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A New Framework to Enable Equitable Outcomes: Resilience and Nexus Approaches Combined

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Abstract Managing integrated social-ecological systems to reduce risks to human and environmental well-being remains challenging in light of the rate and extent of undesirable changes that are occurring. Developing frameworks that are sufficiently integrative to guide research to deliver the necessary insights into all key system aspects is an important outstanding task. Among existing approaches, resilience and nexus framings both allow focus on unpacking relationships across scales and levels in a system and emphasize the involvement of different groups in decision making to different extents. They also suffer weaknesses and neither approach puts social justice considerations explicitly at its core. This has important implications for understanding who wins and loses out from different decisions and how social and ecological risks and trade-offs are shared and distributed, temporally and spatially. This paper conceptually integrates resilience and nexus approaches, developing a combined framework and indicating how it could effectively be operationalized in cases from mountain and mangrove social-ecological systems. In doing so, it advances understanding of complex social-ecological systems framings for risk-based decision making beyond that which could be achieved through use of either resilience or nexus approaches alone. Important next steps in testing the framework involve empirical and field operationalization, requiring interdisciplinary, mixed method approaches.

Key Points:
- We present a new framework bringing together nexus and resilience approaches
- Our new framework enables a more joined up approach to decision making and a focus on more equitable outcomes
- We show how our framework may be used in mountain and mangrove systems. Further empirical testing with field data is required

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1. Introduction

Over time, nature's ability to deliver contributions to people to support both current and future generations is being substantially undermined (Pascual et al., 2017). Land cover is being altered, marine and terrestrial biodiversity is being lost, ecosystem integrity is being degraded, and the climate is changing due to increased concentrations of atmospheric greenhouse gases (MA, 2005). Maintaining a safe operating space for humanity requires us to alter our current relations with the environment (Rockström et al., 2009). Ensuring the necessary transformation proceeds in a desirable direction without over-burdening already vulnerable groups demands a holistic understanding of complex human-environment relations. Indeed, global challenges faced today are linked to one another in multifarious ways, both temporally and spatially. Understanding these links demands consideration of complexity characterized by scale effects, nonlinearities, tipping points, uncertainty, and a lack of predictability (Berkes, 2017), particularly if we are to reduce the risks of undesirable consequences and deliver fair and just decisions (Mathur et al., 2014).

Holistic approaches that integrate social and ecological system perspectives can help unravel the complex linkages and feedback occurring across different temporal and spatial scales (Berkes & Folke, 1998), and between different levels, sectors, and groups. Holistic analyses can harness the strengths associated with complexity to develop more efficient, cost-effective decision options and outcomes, over the long term. This paper combines two holistic ways of thinking: resilience and nexus approaches, developing a combined conceptual framework and setting out how it could be tested on case studies from mountain and mangrove social-ecological systems. In doing so, it advances understanding of complex social-ecological systems framings for risk-based decision making beyond that which could be achieved through use of either approach alone. In this sense, we refer to risk-based decision making as decisions made that consider different options (and possible outcomes) in light of information about trade-offs across different temporal and spatial scales, taking into account for whom, where, and when resilience may be supported or undermined (cf. Grafton et al., 2016).

2. Nexus and Resilience Approaches

Holistic approaches have been applied across a range of different systems, including drylands (Stringer et al., 2017), fisheries (Fulton et al., 2014), forests (Bruenig, 2016), and agricultural systems (Dixon & Stringer, 2015). The literature includes analyses that use institutional approaches (e.g., Anderies et al., 2004; Ostrom, 2011; Ostrom & Basurto, 2011) that emphasize resource allocation and distribution, agent-based modeling (e.g., Walker & Janssen, 2002) that considers the impacts of individual and collective decisions on the system as a whole, and panarchy analysis (Holling, 2001; Walker et al., 2006) that allows focus on the regional scale, but which lacks explicit consideration of social aspects and technological advances (Gotts, 2007).

Many of these approaches support aspects of "resilience thinking" and its key characteristics of multiple metastable regimes, episodic change, adaptation, and distinct scales and their interactions (Folke, 2006; Gotts, 2007). Resilience is defined in a range of different ways depending on the disciplinary lens through which it is studied (Dixon & Stringer, 2015; Martin-Breen & Anderies, 2011). Historically, it has been associated with the ability of social-ecological systems, and the relationships within them, to absorb change and persist, with origins in ecology and engineering (Holling, 1973). More recently, resilience has been defined as "the ability of a social-ecological system to cope with shocks and stresses by responding or reorganizing in ways that maintain its essential functions, identities and structures, while also maintaining capacity for adaptation, learning, and transformation" (adapted from Arctic Council, 2013; Intergovernmental Panel on Climate Change, 2014). Resilient social-ecological systems can cope, adapt, and transform in response to pressures over time, and different economic, ecological, and social processes feed into the maintenance of the system's operation. Aspects such as social learning are vital therein (Berkes, 2017; Reed et al., 2010), joining together different perspectives, and coproducing new knowledge in the process.

However, the concept of resilience is not without critique or limitations. To be able to effectively manage ecological resilience, the ability to accurately detect and quantify the effects of environmental change on ecological processes is a *sine qua non*. Nevertheless, most studies that undertake such long-term projections often use indicators such as a single species or simple communities "impacted by single pressures across limited scales" (Spears et al., 2015, p.1312; see also Allan et al., 2013). Consequently, results may not necessarily accurately project future ecological change (Russell et al., 2012). There is also a lack of empirical evidence on the potential unintended consequences of management measures on the multiple and interacting pressures acting on the target ecosystem (Spears & Maberly, 2014). A paucity of field-based experimental data on positive and negative feedback hinders efforts for effective proactive or preventive management. Studies of resilience further remain largely focused at the system level or at a single scale (Allen et al., 2014). They also often neglect to consider the equity and justness of resilience as a process or an outcome unless they are using institutional approaches, which then tend to neglect environmental dynamics. Approaches to understanding how resilience can be built should traverse multiple scales and unpack a variety of different relationships between variables. Using food production as an example, Bullock et al. (2017) highlight the need for agroecologists to not only focus on resilience of crop and livestock production at the small scale of the field or the farm but also consider the local, regional, and even global scales.

