollnagel et al., 2006; Righi et al., 2015; Provan et al., 2020).

SES resilience evolved more comprehensively as engineering resilience, focusing on a system's persistence, resistance, recovery and robustness, and acknowledging that multiple equilibria or stability landscapes exist (Grafton et al., 2019). It also underscores the importance of developing or maintaining adaptive capacity, learning and innovation potential in a system, in the context of integrated system feedbacks and cross-scale dynamic interactions (Walker et al., 2002; Anderies et al., 2004; Walker et al., 2004). In their citation network analysis, Baggio et al. (2015) found that SES resilience has become an important bridging concept in the interdisciplinary field of SES science.

Resilience as transformation can be viewed as an extreme yet distinct form of SES resilience. A resilient SES operates within a stable landscape where it can cope with minor disturbances. However, if shocks are too severe, a boundary is crossed (viz.

a tipping point reached), resulting in a sudden or gradual transformation of the system into another stability landscape (Rockström et al., 2009; Guillaume et al., 2015). Transformation may imply dealing with risks of unwanted landscape change, but a good share of literature focusses on preparing for opportunity or creating conditions of opportunity for navigating the transformation as well (Scheffer et al., 2012; Béné and Doyen, 2018). Transformations typically take place over longer timescales of decades to centuries (Anderies et al., 2013).

Clearly, there are alternative characterizations to the three-fold scoping of resilience presented here. One such alternative with a strong analogy to the above is by Béné and Doyen (2018), who characterized resilience along a continuum of five degrees of changes allowed to the dynamics of the system at hand. The continuum starts with resilience as resistance, aimed at stability and avoiding system change; coping, aimed at absorption and buffering; adaptation, aimed at flexibility; adaptive preference, aimed at adjustment and changing expectations; and finally, transformation, aimed at changing the structure of the system.

Type of Resilience

The second characterization of resilience is—for the lack of a better term—the type of resilience. Authors may either deal with specified or general resilience. As particularly SESs can become extremely complex, a logical question arises: resilience of what to what? When the answer to this question is clear, this is referred to as specified resilience: it relates to a particular part of a system, a particular control variable within the system, and/or one or more identified kinds of shocks (Carpenter et al., 2001; Folke et al., 2010). Specified resilience therefore requires a careful definition of the system boundaries (Anderies et al., 2013).

In contrast, general resilience refers to any and all parts of a system to all kinds of shocks including novel ones (Folke et al., 2010). It focusses on broader system-level attributes such as the ability to build and increase the capacity for learning and adaptation (Walker et al., 2006). General resilience thus evaluates the effect of factors that affect resilience in SESs, such as (but not limited to) the presence of reserves, redundancies, diversity (of WEF sources), connectivity and modularity of trade networks, social capital, and adaptive governance structures (D'Odorico et al., 2018). By implication, general resilience studies are typically less careful about system definitions, nor about what resilience entails in practice (Anderies et al., 2013).

Methodological Focus

The next differentiating dimension we observe in resilience literature relates to the methodological focus of the research. We distinguish between studies which primarily focus on theorizing, building, measuring, or modeling resilience. The first focus, labeled theorizing, strives mainly to further the conceptual or theoretical understanding or underpinning of resilience, often perceiving resilience as an emergent system trait. Studies that focus on building resilience, in contrast, are primarily concerned with how to develop or design resilient systems. They often have a normative stance toward resilience, and adopt a management or governance perspective (cf Quinlan

et al., 2016; Sellberg et al., 2018). Measuring and modeling studies are more technical in nature and self-explanatory. These four categories are not necessarily mutually exclusive and may overlap. For our review of the pool of publications (**Mapping the Research Landscape**) we tried to select the dominant methodological focus of each publication.

Thematic Domain

Many potential categories exist to describe thematic domains. Quinlan et al. (2016), for example distinguishes between studies focusing on the resilience of a system (e.g., a WEF system) vs. on the resilience of the governance of the system. Pahl-Wostl (2009) splits out resilience governance and management, where the former refers to the social and political process of defining goals for the management of a system, and management as the practical actions taken to achieve these goals. Biggs et al. (2012) address the importance of studying the role of institutions (focusing on building knowledge, incentives, and learning capabilities into institutions and organizations, (cf Folke (2006)), policy, and social capital (including educating and building skills in people, cf Nelson et al. (2007).

We identify infrastructure, (operational) policies, governance (including stakeholder and institutional considerations), social capital (including learning and capacity building), investment and technology (including technological innovation) for resilience as main thematic domains.

Disturbance Source

Another discriminator is the source of the disturbance that is envisioned—if applicable. We differentiate between studies that frame disturbances as originating from within the system—and which are thus an intrinsic part of the defined system and its dynamics—vs. those that identify a disturbance as external to the system. Especially in the latter case, shocks are often assumed uncontrollable, whereas with internal shocks part of the resilience to that shock might lie in altering the system or its variables such that the shock itself is mitigated in conjunction to mitigation its impact on the system.

Disturbance Phase

The last resilience related characteristic that we identified is the phase of the disturbance or shock. We distinguish between studies that identify disturbances as something that is foreseen (to potentially happen in the future), to cope with (in the present) or to recover from (after the shock has happened) (Hollnagel et al., 2006). A similar differentiation by Shin et al. (2018) identified a system's adaptive capability, withstanding capability (mainly relevant for disturbances that are foreseen), adsorptive capability (to cope with present shocks) and restorative capacity (to recover from shocks). The disturbance phase also has a bearing on which phase of the adaptive cycle the system is in—its exploitation, conservation, release or re-organization phase (Holling, 2001).

Spatial Scale and Case Study

Both for characterizing the WEF nexus and resilience, the spatial scale of assessment is important and differs across studies.

