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The Role of Nature-Based Solutions in Supporting Social-Ecological Resilience for Climate Change Adaptation

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Abstract

Social-ecological systems underpinning nature-based solutions (NbS) must be resilient to changing conditions if NbS are to contribute to long-term climate change adaptation. We develop a two-part conceptual framework linking social-ecological resilience to adaptation outcomes in NbS. Part one determines the potential of NbS to support resilience based on assessing whether NbS affect key mechanisms known to enable resilience. Examples include social-ecological diversity, connectivity, and inclusive decision-making. Part two includes adaptation outcomes that building social-ecological resilience can sustain, known as nature's contributions to adaptation (NCAs). We apply the framework to a global dataset of NbS in forests. We find evidence that NbS may be supporting resilience by influencing many enabling mechanisms. NbS also deliver many NCAs such as flood and drought mitigation. However, there is less evidence for some mechanisms and NCAs critical for resilience to long-term uncertainty. We present future research questions to better understand how NbS can continue to support social-ecological systems in a changing world.

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1. INTRODUCTION

Adaptation by humans and nature to climate change is essential, as it increasingly poses severe and cascading risks to the global community and the ecosystems on which it depends (1). There is growing recognition that nature-based solutions (NbS) can be a vital part of adaptation strategies (1, 2). NbS are actions where people work with nature, as part of nature, including nature protection, restoration, or sustainable management, to provide local benefits for people and biodiversity (3, 4). When used alone or as part of an integrated strategy, they have potential to offer a more holistic approach to adaptation than purely engineered approaches (5). In turn, they have been widely reported to be effective in reducing the impacts of climate change and other hydrometeorological hazards across a range of ecological and socioeconomic contexts globally (6, 7). However, work is still needed to understand the mechanisms by which NbS deliver effective adaptation for people and nature (4, 6) [but see Woroniecki et al. (8), Smith et al. (9), and Bruley et al. (10) for recent advances]. This is needed to inform best practice in NbS design and implementation and to avoid maladaptation.

Nature-based solutions (NbS): actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (3)

Climate change adaptation is generally defined as the process to alleviate or moderate its adverse impacts and/or to take advantage of new opportunities (11). One essential element of this process is to ensure adaptation strategies are effective in perpetuity. As such, they need to be effective not only to address present challenges but also to respond to changing conditions and uncertainty into the future (12). This is particularly relevant in the context of climate change where future changes are characterized by high uncertainty (13). In this regard, assessing the adaptation process requires looking at how strategies affect the resilience of their target system (12, 14–16). A resilience perspective highlights the factors that enable a system to respond to change and disturbance, whether or not certain desired outcomes are safeguarded in the face of such change, and the potential to continue responding to changes and providing such outcomes into the future (17). Here, resilience refers to the capacity to deal with current and future threats to supply desired outcomes in the short and long term. In the context of adaptation strategies, such desired outcomes include adaptation benefits that alleviate and/or take advantage of climate impacts. Therefore, assessing how an adaptation strategy affects a system's resilience can indicate if and how it can provide adaptation benefits over time by overcoming current as well as future threats as conditions change (15, 18).

Although there are multiple conceptualizations of resilience that have come from different disciplines including engineering, ecological, social, and development resilience, the concept of social-ecological resilience is most relevant in the context of NbS. This is because NbS address societal goals by forming or augmenting place-based partnerships between people and nature (5). Successful NbS are embedded and build on a particular local social-ecological system (SES) (8, 19–21). In an SES, ecosystems and people are interconnected, interdependent, and fundamentally indivisible (22). There are many different elements within an SES that influence its resilience (23), which we refer to hereafter as resilience mechanisms. Examples include connectivity and diversity among elements within an SES, the potential to learn and manage adaptively, and empowering historically marginalized peoples. Some may be more important for enabling resilience in the short or long term, whereas others can do both (24).

Resilience mechanisms, alone or through interaction with other mechanisms, ensure the persistence or emergence of desired SES outcomes in the face of disturbance and change (25). A key desired outcome for the societal goal of adaptation are nature's contributions to adaptation (NCAs). NCAs are benefits derived from human–nature interactions that enable people to respond to change (26, 27). They are also a key outcome that NbS adaptation strategies aim to deliver (10) (see the sidebar titled What Are Nature's Contributions to Adaptation and What Is

Social-ecological resilience: the capacity of an SES to sustain desired outcomes in the face of disturbance and change, by both buffering shocks and adapting or transforming in response to change (definition modified from 23)

Social-ecological system (SES): integrated system of ecosystems and human society with reciprocal feedback and interdependence (25)

Resilience mechanism: element within an SES that influences its resilience

WHAT ARE NATURE'S CONTRIBUTIONS TO ADAPTATION AND WHAT IS THEIR LINK TO NATURE-BASED SOLUTIONS?

Nature's contributions to adaptation (NCAs) are a subset of nature's contributions to people (NCPs) (116) that enable people to respond and adapt to change. For example, from forests these could include protection from flooding or landslides, ensuring groundwater storage during droughts, and providing food and income sources that are more resistant to climate hazards. NCAs can also be divided into whether they are persistent or novel (27). Persistent NCAs are pre-existing contributions to a particular group of people. Novel NCAs are new types of contributions that arise because of new climate or environmental conditions and/or new human–nature interactions.