More recently, recognizing the magnitude of resource use and the unprecedented rate of change that social-ecological systems are seeing today, nexus approaches have emerged and rapidly integrated into the policy lexicon. The term "nexus" refers to linkages and connections. Nexus thinking highlights relationships, interdependencies, and the need for integrated decision making across sectors (Bazilian et al., 2011). It is most commonly used to examine interactions between water, energy, and food (WEF) within risk-based decision processes. 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. Changes to any one of WEF can have knock-on implications for the remaining two across a range of scales (Hussey & Pittock, 2012).

The WEF nexus has been considered to serve multiple roles, first, as an analytical tool or approach to assess interactions among WEF systems based on a range of quantitative and qualitative methods, data, and models (Keskinen et al., 2016); second, as a conceptual governance framework aiming to enhance policy coherence and promote cross-sectoral collaboration toward a more integrated and holistic approach to sustainability (Smajgl et al., 2016); and finally, as a discourse, providing a foundation for the aforementioned two

interpretations, giving rise to alternative ways of framing problems that facilitate mobilization of stakeholders in a desirable direction (Benson et al., 2015).

Similar to resilience, the nexus concept has not been immune from critique. For example, the lack of a unified nexus conceptualization has left the concept open to differing interpretations, varying according to "the focus of sectoral integration, the geopolitical context and empirical foci of research" (Smajgl et al., 2016, p.534). From a novelty standpoint, a recurring criticism of the WEF nexus is that it adds little to existing integrated management approaches, such as the Integrated Water Resources Management (IWRM) model, which also stresses integration and coordination for efficient, equitable, and sustainable management of water resources (see Benson et al., 2015, for an overview). Nevertheless, a large corpus of literature defends the novelty of the WEF nexus, noting that while IWRM focuses on water when considering WEF interrelationships, the nexus takes a holistic view in understanding the interdependencies between WEF security (Food and Agriculture Organization (FAO), 2014; Mohtar & Lawford, 2016; Ringler et al., 2013).

Considerable policy focus is placed on WEF security as a desirable outcome wherein security encompasses WEF supplies, stability, and access (Lawford et al., 2013). Yet from a practicality standpoint, while taking an integrated approach is agreed upon in principle, moving from theory to practice remains difficult, largely due to governance challenges. Governance is important in delivering WEF security and in supporting resilience. Governance structures and processes that recognize the WEF nexus require attention to the links and connections between policies, institutions, and knowledges (PIK), wherein, similar to WEF, changes to any one component can affect the other two. PIK can therefore also be viewed as a nexus. The nexus literature has nevertheless fallen short of adequately identifying how the nexus can connect with the structures of decision-making processes. Despite calls for cross-sector coordination and collaboration, nexus approaches shed little light on the facilitating or hindering conditions that affect such collaboration and coordination between sectors, institutions, and actors (Weitz et al., 2017). Current nexus thinking is further limited to WEF as resources, thereby overlooking the manner in which dynamics beyond the WEF sectoral boundaries may influence the nexus (de Grenade et al., 2016). Finally, across and within both WEF and PIK, trade-offs are inevitable, but similar to resilience, disaggregation of who "wins" and "loses" through such trade-offs, how are trade-offs negotiated, or how are decisions taken in practice remains largely veiled (Cairns & Krzywoszynska, 2016).

In sum, recent disciplinary and interdisciplinary research has led to a proliferation of frameworks and approaches for assessing and reporting human-environment interactions. While a significant amount of knowledge and experience has been consequently generated, Cox et al. (2016) nevertheless flag the need for theoretical consolidation. As they argue, a growing diversity of disciplinary approaches, coupled with lack of knowledge transfer between different disciplines, has presented two main challenges for contemporary scientific inquiry. First, it has hampered disciplinary cross-fertilization, as "many scholars are simply unaware of alternative hypotheses or theoretical perspectives from other fields" (Cox et al., 2016, p.46). Second, policy analysts and policymakers are denied access to a systematic and integrated body of knowledge that would allow them to more effectively diagnose problems and design solutions.

Despite their shared potential to guide research and holistic, risk-based decision making on the same global problems, resilience and nexus thinking are applied separately, often in different academic, policy, and stakeholder arenas. Researchers are yet to explore how their strengths could extend and enhance both approaches and address some of the shortcomings of each (cf. Foxon et al., 2009; Gotts, 2007). By initiating a process of theoretical consolidation, this gap is targeted in this paper.

3. Combining Resilience and Nexus Approaches

This section delves deeply into the characteristics and strengths of resilience and nexus approaches, highlighting areas in which greater mutual interaction could provide enriched insights. We also discuss the lack of core attention paid to important issues of equity and social justice in both approaches. Our analysis and synthesis of the two approaches are informed by three principles which were empirically derived from a large-scale mixed method (qualitative and quantitative) analysis of dryland systems research but which capture to varying degrees the key characteristics of both resilience and nexus approaches in terms of their focus on multiple scales, time frames, and linkages between stakeholders (see Stringer et al., 2017, for more details). The three principles (which are not discrete but overlap in part) are as follows:

1. *Unpack* relationships and interactions in social-ecological systems, livelihood portfolios, and value chains. This is based on the premise that unpacking these relationships to better understand them can aid boundary setting and problem structuring, allowing linkages and feedback to be identified, as well as illuminating the roles and relationships between multiple actors involved in decision making.
2. *Traverse* scales (temporal and spatial), sectors, stakeholders, and ways of knowing. Social-ecological systems are subjected to interactions between multifarious drivers of change, socio-technical innovations, and investment options across scales and sectors. Variables within social-ecological systems proceed at different rates, some of which may cross thresholds leading to nonlinear dynamics and unpredictable outcomes. Any combined conceptual framing of resilience and nexus thinking therefore needs to be grounded in a particular context and to consider the multiple institutional aspects and types of knowledge appropriate to that context.
3. *Share* knowledge, learning, and experience to empower. Interdisciplinary or transdisciplinary approaches that combine local and scientific knowledge to coproduce options and outcomes are vital in understanding all aspects of social-ecological systems. Outcomes can become situated at broader spatial or social scales through social learning and other up- and out-scaling mechanisms, which can empower and lead to fairer and more just outcomes.

We explain these principles below in relation to resilience and nexus approaches, drawing on the literature and informed by discussions between the authors.