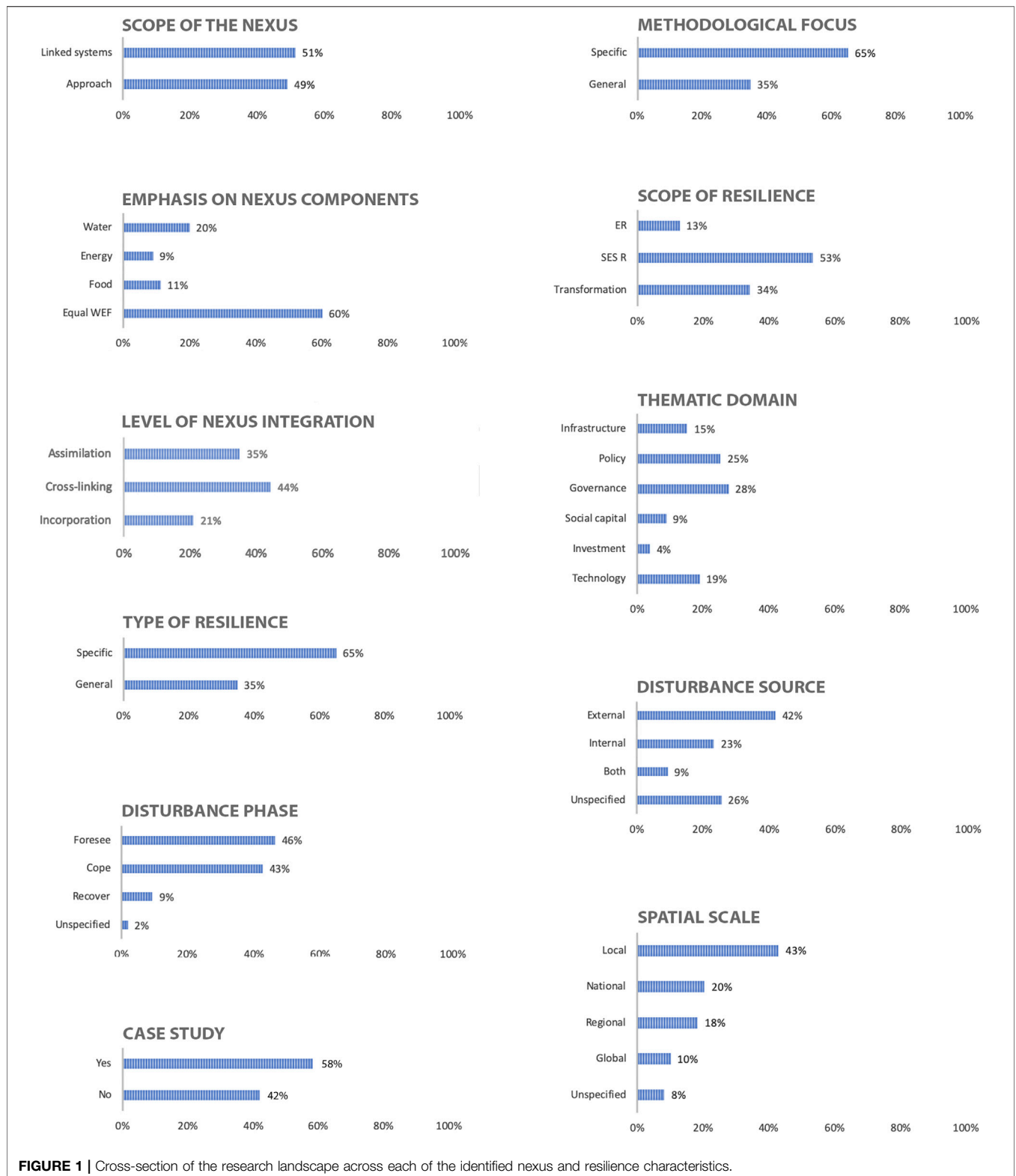
Especially for SES resilience and transformation, cross-scale dynamics and interactions with both lower and higher-level systems imply that resilience at one level of assessment may affect resilience in other levels (Holling, 2001; Gunderson and Holling, 2002). If the system is relatively small or narrowly defined, there is a risk of getting stuck in a particular domain of attraction and missing context; if, in contrast, the system is exceedingly large (e.g., the Earth System), complexity may be overwhelming and moreover—if that is part of the objective—management or governance decisions are typically not made at this level (Musters et al., 1998). The spatial scale (or grain) of the study thus matters and differs across current literature. We distinguish between local (meaning sub-national), national, regional (meaning supra-national) and global scales of assessment. Since spatial scale often becomes evident from case studies, we checked reviewed publication on the presence or absence of a case study as well.

Mapping the Research Landscape

Our scoring of reviewed publications that conflate nexus and resilience concepts reveal that half the studies scope the nexus as a connotation of linked water, energy, and food systems, while the other half scopes the nexus as an approach (**Figure 1**). If studies place more emphasis on one WEF component over the others (40%), it is on the water component (20%). This could be explained by the roots of the nexus originating from the water space. Most publications, however, treat the nexus as an integrated whole, placing equal emphasis on water, energy, and food components in their research (60%). In terms of the level of integration, however, we find that the highest level (i.e., incorporation) is only adopted by 21% of the publications. Coles and Hall (2012), for example, provide a clear overview of what such incorporation can entail in a WEF security context.