3.1. Unpack

Interactions, interconnectedness, and interdependence between human and biophysical components of social-ecological systems are appreciated in both resilience and nexus thinking (Berkes et al., 2003) and lend themselves, to different degrees, to unpacking these relationships both within and between social-ecological systems (Duit et al., 2010; Hoff, 2011). While resilience approaches focus on the capacity of social-ecological systems to absorb, adapt, and transform in the face of change (Béné et al., 2014), and so maintain options and alternatives for resource use (Johnson et al., 2013), nexus approaches tend to focus on increasing productivity and resource use efficiency in the context of WEF scarcity, through policy coherence and enabling institutional conditions that allow recognition of different knowledges and perspectives (Hoff, 2011). A nexus approach therefore seeks development of coherent PIK that reduce transaction costs, and deliver synergy and multiple wins, across WEF sectors (Ringler et al., 2013). Linking nexus and resilience approaches could help to extend nexus thinking beyond its current focus on sustainable intensification (Rockström et al., 2009) to consider other options and alternatives that still harness efficiencies and synergy, while also addressing a key weakness of resilience approach in that it rarely gives social and ecological aspects equal treatment.

3.2. Traverse

Both resilience and nexus thinking recognize the need to traverse multiple geographical, spatial, and temporal scales and the inevitable trade-offs therein (Dixon et al., 2014; Suckall et al., 2014). However, the scales of research (both temporal and spatial) and levels of focus differ between the two different ways of thinking. Resilience research often focuses on the ecosystem or regional scale, linking social systems to ecosystem processes and functions, or analyses take place at the household level, exploring how particular livelihood-environment interactions enhance or erode household resilience (Arouri et al., 2015; Levine et al., 2016). However, human actions and decision making are complex, multiscale, and multilevel (Zurlini et al., 2006), with processes of globalization playing an increasing role in shaping social-ecological system resilience (Young et al., 2006), even at subecosystem scale. Calls have been made for greater scale sensitivity in resilience research (Medd & Chappells, 2007), as well as a greater focus on multilevel and poly-centric governance (Ostrom, 2010). These kinds of considerations can help us to better understand which aspects and consequences of human decisions traverse scales, when and why, and which aspects do not.

In nexus thinking, multiscale interactions are illustrated through the connections within WEF and PIK. In a biophysical sense, water is controlled by the hydrological cycle, with precipitation and evaporation determined by a combination of the global climate system and regional and local convection and orography. Topographic and geological characteristics of any given area shape water storage and flows both at and below the Earth's surface. Humans intervene in this cycle and extract water, according to need, in line with

prevailing political boundaries (including national borders) and the institutional factors shaping extraction rights. Society's formal institutions at local, national, regional, and global levels make and enforce the policies and laws that set out access, extraction, and use. While these are often based on scientific research and knowledge, they are also sometimes based on political agreements across national boundaries and may be interest rather than evidence based (see, e.g., analyses by Mekonnen, 2010, and Zeitoun et al., 2011, on the Nile basin agreement). Informal institutions and societal norms further shape local water use by drawing on different knowledges and through the use of particular practices (Pahl-Wostl et al., 2007).

Extraction, treatment, and distribution of water, as well as wastewater, each have an energy demand, and again, are shaped by PIK. Energy sources are often found in one place but transported to another location where they are consumed. Nonrenewable energy resources are subtractable: their use by one group precludes their use by other groups at later points in time (Carpenter, 1998), resulting in a temporal trade-off, while renewable energy can create spatial trade-offs and create difficulties for downstream users. For instance, energy infrastructure can disrupt water flows through the building of hydropower dams, which have a high water demand. Dams can also displace local residents who formerly used the water for food production and food security (Ringler et al., 2013). PIK becomes vital in these kinds of decisions, which traverse scales. It is necessary to consider the implications for multiple groups, places, and sectors, which may sit well beyond the scale of the original decision.

At the same time, water and other energy-intensive agricultural inputs such as fertilizer are used for food production. Fertilizers are often manufactured far from their site of application and can enrich water bodies through eutrophication and deplete terrestrial systems through nutrient extraction. Runoff from agricultural production, alongside wastewater from the energy sector, can alter the quality of water supplies under the governance jurisdictions of groups, who were not involved in the water use, while at the same time, reducing soil fertility for future production. In turn, while food is largely grown by smallholder farmers in much of the world (Dixon et al., 2014), supply chains and markets link the local scale to national, regional and international scales. Food consumption often takes place thousands of miles away from the site of its production, and the food sector is highly energy-dependent for its transport. These spatial trade-offs mean that some groups in some locations benefit from WEF security, framed by prevailing PIK, whilst others lose out (Leach, 2008).

Within the broader governance context, there are similar networks of relations in the PIK nexus, which combine to shape WEF security. Policies are developed by different institutions operating across different scales and within each of the WEF sectors. These policies draw on particular knowledges, privileging some forms of knowledge (often scientific knowledge) over locally held, traditional and indigenous knowledges, particularly at the national level. In some instances, deficits of knowledge about the broader context in which local level actions and practices are situated can combine, causing larger scale problems elsewhere. An example of this would be the aggregate effects of local water extraction from rivers leading to larger scale food or energy security problems further downstream. At the same time, there are varying degrees of interplay between PIK at different scales and levels, which can change over time in their strength and direction. Cash et al. (2006) use the example of decentralization reforms, which can trigger strong interactions between national institutions and those at the local government level as power distributions are renegotiated, but which then even out as a steady state degree of interaction develops. The particular combination of cross-scale and cross-level interactions at a single point in time can sometimes undermine the resilience of a system (Cash et al., 2006). This demonstrates the importance of thoroughly considering the impacts of decisions across scales and levels because the level of decision and scale of impact are not necessarily the same.

Policies made by one set of institutions can have important implications (and set up trade-offs) for other institutions both at the same and other levels, and are not always coherent with one another (see, e.g., England et al., 2017). This can cause problems for WEF security, even if those policies do not directly address WEF. For example, within the international biodiversity arena, there are multiple conventions and treaties that deal with different aspects of biodiversity (Velazquez-Gomar et al., 2014). These include the Ramsar Convention, the Convention concerning the protection of the World Cultural and Natural Heritage (WHC), the Convention on International Trade in Endangered Species of wild fauna and flora (CITES), the Convention on the Conservation of Migratory Species of wild animals (CMS), the Convention on Biological Diversity (CBD), and the International Treaty on Plant and Genetic Resources for Food and Agriculture (ITPGFRA). Each agreement entered into force at a different point in time, has the commitment of different country

parties, and therefore is applicable over a different space. Yet each is part of a broader biodiversity complex that shares certain desired outcomes that indirectly support WEF. In situations of poor policy coherence, this causes some components of the regime to be winners while others lose out. In extreme situations, overall system resilience can be undermined.

3.3. Share

Much resilience research has shown the importance of learning from past exposure and responses to shocks and stresses in order to identify areas for current and future policy support (e.g., Carpenter et al., 2001; Dixon et al., 2014; Fazey et al., 2007). Ensuring that knowledge is appropriately shared becomes important here. Trajectory analyses (Sallu et al., 2010) can help to pinpoint how particular PIK erode or enable resilience, offering an insight into temporal social-ecological system dynamics that look backward as well as forward, particularly given the present is rooted in the legacy of the past (Stringer & Harris, 2014). Resilience thinking also recognizes the importance of flexibility, learning, and sharing experiences as systems evolve over time (e.g., Tschakert & Dietrich, 2010). This is reflected in approaches such as adaptive management, which uses experimentation to promote learning, using the new knowledge gained to guide the future management of integrated social-ecological systems (Armitage et al., 2008). A key point here is recognition that the outcomes, or what counts as a resilient system, change over time, reflecting evolution of the social-ecological system and its various components.

Historical factors, learning from experience, and sharing, and coproducing knowledge, have been less well captured in nexus thinking. Nexus research tends to take more of a forward-looking stance, employing methods such as scenarios and back-casting to extrapolate system changes into the future and assess the interlinkages therein (Hoff, 2011). Emphasis is thus more on unpacking relationships between variables. The WEF sectoral focus of nexus thinking also fails to adequately capture the trade-offs and synergies between the different constituents of PIK, both within and between different governance levels, meaning that the PIK nexus is underexplored beyond a focus on particular snapshots in time (e.g., Kalaba et al., 2014; Stringer et al., 2009) and without linking to other sectors such as health, education, and so on. This underemphasizes the importance of traversing sectors beyond WEF (Stringer et al., 2017). Additionally, little nexus research has been conducted at the household or community scale, assessing household WEF security and how this shapes and is shaped by PIK operating at larger scales (Allouche et al., 2014). These gaps represent important considerations, while the areas of divergence between resilience and nexus thinking offer considerable potential for cross-fertilization.

Although trade-offs across sectors have been recognized in nexus research, neither resilience nor nexus thinking pay explicit attention to investigating issues of justice or equity in terms of social, economic, and/or environmental outcomes. Several researchers acknowledge that justice and equity are important but work is only starting to emerge that seeks to make these aspects more central (e.g., Larcom & van Gevelt, 2017; Middleton et al., 2015; Ziervogel et al., 2017). A system-level focus in resilience research can overlook choices made by individuals or groups (Coulthard, 2012) and neglects to appreciate the notion of "winners and losers" (Béné et al., 2014). Scale is important here too. While some attempts have been made to measure household resilience by, for example, looking at the connections and relationships between different types of household assets (Folbre, 1986), less focus has been placed on the role of links between WEF at larger scales in determining resilience, and for whom. Even within the same level, scale matters. For example, overall household resilience may increase as a result of a particular process or action but potentially to the detriment of one or more individuals within the household. Similarly, strengthening resilience in the short-term can reduce it in the long term and vice versa (Cabell & Oelofse, 2012), reminding us of the importance of temporal trade-offs.

A seemingly resilient system that can maintain WEF security both quickly and cost-effectively is largely shaped by PIK via the WEF-PIK nexus but is not necessarily an equitable or just system (Pelling, 2011). Justice and equity are often analyzed according to participation, distribution, and recognition (Schlosberg, 2007) and link to economic and environmental equity, as well as people's capabilities, power, and agency to make choices that can enable their resilience (Sen, 1999, 2009). As such, resilience outcomes can be unequally distributed among and between a system's economic, ecological, and social components. Similarly, policies and institutions are informed by particular knowledges (often scientific), which, usually through the mediation of institutions, can result in a lack of recognition and the marginalization of other

ways of knowing (Raymond et al., 2010). This can restrict the participation of some groups (Schlosberg, 2007), weighting governance decisions such that adverse impacts disproportionately affect some people and some ecosystems. This again creates "winners" and "losers" and can determine whether or not certain groups and ecosystems are considered in subsequent distributional patterns (Young, 2010), with implications for their ultimate resilience outcomes.

Resilience and nexus thinking therefore bring different strengths in terms of the systems approach they apply, while neither makes explicit ideas around social justice as a matter of course. We argue that combining resilience and nexus approaches can build on the strengths of each and deliver a more holistic approach to risk-based decision making. It also provides an opportunity to reorient decisions to take better account of their social justice implications. Exploring the trade-offs within and between each nexus, and how they affect the equity and justness of economic, environmental, and social resilience outcomes, can provide valuable insights into issues of power and agency, informing actions so that actors can be enabled to make risk-based decisions that enable resilience outcomes. It also pushes us to ask whether an unjust and inequitable social-ecological system really is resilient. A system may exhibit persistence, resistance, and robustness (i.e., be classified as resilient within the prevailing resilience research literature). However, without equitable recognition, participation, and distribution, the capabilities of system components to be resilient, both individually and as a social-ecological system, are called into question.

Taking into account the shortcomings in existing ways of thinking, alongside the characterization of resilience winners and losers at different points in time, operationalized through the principles of unpack, traverse, and share (Stringer et al., 2017), leads us to present the WEF-PIK resilience framework. Combining nexus and resilience approaches allows us to tap into the strength of nexus thinking in terms of seeking synergies and reducing trade-offs by unpacking relationships, while drawing on aspects of resilience thinking permits an insight into factors such as social learning and sharing that enable the social-ecological system to cope with and adapt to change over time. By traversing scales, sectors, and groups, building on the efforts of both approaches to do this, it guides us to identify who benefits and loses out in the process and encourages knowledge sharing and coproduction.

4. The WEF-PIK Resilience Framework

This section presents a novel conceptual WEF-PIK resilience framework that can be used to address some of the gaps outlined above and extend contemporary nexus thinking. We illustrate the sorts of complex contexts in which the framework could yield useful information to decision makers by considering how it could potentially be applied in mountainous systems in the Hindu Kush Himalaya (HKH) and mangrove social-ecological systems in Vietnam.