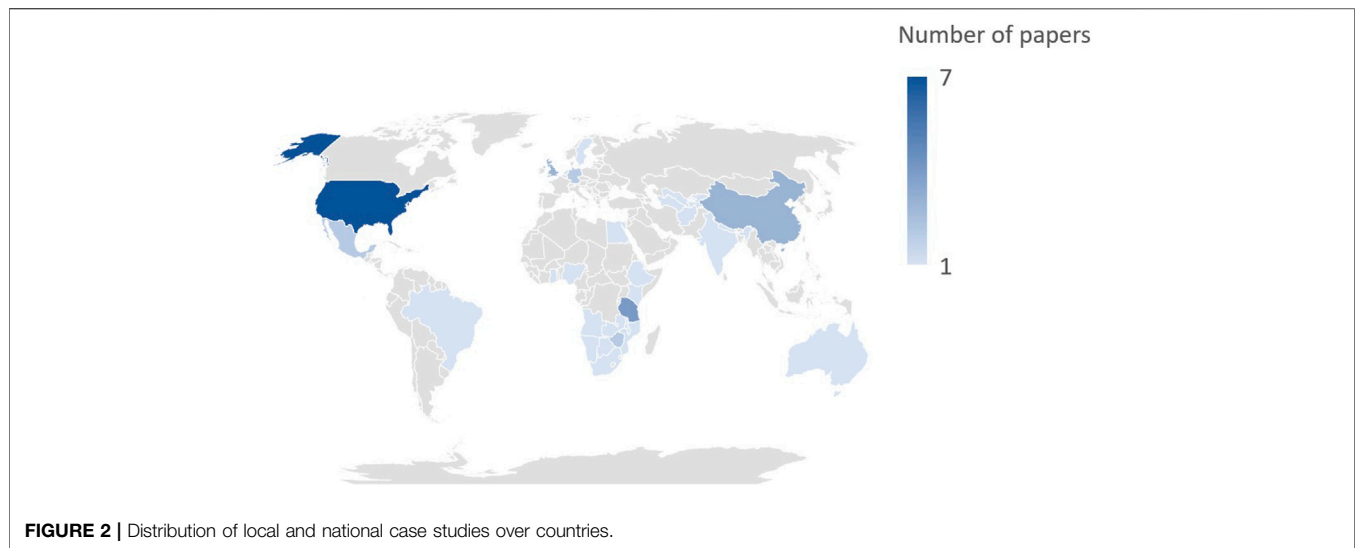
Most publications scope resilience as some form of SES resilience (53%), vs. 13% on engineering resilience and 34% on transformation. Typical examples of SES resilience can be found in the study by Gragg et al. (2018)₂, who set out to generate environmental, social as well as economic perspectives and practices on rapidly urbanizing food systems, while identifying key drivers and their cross-scale interactions across the urban WEF nexus; of engineering resilience in Ajami et al. (2008) who developed a hydrological reservoir model and indicated the recovery speed of the system from a state of failure, considering a range of rules on how to operate the reservoir; of transformation in Hoolohan et al. (2019) who built scenarios that capture complexity and multidimensionality of changes across the WEF nexus in order to facilitate transformative action.

Two-thirds of the publications deal with specified resilience ('of what to what') and one-third with general resilience. With regards to specified resilience in a nexus context, Jarvie et al. (2015) provide an example in studying resilience of USA farming system to a clearly identified shock, i.e., disturbed phosphorus cycles. McCormick and Kapustka (2016) elaborate on general resilience in a nexus context, arguing to ask resilience-related questions when evaluating alternative environmental policy options, regardless the environmental issue or shock of concern.



Regarding the methodological focus, 37% of the reviewed publications focus on conceptualizing or developing theory on resilience in a WEF nexus context. Thirty per cent of studies aim at building or managing for resilience. Fewer studies

model (20%) or measure (13%) resilience. Representing modeled resilience, Govindan and Al-Ansari (2019) presents a computational framework that incorporates ‘algorithmic resilience thinking’ toward adaptive and robust WEF



systems. Regarding measuring resilience, Dal Bo Zanon et al. (2017) measured resilience in terms of the amount of nutrients that could be recycled, in their study evaluating the contribution of floating systems that produce algae, food and biofuel to resilience of urban areas.

Divisions across thematic domains reveal that most publications are in the governance (28%) and policy (25%) domains, followed by technology or innovation (19%) and infrastructure (15%). Social capital, which includes learning and capacity building, is a major topic in 9% of the publications. Only three studies (4%) deal with investment, including Al-Saidi and Saliba (2019)'s study on investments mitigating (WEF) resource supply risks in the Gulf region and Bennett et al. (2016)'s study into the general role of investments in both engineered and natural infrastructure to increase resilience of WEF systems. These findings depart from those of generic WEF nexus review studies by, among others, Albrecht et al. (2018), who found that studies focusing on governance and policy are underrepresented. The difference may be explained by the prevalence or importance of adaptive governance in resilience studies, skewing the thematic distribution of the nexus-resilience sub-section of WEF nexus literature.