Figure 1 links the WEF nexus with the PIK nexus, presented as a double helix, embedded within multiple spatial and temporal scales, and organized through unpack, traverse, and share principles. It guides us to look backward, forward, and assess the present (t_1, t_2, and t_3, respectively, in Figure 1), facilitating analysis of actions and decisions surrounding past disturbances and the resilience outcomes of responses (Engle, 2011; Lemos et al., 2007). This is captured by the spaces between each of t_1, t_2, and t_3. Although the framework shows local-level outcomes embedded within multiple spatial scales in its current presentation, it can be applied flexibly such that any of the scales can be brought to the fore, allowing exploration of the same outcome as evident at different levels.

The interactions between WEF and PIK determine, and are determined by, justice and equity across social, economic, and environmental dimensions, represented by "resilience bases" that unite WEF and PIK. Economic equity encompasses issues surrounding the distribution of economic costs and benefits, social justice allows focus on issues of equity and fairness relating to different groups, while environmental equity captures issues such as access to resources and resource distributions. Each of these "bases" can be further investigated, disaggregated, or aggregated as required, in order to determine the equity and justness of resilience across dimensions such as gender, culture, age, and ethnicity.

Trade-offs are present not only in the interactions in the WEF nexus but between sectors and actors at different temporal and spatial scales, within the PIK nexus, and between the resilience of different components of the overall social-ecological system. Combining the strengths of nexus and resilience approaches enables trade-offs to be identified and assessed in terms of how they affect the capacity of the system to cope

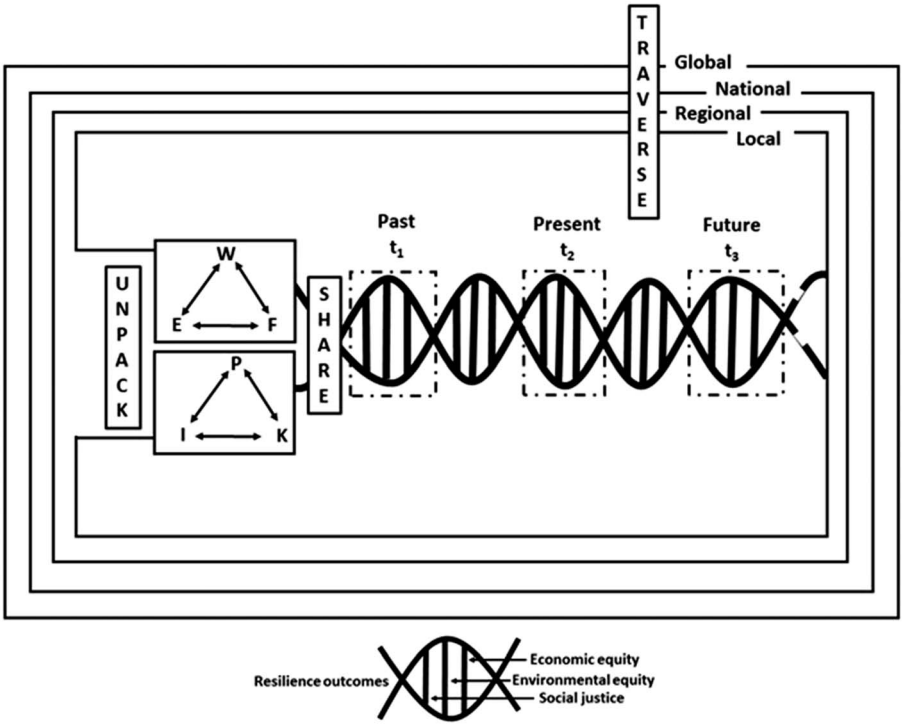


Figure 1. The WEF-PIK resilience framework. The figure presents a lock-in trajectory over time, in which decisions reinforce existing inequalities.

with, and adapt to, change over time. As such, the framework can be used to identify the direction of travel along a continuum of resilience outcomes, with particular focus on equity and justice therein.

The interaction of PIK with WEF emphasizes the importance of governance at all levels and across multiple scales in achieving WEF security and resilience. It enables unpacking of the relationships between governance and WEF security, as well the distributions of social, environmental, and economic outcomes they deliver. Understanding this interaction allows us to assess the conditions under which WEF security can be achieved in more just and equitable ways. It permits consideration of how different knowledges are able (or not) to be shared to frame policies and institutions that affect WEF security, and how, in turn, the status of WEF sectors influences the recognition and capabilities of individuals within and across sectors and scales to participate in and shape risk-based decision making through PIK. There is further opportunity to use the framework to guide research that can identify and reduce conflicts between stakeholders operating at different scales, and across social, economic, and environmental dimensions, in line with the traverse principle. Through PIK, there is scope to identify institutional gaps and to develop governance arrangements that crosscut WEF sectoral boundaries, which in the process, can help to facilitate resilience outcomes within the system, over time.

5. Toward Application of the WEF-PIK Resilience Framework

Effective application of the framework demands interdisciplinarity and transdisciplinarity to reduce the challenges associated with the dominance of particular disciplines in nexus research (Stirling, 2015) and to deliver holistic insights into the system of focus. The selection of methods is critical because the ways in which they are combined offers the route to advancing new knowledge and research outcomes that may not have been generated using existing or separate ways of thinking. A systematic review by Albrecht et al. (2018) found that use of specific and replicable methods in nexus investigations is currently sparse and that research often misses interactions that are conceptually purported to target WEF interactions. They also noted an emphasis on quantitative approaches and a lack of social science and mixed methods.

In Figure 1, the principles "unpack," "traverse," and "share" can help to address some of these challenges. For example, existing methods could be used to identify and unpack key variables and the relationships

between them, both quantitatively and qualitatively. Specific variables to be unpacked will depend on the specific research questions under consideration but could come under ecological, social, economic, cultural, and political categories, with clusters of variables within livelihood portfolios, actor networks, and ecosystem service cascades being targeted. Data collection could involve use of methods such as questionnaire surveys combined with well-being rankings, focus groups, and other participatory methods, as well as policy and institutional analysis, allowing investigation of the embeddedness of PIK across spatial scales and stakeholder groups as part of the traverse principle. This can be complemented with biophysical data, mapping, and quantitative data on, for example, WEF production/consumption across scales and governance levels. Addressing the traverse principle could make use of empirical research that focuses on different points in time (past, present, and future), drawing on an array of quantitative and qualitative methods, alongside a range of different environmental, social, economic, political, and institutional indicators (Adger, 2000; Twyman et al., 2011), depending on the research questions being targeted. This would allow the capture of a range of different knowledges while asking the same questions. Overall, the traverse principle encompasses different temporal as well as spatial scales, different stakeholder groups, sectors, disciplines, and ways of knowing. Depending on the context of application, it could also require methodological innovation. For instance, Bekchanov and Lamers (2016) developed an integrated modeling technique for effectively addressing challenges related to WEF/livelihood nexuses, whereas Perrone and Hornberger (2016) adapted a standard economic approach called a "trade-off frontier" to visualize the trade-offs among food, energy, and water in times of water scarcity. In the context of risk-based decision making, such novel approaches will be vital to capture rapid, slow, and prolonged risks and to assess their equity implications over time (e.g., for future generations) but also at different scales (e.g., individual household resilience could be eroded while collective resilience at larger scales could be increased through particular decisions). At the same time, the share principle reminds us that we need to be looking beyond disciplinary silos, while making explicit, the K in PIK allows emphasis on different types of knowledge (scientific and nonscientific) and consideration of its influence, in both policy decisions and institutional structures and practices. Share represents an inclusive coproduction approach innate to the framework, rather than requiring specific variables to be measured. Nevertheless, impact assessment methods, social network analysis, and Q-methodology could allow analyses to be reflexive and monitor progress in terms of this approach.

Outputs from disaggregated empirical data analysis allow the assessment of (in) equalities and (in) justices along social lines of gender, culture, ethnicity, and within and between different social groups, using quantitative approaches such as correlations, as well as qualitative approaches (e.g., matrices and visualization techniques such as web diagrams. Economic equity outcomes can be identified using methods such as household surveys, wealth ranking, and market price trend analyses. Timelines (constructed by both individuals and groups at different spatial scales) can be useful in identifying economic incentives present in particular policies or promoted by certain institutions to support particular behaviors and decisions. This would provide insight into the outcomes of specific resource allocation mechanisms for different social groups and their resilience, alongside the identification of subsidies that harm the environment, such that they might be removed. Environmental outcomes can focus on particular land uses, ecosystems, communities, or even drill down to the level of individual species depending on the decision scale of focus. Methodologically, environmental assessments could involve participatory mapping of ecosystem services over time (t_1-t_2), use of secondary data on vegetation, plant species, meteorological aspects (e.g., rainfall and temperature), soils, topography, and so on. These can be analyzed in the context of ecosystem goods and services that together provide WEF security and the PIK that shape and inform access to and use of environmental resources. Taking this kind of approach facilitates recognition of the vast body of environmental knowledge that is held both locally and at other scales (Sallu et al., 2010).

The ability of our framework to deliver in practice will inevitably depend on whether obstacles similar to those that have been encountered by previous integrative approaches are effectively overcome. Leck et al. (2015), for instance, highlight the need for the political economy of the nexus to be more explicitly addressed, drawing attention to the manner in which power and vested interests control or influence resource allocation processes. Other studies have noted the difficulties involved in developing transdisciplinary approaches due to the subdivision and specialization of research disciplines and the consequent lack of common language between them (Couix & Hazard, 2013; Fox et al., 2006). Finally, Khan et al. (2017), stress the imperativeness

of standardizing and harmonizing time and spatial resolutions to facilitate implementation of integrative approaches.

The WEF-PIK resilience framework requires testing through its application to a range of different social-ecological systems, as well as an evaluation of its ability to assess the resilience outcomes that take into account social justice, and both economic and environmental equity. Below we consider the WEF-PIK resilience framework's potential utility in mountain and mangrove systems: two very different social-ecological contexts, selected for illustrative purposes as a result of the authors' interests. We use these examples in the absence of empirical data, drawing on the literature, to indicate the types of complex settings to which the framework can be applied, and to demonstrate the sorts of context-appropriate mixed-methods that could be used to yield information needed by decision makers to support more equitable outcomes. The mountain system offers a different scale to the mangrove system, taking into account changes in altitude and the broader geohazard risk context, which shapes the nexus, while the mangrove system example places more emphasis on the policy and economic drivers and the prioritization of aquaculture activities within subnational governance processes.

5.1. Mountain Systems: the Hindu Kush Himalaya Region

5.1.1. Context

The HKH region is characterized by mountainous topography, fragile ecosystems, and several transboundary river basins. Elevation zones in the region extend from tropical areas to alpine ice-snow ($<$500 to $>$6,000 m above sea level), with a principal vertical vegetation structure comprising tropical and subtropical rainforest, temperate broadleaf deciduous or mixed forest, and temperate coniferous forest, including high-altitude cold shrub or steppe and cold desert (Guangwei, 2002; Pei, 1995). Ensuring food security, providing reliable access to clean energy and delivering sufficient water for agricultural, industrial, and domestic uses are key in advancing sustainable development in the HKH. This is essential given that, as a whole in South Asia, around half the population live without sufficient food and energy (Ahmed et al., 2007).

The HKH region is also characterized by a diverse natural hazard risk mosaic in which different geological, climatic, and hydrological hazards combine with socio-economic factors to shape social-ecological resilience (Xu & Grumbine, 2014). Paralleling WEF nexus issues, the value of more joined-up multisector approaches is increasingly recognized in international natural hazard policy, but has yet to be implemented. This gap remains even in major disaster management frameworks such as the Hyogo Framework for Action, which aims to enable countries and their populations to become more resilient to the hazards that can undermine development.

Rapid population growth, limited land, unreliable and inadequate energy supplies, increasing flood risk and water stress due to extraction and climate change, and a diverse natural hazard risk mosaic all suggest that applying the WEF-PIK framework (Figure 1) could yield important new insights in moving toward more equitable resilience outcomes, especially as the onset and speed of these risks vary over time and for different groups.

5.1.2. Unpacking Relationships in the HKH

Varying social-ecological relationships along the elevation gradients of the HKH add complexity to the interactions between components of the WEF nexus alongside other challenges (e.g., building climate resilience and managing natural hazards; Xu & Grumbine, 2014). Unpacking these interactions is vital if trade-offs are to be identified, especially as they crosscut the remits and responsibilities of different policy sectors. For example, in the upper reaches of the Ganges River basin, Nepal provides a dynamic context in which to unpack the role of environmental change and natural hazard risk exposure in shifting the relative importance of WEF within the nexus. The country has an extreme altitudinal profile. It depends on water to generate energy (from hydropower), irrigate crops, and for standard domestic/industrial uses. As the climate changes and human populations are expanding over time (trends that could usefully be assessed under t_1 and t_2 in Figure 1), water shortages for power and food production are becoming more acute (projections to t_3; Xu et al., 2009). At the national scale, the extent to which water is required for irrigating crops, power generation (or both) varies spatially. However, local-scale decisions to convert land (for urbanization or agriculture), extract water for irrigation or construct a dam for hydropower, often limit resilience or increase natural hazard risk exposure elsewhere. Unpacking these interactions, through, for example, interviews combined with spatial modeling of the role that past land use change has had on water availability and hazard vulnerability,

would allow a more complete understanding of the winners and losers, locally, nationally, and regionally, resulting from decisions taken with the intention of improving WEF security in one particular location. Following the framework in Figure 1 would require that traditional institutional and administrative scales are crossed and that winners and losers are identified as a result of possible decision options. Knowledge would need to be shared in order to catalyze necessary changes and put in place mitigation options for those who lose out (Gentle & Maraseni, 2012). Analysis of how any decision affects the policies in each of the WEF sectors would also need to take place.