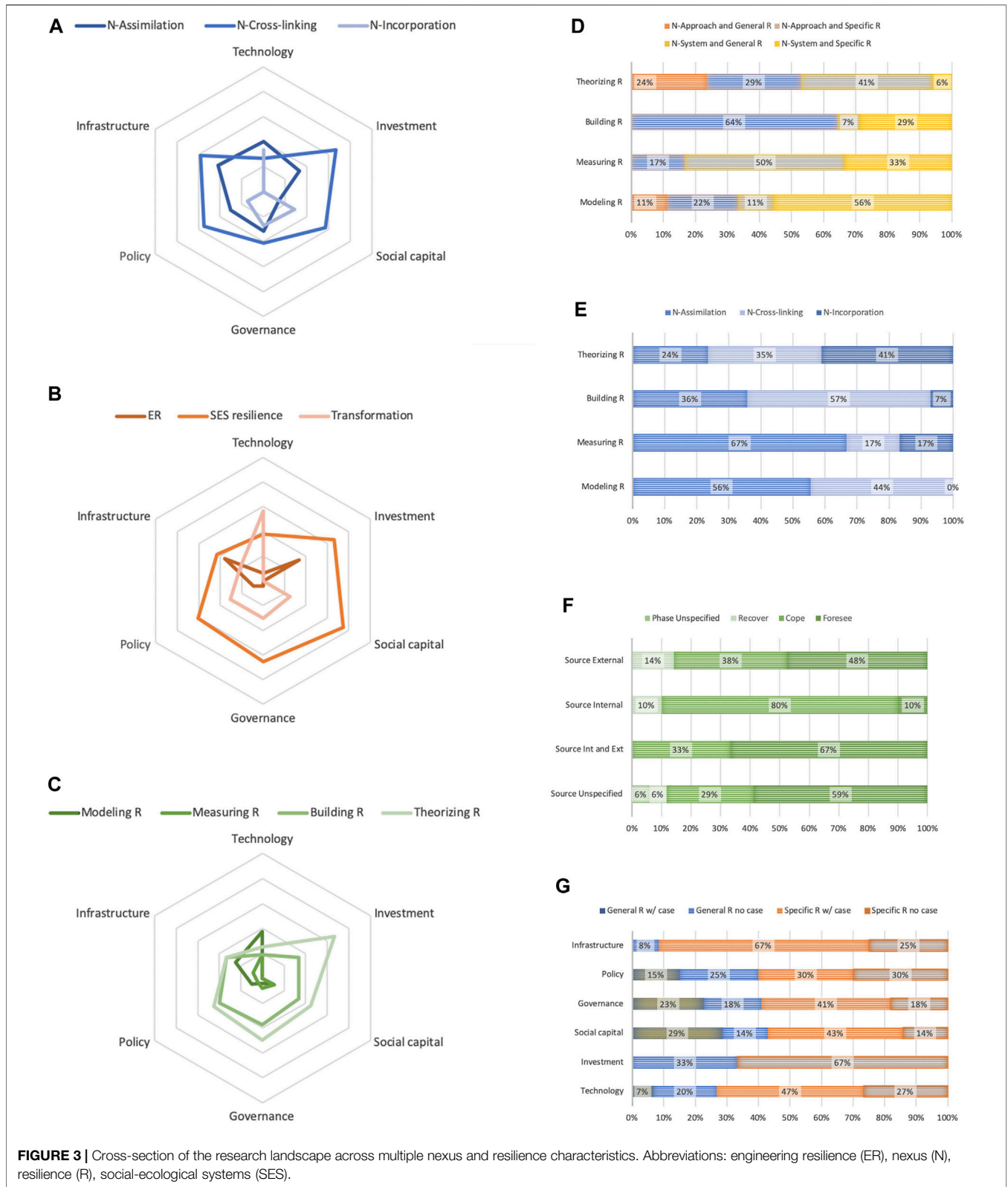
In terms of the source and phase of disturbances against which to build, manage, understand, measure or model resilience, most studies that specify the disturbance (74%) identify it as external (42%). Typically listed external shocks are climate change (and related disturbances such as altering rainfall patterns, weather volatility and droughts, see e.g., Adegun et al., 2018); resource supply limitations including water, nutrients and land (e.g., Keairns et al., 2016); and migration (e.g., Lambert et al., 2017). Some authors internalize shocks that are perceived as external by others, such as Schreiner and Baleta (2015) does with variability in resource supply. Other typical internal disturbances are habitat loss (e.g., Githiru et al., 2017) and urban transformation (e.g., Rohrer and Kohler, 2019). Most studies anticipate foreseen disturbances (46%) or cope with present disturbances (43%). Nine per-cent of studies focusses on recovering from shocks

suffered in the past, such as soil erosion in a study by Blake et al. (2018).

The local scale is targeted in 43% of the publications, while 20, 18, and 10% of the studies focus on the national, regional, or global scale, respectively. A case study is included in 58% of the publications investigated. **Figure 2** highlights the countries in which either local or national case studies are located, or which are explicitly mentioned as locality of interest. Eighteen of 48 reported case studies refer to Africa, four of which to Tanzania. Seven studies focus on the USA, three on the United Kingdom and three on China. Not listed in **Figure 2** are regional studies, which in our pool included Europe, the Gulf region, West Africa, Southern Africa, and Asia.

Figure 3 shows cross-sections of the research landscape across combinations of some of the characteristics discussed individually above. Combining the resilience thematic domain and the level of nexus integration, we find that most thematic domains adopt a cross-linking level of integration of the WEF nexus (**Figure 3A**), accounting for 41–67% of each domain's studies, except for technology (27%). Examples are Allan et al. (2013) for the policy domain and Al-Saidi and Saliba (2019) for the investment domain. Assimilation is prevalent in most domains as well (30–42% of studies across domains), but to a lesser extent in the social capital domain (14%). No studies in the investment and infrastructure domains integrate the nexus at the highest level of *incorporation*.

Combining the scope of resilience with thematic domains reveals that SES resilience (**Figure 3B**) is the most common scoping for policy, governance, social capital and investment studies (61–75%), such as those by Blake et al. (2018), Givens et al. (2018) and Howarth (2018). Technology or innovation studies, on the contrary, are most interested in resilience as transformation (56%), e.g., Florentin (2019) and Song et al. (2019). Not surprisingly, infrastructure is most often the topic of engineering resilience studies (36% of infrastructure studies adopt an engineering resilience scope), such as in the studies by He et al. (2019) and Karan et al. (2019).



The comparison of the methodological focus with the thematic domain of resilience studies (Figure 3C) reveals that infrastructure studies chiefly model (25%) or build (33%) resilience, e.g., Amjath-

Babu et al. (2019) and Haupt (2019); studies in the policy and governance domains theorize (45 and 50%, respectively), e.g., Uden et al. (2018) and Karlberg et al. (2015) or build resilience (40 and

38%, respectively), e.g., Mpandeli et al. (2018) and Antwi-Agyei et al. (2018); social capital and investment themed publications theorize about resilience (44 and 67%, respectively), e.g., Givens et al. (2018); and technology focused research mainly models (38%), e.g., Johnson et al. (2019) or measures resilience (19%), e.g., Schlor et al. (2017).

Figure 3D starts from the methodological focus and intersects this dimension with the scope of the nexus and resilience type. We learn that theorizing studies mostly deal with resilience of the general type and the nexus scoped as a system (41%), e.g., van Vuuren et al. (2015). Studies set out to build resilience, on the other hand, mostly build resilience ‘of something to something’—i.e., specified resilience—while taking a nexus approach (65%), e.g., Pardoe et al. (2018). The lion’s share of resilience measuring and modeling studies interpret the nexus as a system, irrespective of the resilience type, e.g., Schlor et al. (2018).

Taking again the methodological focus as a basis and comparing it across the level of nexus integration, **Figure 3E** shows that 41% of studies theorizing resilience assume a high level of nexus integration. This share is much lower for resilience building (7%) and measuring (17%) studies, and even nil in resilience modeling studies. In these latter categories, nexus integration is mostly at the level of cross-linking (building resilience, 57%) or assimilation (measuring resilience (67%) and modeling resilience (56%)). This could be explained by the observation that theorizing studies typically emphasize the complexity of the systems they investigate—a complexity most often found at higher levels of nexus integration (cf. Scott et al., 2018). More pragmatic resilience measuring and modeling studies, in contrast, generally need to simplify systems to make them manageable. This seems to be more feasible for lower levels of nexus integration (cf. Gomo et al., 2018 and Namany et al., 2019).

With regards to the intersection of source and phase of the disturbance(s), **Figure 3F** illustrates that there is just a small percentage of studies that specify neither source nor phase (6%)—which could be expected particularly for general resilience type studies. Authors that identify a disturbance externally typically try to cope with this disturbance in the present (38%) or anticipate this disturbance to potentially happen in the future (48%). Internally identified disturbances, in contrast, overwhelmingly occur in the present (80%) where attempts are made to cope with (and adapt to) them.

Figure 3G revisits the thematic domain once more, but in this instance in combination with the type of resilience, and whether the publication includes a case study. We learn that few domains employ general resilience in combination with a case study (policy domain 15%, governance 23%, social capital 29%), e.g., Gragg et al. (2018) and Uden et al. (2018). In contrast, studies that focus on specified resilience by and large do have a case study across domains, particularly in the infrastructure domain (67%), e.g., Romero-Lankao et al. (2018).

TOWARD A RESEARCH AGENDA

Mapping the research landscape demonstrates that not every dimension of resilience and nexus research has received equal attention. The landscape thereby lays bare potential knowledge gaps that may warrant further scrutiny. The reviewed publications also provide recommendations for future research

but given the divergence of the research landscape these recommendations are often context and project specific. At the risk of overgeneralizing, we identified the following five research avenues through synthesizing landscape lacunas and publication’s recommendations. **Table 2** presents an overview of example research questions per line of inquiry.

Improving the Understanding of Resilience Across the WEF Nexus

When Holling (1973) introduced resilience thinking, he studied the resilience of fish levels in a lake to fishing. Translated to our analysis, he studied specified resilience of a local, siloed water-food (sub-)system to an external disturbance. Deliberating the implications for larger, more complex systems, he wondered if we were ever able to see beyond the boundaries of local domains of attraction and understand the configuration of forces caused by both positive and negative feedback relations. This would “require an immense amount of knowledge of a system and it is unlikely that we will often have all that is necessary” (Holling, 1973). While many studies since have shed light on the matter, there is still a clear need to better grasp resilience in the WEF nexus.

First, there is a need to better understand the WEF nexus dynamics itself. As Leck et al. (2015) warned, siloed WEF systems are already complex to assess, let alone taking a nexus perspective or applying resilience thinking. The study by Guillaume et al. (2015) illustrates this cross-system complexity in a case from Central Asia, where they observed that changes in the water system were mainly driven by interventions in other systems, such as the loss of ecosystems. They therefore stress the importance of paying close attention to which (sub-)systems to include or exclude from any nexus assessment, and what boundaries to assume.

A second opportunity lies in better understanding the place of resilience thinking in these cross-system WEF nexus dynamics. A popular yet partial means to obtain insights on resilience of cross-system dynamics is to study synergies and tradeoffs between WEF systems (Jarvie et al., 2015; Cader et al., 2016; Deryugina and Konar, 2017; He et al., 2019). However, most of these assessments consider synergies and tradeoffs only between subsystems within the larger WEF nexus and overlook cross-system resilience linkages. Grafton et al. (2016), for example, show how increasing food production resilience may (unbeknownst to the managers) erode the resilience of water systems. This indicates a niche for more comprehensive cross-sectoral investigations, taking a broad scope of resilience across a well-defined nexus.

Third, insights may be gained by including a broader set of thematic domains. Our characterization of the research landscape also found that most studies focus on one or two thematic domains, and do not account for developments, incentives or dynamics in other domains. de Loe and Patterson (2017), for example, observed that although resilience thinking pays attention to external drivers such as climate change and teleconnections, it remains unclear to what extent water resilience accounts for connections between water and other sectors, since studies tend to emphasize processes that are internal to water governance over external connections that can influence water governance. In another study, investigating

TABLE 2 | Overview of example research questions per identified research avenue.