5.1.3. Traverse

Given steep altitudinal gradients and the major transboundary river basins in the region, multiscale interactions that traverse traditional management scales (both temporal and spatial) are particularly apparent (Qasim et al., 2011). Indeed, the ways in which land is managed in upstream parts of river basins often has profound impacts on the delivery of WEF security downstream (Rasul, 2016). In HKH impacts would be felt in Nepal itself and across international borders in nations such as India and Bangladesh. This necessitates policy and institutional analysis both horizontally (traversing sectors) and vertically (traversing governance levels).

Institutions charged with governing these resources at different points (in space and time) depend therefore on decisions made elsewhere (and/or at an earlier point), as well as within their own communities. However, currently there is little in the way of cross-scale flows of human capital nor exchanges of experiences and perceptions relating to previous decisions. The complex patterns of interactions and feedback, operating across different spatial and temporal scales, between communities, ecosystems, and the natural hazards to which they are exposed, remain poorly understood. Although policymakers recognize the need to work across WEF sectors, they largely fail to take a holistic approach to understanding connections across scales and stakeholder groups, even within the scale of their own administrative jurisdiction. This means the PIK nexus is often neglected. Further, decision makers within a single country at subnational scales rarely take account of resilience implications at the national scale (and vice versa), let alone the complex trade-offs that will also be occurring both down and upstream from where their decisions have immediate implications, including across international borders (Sud et al., 2015). This demonstrates the importance of explicitly applying the traverse principle in the HKH and Nepalese contexts.

5.1.4. Share

Given the spatial overlap between natural hazards and the WEF nexus, before any one of these issues can be addressed, unpacking spatial and societal covariation between them is essential. This requires sharing information and knowledge across different disciplines to address environmental, social, and economic aspects that can inform decision making and draws particular attention to the kinds of methods that could be used. Data and methods could focus specific attention on relationships between biophysical (geological, climatic, and hydrological) factors and human resilience to hazards within a vulnerability analysis, or focus on altitudinal and spatial/river basin characteristics that also affect the WEF nexus, such as hydrological modeling to understand seasonal water availability for crops. Doing so will require the application of existing and novel research approaches to ensure that as wide a range of data and knowledges as possible are captured and shared, including from sources that are traditionally ignored. Doing this would respond to calls in the literature that nexus approaches fail to engage sufficiently across disciplines and use too limited a range of methods (Albrecht et al., 2018). The share principle in Figure 1 helps to make this more explicit than in other existing approaches. Documentary analysis, participatory methods, and oral histories could uncover past environmental hazards and socio-economic shocks and responses at agreed points in time (t_1, t_2). Combining this with quantitative data on hazard risk profiles (e.g., flood risk and earthquake risk), land use change, records of water use, energy generation, agricultural yields, international trade, and aid flows or patterns of rural to urban migration could identify trends and trajectories, revealing how community responses to hazards vary both spatially and temporally. These data could also feed into projections and participatory scenarios that target t_3 in Figure 1, helping to identify tensions and trade-offs. Use of these kinds of methods and approaches would allow experiences to be shared across multiple scales, sectors, knowledge types, and institutions. For instance, in this way, past WEF implications of a major landslip resulting from an earthquake could be used to inform decision making that seeks to build resilience to future events in at-risk communities, taking more explicit account of the winners and losers than is standard with existing frameworks.

5.2. Mangrove Social-Ecological Systems in Vietnam

5.2.1. Context

Mangrove systems are found along the Vietnam coast, from Ngoc Cape in the north-east to the rich and largest mangrove forests in the Mekong Delta in the south (Hong & San, 1993). They are an important habitat for migratory birds, bats, and marine fish, among others (Hong & Dao, 1997; Le, 1994). They are also critically important to many local communities for the provisioning ecosystem services they provide, including food, timber, firewood, charcoal, and medicines (Ha et al., 2014). At national scale they provide storm protection along the coast (including protecting surface freshwater resources). They also support increasing tourism revenues, while internationally they play a vital and increasingly recognized role as a carbon store (Nguyen et al., 2017).

However, mangrove systems in Vietnam are facing significant threats. The most critical driver of mangrove loss has been the development and expansion of aquaculture since the 1980s. Increasing demand for shrimp and crab in both domestic and international markets has led to the widespread clearance of mangroves and conversion into aquaculture ponds. This land use change has been supported by national government policy. Aquaculture development has been actively promoted as part of a wider set of policy reforms for economic development (*Đổi Mới*) that has seen abandonment of collectivisation and paved the way for privatization of land, including mangroves (Fortier & Thi Thu Trang, 2013). This has led to commercialization of aquaculture, marginalization of local communities in management decisions, and the prioritization of certain ecosystem services over others, with food being prioritized within the nexus.

The transformation of the coast in Vietnam is coming at a time of significant economic development that is increasingly integrating the country into the global economic system. Growth, so far, has been rapid with increasing incomes and dramatically falling poverty levels. However, this has been fuelled in large part by the exploitation of natural resources including upstream hydropower development and agricultural intensification. Trade-offs continue to prioritize short-term economic benefits at a cost to environmental quality. As a result, there is an urgent need to understand the complex human-environment interactions in social-ecological systems in order to achieve more equitable and sustainable outcomes that are cognisant of who wins and who loses, and why. The WEF-PIK framework can provide the structure for such an approach.