Research avenue	Example research questions
Improving the understanding of resilience across the WEF nexus	<p>How much water and land is needed to produce food and energy for all by 2050?</p> <p>To what extent will renewable energy mixes based on biomass affect resilience of water provision and food production systems?</p> <p>How can policies that promote health and nutritional diets concurrently reduce carbon and water footprints, by advising foodstuffs with low associated energy and water use/pollution?</p> <p>To what extent are international and interprovincial trade networks reflective of local WEF scarcity/insecurity levels?</p> <p>How can short-term disturbances such as droughts, crop pests and animal diseases, act as a catalyst for long-term WEF system transformation?</p> <p>How can (inter)national funding organizations support interdisciplinary research lines across the broad resilience/WEF nexus spectrum to boost collaboration on holistic projects?</p>
Tools and indicators	<p>Which indicators can express resilience of urban WEF systems and what are their constraints for applicability in urban planning?</p> <p>To what extent can agent-based modeling techniques capture resilient behavior patterns of smallholder farmers in WEF nexus simulations?</p> <p>How can remote sensing techniques measure and monitor resilience of WEF nexus systems over large spatial and temporal scales?</p> <p>Which forms or platforms of data collection and sharing fit best with general practices currently used in water, energy, and food domains?</p>
Bridging the implementation gap	<p>How can examples of successfully negotiated bilateral treaties on sharing proceeds of offshore wind parks inspire transboundary water pricing and sharing?</p> <p>What is the role of financial institutions in building resilient WEF systems and to what extent do their investment policies hamper or hasten implementation of resilient WEF projects?</p> <p>Which institutional structures facilitate experimentation and learning in local waterboards who have indirect responsibilities for energy and food systems?</p> <p>What are best practices of governing for resilience in local WEF systems in public private partnerships?</p> <p>What further lessons can resilience and WEF nexus scholars learn from systems thinking and integrated assessment?</p>
Integrating resilience and nexus thinking	<p>In which contexts (e.g., environmental policy, risk management, security studies) would a shared resilience-nexus thinking heuristic be advantageous and which key elements of each school of thought would such a heuristic include or exclude?</p> <p>To what extent can resilience and WEF nexus thinking help achieve the UN's Sustainable Development Goals (most notably SDGs 2, 6 and 7 on food, water, and energy, respectively)?</p>
Beside and beyond resilience	<p>In promoting resiliency, how are social, environmental, and economic costs incurred by diversifying national WEF sources (e.g., by building a hydroelectric dam) distributed fairly over stakeholders?</p> <p>What different WEF outcomes can be expected when policymakers and practitioners in natural resources management would focus solely on building resilience vs. on improving efficiency, sustainability, or equity as a guiding development principle?</p>

risks of climate extremes to WEF security in cities, Romero-Lankao et al. (2018) stress the need to consider the role of technology in mitigating impacts, while Uden et al. (2018) warn in their study on transforming agricultural landscapes that neglecting considerations from financial, technological and policy domains may create unsustainable feedbacks between WEF systems. These cross-domain feedbacks may form so called rigidity traps, which impede transformation by locking the nexus into an undesired trajectory. However, these traps are typically ill-understood. Insights from resilience thinking, which emphasizes cross-domain feedbacks and dynamics, might help analyze and avoid such traps.

Fourth, we identify a knowledge gap pertaining to cross-scale dynamics, or panarchy. One of the key lessons from resilience thinking is that we need to understand the implications of cross-scale dynamics or interventions that operate at different scales for the system as a whole (Anderies et al., 2013). In fact, even the nature of the challenges under investigation depends on the scale of the assessment. However,

our mapping of the research landscape reveals that many studies—both regarding the scope of resilience and the level of nexus integration—largely overlook this spatial multi-dimensionality. These findings resonate with other observations. For instance, Florentin (2019) found that cross-scale dynamics of municipal (energy) utilities in Germany are insufficiently accounted for. Meyer (2020) argued that studies on resilience of food systems in low- and middle-income countries are largely concerned with primary production only, mostly quantify resilience at the global scale while failing to quantify resilience at the regional scale. Falkenmark et al. (2019) called for further research to understand how the erosion of water resilience at local and regional scale may potentially interact, cascade, or amplify through networks of the Anthropocene.

Fifth, we highlight a knowledge gap relating to resilience scoped as transformation. Despite our finding that one third of the reviewed publications interprets resilience as transformation (Figure 1), most studies remain shallow in

their assessment, and, moreover, are not always explicit about the system whose transformation they seek to study. These observations echo similar concerns by early studies on resilience as transformation by Folke et al. (2010) and more recently by D'Odorico et al. (2018). Transformation often implies interventions be made in WEF systems; hence it is important to understand how these interventions (e.g., policies aiming to reduce trade-offs) will modify system dependencies. These modified dependencies may create new, perhaps unforeseen, trade-offs (Guillaume et al., 2015; Tu et al., 2019).

To capture the required holistic perspectives listed above, interdisciplinary collaboration across WEF sectors should be improved. Clearly, the level of nexus integration matters, as assimilation requires fewer interdisciplinary connections than incorporation does. However, our analysis of the research landscape shows that few studies employ the highest level of nexus integration (incorporation, **Figure 3A**), which may be a consequence of limited collaboration across relevant disciplines. It has been noted that collaboration is still hampered by fundamental gaps between the evidence bases of different disciplines, not in the least due to differences in conceptualizing resilience (de Grenade et al., 2016; Howarth and Monasterolo, 2016; Blake et al., 2018).

Tools and Indicators

“Measuring resilience is essential to understand it” (Pimm et al., 2019). However, developing tools and indicators to measure, monitor, model and evaluate resilience in the WEF nexus remains as an under-represented theme in the current research landscape. This observation can be explained partially by the complexity of both concepts, which makes it difficult (if not impossible) to capture resilience in the nexus using a limited number of methods and indicators (Quinlan et al., 2016; Hoekstra et al., 2018). Conceptual variations and subsequent differences in operationalization of both concepts are another potential explanation for this research gap (Givens et al., 2018).