5.2.2. Unpack

The complex nature of mangrove social-ecological systems presents a significant challenge for management and requires sustained and coordinated responses by various stakeholders at multiple levels. At the system level, by unpacking the relationships between resource users/service beneficiaries and mangrove management through ecosystem service assessments and livelihood analyses, we can better understand the trade-offs that are happening between mangrove ecosystem services as a result of policy, and who the winners and losers are. For example, in Vietnam, the poor in coastal communities often emerge as the traditional losers from aquaculture development because of loss of access to resources, but reductions in storm protection caused by mangrove loss may well create more losers over larger spatial scales in the future. Vietnam is already considered to be one of the most vulnerable countries to sea level rise, particularly in relation to the risks to agriculture (Dasgupta et al., 2007), and continued mangrove loss is likely to make the impacts of storm surges and sea level rise worse. As a result, evaluation of mangrove social-ecological systems in Vietnam has begun to provide evidence about how, when, and where, and for whom, mangroves provide more than just food but also other services (Orchard et al., 2016) and so starts to identify how cross-sectoral institutional arrangements might be instigated to create more equitable and sustainable management of mangrove resources.

However, conflicting national priorities are also likely to have resilience consequences, through the loss of storm protection that mangroves provide. Land use change in mangrove systems needs to be considered in the context of upstream activities, such as hydropower developments that have consequences for flows of water and sediment deposition in delta areas, and in broader climate processes that are likely to shift the timing and location of cyclone events (Darby et al., 2016). Food, particularly for domestic markets and export, has dominated policy that governs mangrove systems, and energy has historically been prioritized in catchment-scale water management. As yet the interactions between these dominant policy processes and outcomes across the WEF sectors have not been unpacked in any meaningful ways.

5.2.3. Traverse

Evidence suggests a lack of horizontal coherence between national policies on aquaculture and the range of ecosystem services at different spatial scales that are provided by mangroves (Nguyen et al., 2016). This indicates that national interests are being prioritized, through the development and expansion of aquaculture,

over local needs for the provisioning services that mangroves provide, but also over alternative national priorities for coastal protection. In some situations these conflicts are being played out at local levels as the better off within local communities take advantage of national policy to obtain land for aquaculture development, or sell land to commercial aquaculture interests (Orchard et al., 2015; Vu, 2012). This has led poorer members of these communities to lose access to mangrove resources and so some of their livelihood options. These winners and losers have come about because of elite capture of land (through privatization policies) and institutions for mangrove management, but also because knowledge about mangrove management at higher levels of governance is likely dominated by particular economic development narratives that exclude alternative uses of and services from mangroves.

A traverse approach as outlined in the WEF-PIK framework would enable examination of the processes by which mangrove social-ecological systems have been transformed by social and economic change (by assessing trends under t_1 and t_2 in Figure 1), particularly at local and national levels. Combined use of methods such as livelihood trajectories (Orchard et al., 2016), the Drivers-Pressures-States-Impacts-Responses approach (Quinn et al., 2017) and institutional analysis over time, would enable this kind of trend assessment. Critically, examination of WEF and PIK across governance levels, through the use of a mixed methods approach, would enable a more nuanced understanding of how different knowledges have been translated into policies that prioritize different elements of the WEF nexus. Evaluation of trajectories of change, their drivers and their interactions, would also enable elucidation of potential future scenarios (t_3) under conditions of future vulnerability to sea level rise (Dasgupta et al., 2007) and changing cyclone activity (Darby et al., 2016).

5.2.4. Share

There is recognition that interdisciplinary and cross-sectoral approaches are needed for research in and management of social-ecological systems. However, in Vietnam, a largely technical approach to the relationship between mangrove protection, restoration, and aquaculture has prevailed, where socio-economic factors have not been given adequate attention. Without sharing knowledge across governance levels and pooling knowledge and expertise in both biophysical, ecological, and socio-economic domains, there is a danger of unforeseen and unintended consequences. For example, research in the Mekong Delta has shown that a triple cropping system facilitated by the raising of dykes to reduce flooding is leading to unintended consequences for sediment movements and soil fertility (Chapman et al., 2016). While triple cropping has enabled farmers to increase production, and so incomes, the impacts of reduced sediment deposition and the resultant reductions in soil fertility are unequally distributed with more significant consequences for poorer farmers who are unable to mitigate the effects through the use of artificial fertilizers. This example demonstrates how an integrated approach that combines expertise from across the disciplines and considers how biophysical, social, and policy processes interact enables the consequences for WEF, and who wins and who loses, to be better understood. Combining interdisciplinary research with sharing of knowledge from research into policy, and from local to national levels, is needed to understand the trade-offs and consequences and determine if decisions will lead to the future outcomes envisaged (t_3).

6. Conclusion

Resilience and nexus approaches share considerable common ground and can be usefully combined to build on the strengths and address the weaknesses of each approach. The WEF-PIK resilience framework developed in this paper can guide research into resilience trajectories, informing assessment of multiscale system dynamics through the use of mixed-methods and interdisciplinary approaches. It considers the spatial nature of interactions by focusing on multiple scales and sectors and the links between them, both within and between each strand of the double helix, as well as the way these relationships change over time: past, present, and future. Through the use of the three principles of unpack, traverse, and share, the framework offers potential to fill a key gap in both nexus and resilience thinking by guiding a more prominent focus on issues of social justice, environmental equity, and economic equity, all of which are important in risk-based decision processes.

The next steps are to empirically operationalize the framework in the case study contexts, advancing it beyond desk-based feasibility testing through its application to real-world settings. Information gained through application of the framework can be used to support risk-based decision making as a result of improved multiscale data provision, both temporal and spatial, such that social-ecological systems can be

guided toward more equitable and just resilience. We contend that if the results of empirical testing are favorable, it could act as a useful springboard for the development of more integrated approaches to environmental policymaking and more mainstream use of risk-based decision making across multiple scales and geographies. In particular, it will be useful to assess the framework's ability to (a) guide enhanced policy decisions through the provision of improved data across scales; (b) inform steps toward improved coherence between WEF PIK, such that trade-offs are reduced; (c) reduce institutional gaps such that organizational arrangements crosscut WEF sectoral boundaries; (d) reduce the marginalization of particular knowledges; (e) improve identification of PIK that can promote more environmentally and economically equitable and socially just outcomes across WEF dimensions; (f) reduce conflicts between different stakeholders operating at different scales and between economic, social and environmental bases; and (g) improve the management of risks and trade-offs. Applying, testing, and reflecting upon the WEF-PIK resilience framework provide an exciting new challenge for nexus researchers from a range of disciplines who seek to identify how more equitable and just resilience outcomes can be enabled in integrated social-ecological systems.

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