Several tools—meaning methods, models, and frameworks—are being developed to overcome this gap. We identify two directions of development. The first is the development of tools to improve the understanding of cross-sector, cross-scale, cross-domain, and complex dynamics. Proposed examples are scenario building (e.g., Hoolohan et al., 2019), trade-off analysis (e.g., Cader et al., 2016), integrated assessment modeling (e.g., Johnson et al., 2019), environmental footprinting (e.g., Vanham et al., 2019; Hogeboom, 2020) and agent-based modeling (e.g., van Voorn et al., 2019). The second direction is to develop tools and methods that support more consistent policy formulation. Examples include decision-making frameworks and mixed method approaches (e.g., Knox et al., 2018; Namany et al., 2019), and participatory, stakeholder and networking methods (Karlberg et al., 2015; Hoolohan et al., 2019).

Despite ongoing developments, it remains unclear which tool can be applied in which resilience or nexus context. In this regard, Zhang et al. (2018) made a preliminary effort by identifying eight nexus modeling approaches and providing guidance on their selection within appropriate nexus settings.

Another open question is to what extent these tools can potentially be scaled-up, used in conjunction, or be integrated. A recent study by Vinca et al. (2020), for example, presents a new open modeling platform that integrates multi-scale nexus resource optimization with distributed hydrological modeling, and “provides insights into the vulnerability of water, energy and land resources to future socioeconomic and climatic change and how multi-sectoral policies, technological solutions and investments can improve the resilience and sustainability of transformation pathways while avoiding counterproductive interactions among sectors.”

Broadly accepted indicators for resilience are rare, as are those that pertain to the WEF nexus. Some examples in our pool of reviewed publications are the Nexus City Index and the WEF nexus index (Schlor et al., 2018, 2017), and an event-specific resilience measure for WEF infrastructure (Lambert et al., 2017). Caution is warranted, however, in developing overarching indicators. As Quinlan et al. (2016) observes: “Measuring and monitoring a narrow set of indicators or reducing resilience to a single unit of measurement may block the deeper understanding of system dynamics needed to apply resilience thinking and inform management actions.”

Finally, many authors point out that even if tools and indicators are available, challenges remain in data availability and collection options (Coles and Hall, 2012). More efforts are thus needed to collect data across studies and to develop new approaches that facilitate data collation and sharing.

Bridging the Implementation Gap

Many scholars critique the lack of practical application of both nexus and resilience thinking (particularly pertaining to SES resilience and transformation) (Bizikova et al., 2013; Sellberg et al., 2018). Our mapping exercise supports the argument that there is a divide between two major types of studies. On the one hand, practice-oriented building, measuring and modeling studies often employ specified (engineering) resilience of a particular (local) nexus system to a known disturbance, showcased by a case study. On the other hand, theoretical studies on general (SES) resilience embrace the complexity of WEF systems incorporated across scales, but they lack practical grounding.

Identified barriers to implementation of the nexus as an approach and higher levels of nexus integration are similar to those listed for practical uptake of resilience thinking. Barriers include a lack of data, knowledge and observability that match the level of complexities involved (Gomo et al., 2018); physical challenges of managing resources over a large area (Schreiner and Baleta, 2015); and a lack of public and private investments (GARI, 2016; Howarth and Monasterolo, 2016).

Most often, however, governance is underscored as impeding factor for practical uptake of resilience and nexus thinking. Reported barriers include institutional contexts that hinder flexibility, experimentation, learning and collaboration (Dietz et al., 2003; de Loe and Patterson, 2017); a lack of coordination among institutions and agencies, both across scales and across domains (Antwi-Agyei et al., 2018; Stringer et al., 2018); issue prioritization that is missing or left to

policymakers' ad hoc choices (Al-Saidi and Elagib, 2017); lacking examples of best practices to take as an example, particularly for commercial applications (Keairns et al., 2016); and an absent heuristic for resilience management (Grafton et al., 2019). Given these barriers, Weitz et al. (2017) advocate to develop shared principles to guide trade-off negotiations and to emphasize that policy coherence be viewed as a learning process rather than as an outcome. Both governance and non-governance barriers to implementation, however, are challenging and not easily overcome.

Integrating Resilience and Nexus Thinking

We started this study by presenting resilience and nexus thinking as two promising frames to help deliver on the grand development challenges of reaching WEF security for all while sustaining that security under threats. In the diverse research landscape that conflates the two schools of thought, we observed a pronounced distinction between the starting frame scholars assumed for their assessment. Some—particularly but not exclusively those involved in public policy debates—assumed a nexus approach, which they applied to enhance (specified) resilience of linked WEF systems (e.g., Pahl-Wostl, 2019). Others, on the other hand, started from a (predominantly academic) resilience perspective, in which water, food and energy systems happened to be the (SES) arena where adaptations and transformations take place (e.g., Uden et al., 2018).

While historical developments in different research arenas, conceptual variations, and personal preferences can explain why some authors start from a nexus and others from a resilience frame, we also observed a great deal of overlap in the concepts and ideas employed in both schools of thought. This is particularly the case for studies that scope resilience as SES resilience or transformation and the nexus as an approach with a high level of integration. Elements common to both the nexus and resilience thinking are the application of systems thinking, taking an integrative management perspective and considering complex dynamics across scales, domains and sectors (cf Al-Saidi and Elagib, 2017). Also the notion of enhancing security against shocks or risks appear to be a common connection between nexus and resilience discourses (cf Al-Saidi and Saliba, 2019). Given these similarities, a sensible question is to what extent the two frames could or should be integrated or mutually embedded (cf Grafton et al., 2016; de Grenade et al., 2016; Scott et al., 2018).

Research addressing the integration question can for example investigate areas in which greater mutual interaction could provide enriched insights (Howarth and Monasterolo, 2016). Beck and Walker (2013), for example, distilled lessons from resilience thinking to be applied in nexus debates, including the need to increase diversity, and tolerating soft redundancies and inefficiencies of function within a system. How this translates to practice, however, is yet unclear. Another question is to what extent embedding resilience thinking in nexus thinking will change to role of e.g., systems thinking, or the current emphasis on water as first among equals (Figure 1).

Alternatively, investigations can look into fully merging the two frames. The most comprehensive attempt to our knowledge is by Stringer et al. (2018). Their integrated nexus-resilience thinking framework highlights three principles: unpack,

traverse, and share. Here, unpack refers to unpacking relationships and interactions in SESs to better understand and structure (WEF security related) issues; traverse refers to traversing temporal and spatial scales, sectors, stakeholders, and ways of knowing to detect nonlinear dynamics and unpredictable outcomes; and share refers to sharing knowledge, learning, and experience to empower stakeholders involved.

Beside and Beyond Resilience

Studies that build, model or measure resilience in the WEF nexus by and large take a normative stance toward the concept of resilience, portraying resilience as a desired capability of WEF systems or a welcome feature of the WEF nexus approach. However, these same studies are less explicit about both the cost of achieving resilience and potential alternative outcomes, processes or principles that are being foregone by adopting a singular focus on resilience (cf Anderies et al., 2013; Moser et al., 2019). We see a need to address the tradeoffs and synergies between multiple development objectives and their implications, including control, efficiency, robustness, sustainability, equity, and fairness, to enrich policy design frameworks with perspectives from beside and beyond the resilience rationale.

Givens et al. (2018), for example, found that a resilience focus applied to the WEF nexus can strengthen the status quo imposed by stakeholders that are already in power, leading to starkly unequal outcomes. Researchers are therefore heeded to critically examine the desirability of WEF system resilience, “which presupposes the value of maintaining the system, rather than aiming for system change (...). If the desirability of maintaining the system as a whole is questioned, identifying system functions may be an alternate way to identify what is desirable to sustain and what is meant by adaptation vs. transformation. However, focusing on a system's function tends to ignore inequality and conflict in the system by not attending to who gets to identify what functions are valued and benefit most from valued functions” (Givens et al., 2018). Similar pleas to better incorporate the principles of equity and fairness in WEF nexus management are voiced by Schlor et al. (2018) and Fainstein (2018).

It is said that the best way to build resilience of a forest to fire is to burn it. However, in a WEF nexus context—as is the case in other SES contexts—the amplitude of shocks cannot be too large, even if it promises to build additional system resilience. Hoekstra et al. (2018), therefore, argued to pay attention to the merits of control as a guiding principle for managing (WEF) systems under uncertainty. Their study provides an illustrative framework for contrasting and reconciling control and resilience principles.

CONCLUSION

New ways of thinking on natural resources governance are needed for the 21st century, if we are to provide basic human necessities of water, energy, and food to all, in an environmentally sustainable, economically viable and socially inclusive manner that is moreover capable to cope with shocks and disasters. This paper distilled key characteristics of two such paradigms—the (WEF) nexus and resilience thinking—that are said to have the potential to deliver on these grand development challenges. In the research landscape

that is constituted of publications that conflate both framings, we observed pronounced differences regarding the nexus' nature, scope, emphasis and level of integration, and resilience thinking's scope, type, methodological and thematic foci.

We found that the landscape is divided over whether the nexus refers to (simply) a connotation of linked systems, or to a management approach. Moreover, while many studies on the nexus strive to interconnect the three WEF nexus components of water, energy and food, few studies integrate the nexus to its fullest extent. Resilience in these studies is characterized chiefly as specified SES resilience, where a local subset of the WEF nexus forms the SES arena of interest. In contrast to the generic body of literature on the WEF nexus, governance and policy issues are the thematic domains most often addressed in our pool of reviewed publications. One third of the reviewed publications scope resilience as transformation, particularly those addressing themes related to technology and innovation. The level of analysis attained, however, is typically quite shallow, particularly lacking depth in how transformative action may alter system dynamics. Not surprisingly, infrastructure is the dominant topic of interest in engineering resilience studies. While both social and financial capital are ascribed important roles in building resilience across (the governance of) the nexus, few studies focus on the role of learning, capacity building and investments.

Knowledge gaps and opportunities found by our mapping exercise unveiled five overarching avenues for future research:

- While plenty publications develop theories and conceptual frameworks, we see a clear need to improve the understanding of resilience across the WEF nexus, in all its cross-sectoral, cross-domain and cross-scale complexity. This calls for an interdisciplinary research approach that brings together scholars from disciplines relevant to both nexus and resilience discourses.
- Few studies measure and model resilience, giving rise to the opportunity to develop tools and indicators that measure and monitor resilience in the WEF nexus. Ideally, these tools and indicators are designed such that they can be scaled-up, used in conjunction or be integrated across various nexus contexts.
- The role and structure of governance in particular warrants further scrutiny, as it is repeatedly mentioned as a barrier to implementing resilience thinking in a WEF nexus context.
- A significant overlap exists in the concepts and ideas employed in both schools of thought, particularly in studies that scope resilience as SES resilience or transformation, and the nexus as an approach with a

high level of integration. Future research may reveal the extent to which integration is possible or desirable, as well as areas in which greater mutual interaction and exchange could provide enriched insights for natural resources governance.

- There is no panacea to natural resource governance (cf Ostrom, 2007). In emphasizing resilience thinking in WEF nexus governance, other governance or development principles, such as control, efficiency, robustness, sustainability, equity, and fairness, may be overlooked. A knowledge gap remains in understanding tradeoffs and synergies between such different principles and addressing their implications for WEF nexus governance and policy making. Widening the scope could enrich policy design frameworks with perspectives from beside and beyond the resilience rationale.

AUTHOR CONTRIBUTIONS

RH and AN conceived the conceptual design and methodology of the article. RH and MD carried out the formal (review) analysis, which was validated by all co-authors. RH wrote the manuscript with contributions from all co-authors.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2021.630395/full#supplementary-material>.

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