As with NCPs more broadly, NCAs are not generated from nature alone but through a series of social-ecological functions and interactions. Such so-called NCA co-production interactions (117) include safeguarding and managing ecosystems, mobilizing and harnessing ecosystem functions that generate NCAs, and accessing and appreciating NCAs. All of these interactions involve human values, assets, and institutions (10, 31, 120). Nature-based solutions (NbS) are part of or facilitate many or all stages of this co-production process to secure the supply of NCAs [see Bruley et al. (10) for an overview]. This can be illustrated by building from the NCA examples above. In an NbS such as community forestry, people regulate forest use to maintain forest conditions and its ecosystem functions such as soil and water regulation and tree growth. These functions generate timber NCAs, harnessed by the NbS through sustainable harvesting. Other NCAs, such as protection from flooding, landslides, and droughts, are appreciated by communities through their participation in the NbS and through educational outreach components of the NbS.

Their Link to Nature-Based Solutions?). Therefore, understanding how NbS may contribute to resilience to sustain adaptation goals entails, first, understanding how NbS affect underlying resilience mechanisms and, second, resultant resilience effects on NCAs.

There has yet to be a comprehensive review of how NbS may support this two-step process. Thus it remains unclear how NbS may provide adaptation benefits through time and as conditions change. However, recent conceptual advances, reviews, and other research on NbS have set the stage and identified the need for such work. For example, Woroniecki et al. (8) assess NbS effects on people's vulnerability to climate change. They looked at how NbS affect social and ecological exposure to climate hazards, sensitivity (i.e., the degree to which they are impacted by such exposure), and their adaptive capacity (i.e., ability to respond to the hazard's impacts). Both sensitivity and adaptive capacity are related to resilience (28) in that they describe how a system resists and responds to change, respectively. The study found that NbS affected these dimensions in many cases. However, the study did not systematically unpack the specific mechanisms through which they were affected.

Nature's contributions to adaptation (NCAs): a subset of NCPs that provide benefits to people from increased ability to respond to change (27)

Nature's contributions to people (NCPs): all the positive contributions (or benefits) and occasionally negative contributions, losses, or detriments that people obtain from nature (116)

Persistent NCA: previously existing nature contribution that continues to or increases its contribution in the face of climate change impacts (definition modified from 27)

Novel NCA: new nature contribution generated—through climate-induced ecosystem transformation and/or novel human–nature interactions—to support adaptation (definition modified from 27)

NCA co-production: a multistep process of social-ecological functions and interactions that enable the supply of NCAs (definition modified from 117)

Other research on NbS suggests their potential to influence many of these mechanisms. For example, Key et al. (29) assessed the different types of ecosystem health outcomes of NbS, many of which overlap with resilience mechanisms within the ecological elements of the SES, and found predominantly positive effects. However, their typology of outcomes was not designed to capture all the ways in which resilience could be supported. Meanwhile, Hajjar et al. (30) reviewed effects of REDD+ initiatives on resilience mechanisms but focused on social rather than ecological aspects. Indeed, there have yet to be studies on NbS that assess a more complete spectrum of resilience mechanisms across the whole SES. Moreover, Lavorel et al. (26, 31) established a framework to clarify how social-ecological interactions produce NCAs, explore a small set of mechanisms that enable these interactions, and test them in a small number of case studies. However, their mechanisms are not exhaustive and point to the need to analyze larger datasets.

Furthermore, there are different types of NCAs (see the sidebar titled What Are Nature's Contributions to Adaptation and What Is Their Link to Nature-Based Solutions?). These can be informative of the diverse types of adaptation outcomes that building resilience through NbS can enable (27). Lavorel et al. (26, 31, 32), Bruley et al. (10), and Colloff et al. (27) explore a small set of case studies on the effects of SES interactions more broadly on NCA delivery. However, different NCA types have yet to be evaluated from specific NbS.

Understanding NbS within an SES is also needed to address rising concerns that NbS are being framed such that nature is external and separate from people (33). Although such framing is problematic for numerous reasons, one particular problem is that it severely limits our understanding of NbS effectiveness for adaptation in a changing climate. For example, in some frameworks and debates on the effectiveness of NbS as adaptation strategies, the so-framed external ecological elements are not viewed as potentially vulnerable to the climate hazards they are implemented to address (34). Other frameworks account for this in that the external ecosystem's vulnerability is an important consideration of the limits to using NbS as an adaptation strategy (e.g., 34). Yet what remains neglected in these dichotomies is that ecosystems, through their interactions with the people who are part of and not external to them, have many mechanisms that enable ecosystems to build resilience and thus reduce vulnerability to such hazards (8, 26). The long history of indigenous land stewardship is a key testament of such potential (e.g., 35–37). For example, indigenous forest practices cultivate and maintain diverse species of plants, exceeding diversity levels in forests without their influence (38). Indeed, diversity is a key mechanism that can explain the persistence of such forests through time.

To address these gaps, we synthesize in this review research on the role of NbS on social-ecological resilience and their effects on NCAs. In the following sections, we first define and elaborate on a conceptual framework linking NbS to social-ecological resilience and NCAs we have introduced here. We then apply this framework to synthesize published evidence of NbS. In the process we ask, which resilience mechanisms are reported to be affected by NbS and what are the reported effects of NbS on NCAs. By assessing a large number of published studies on NbS, we reveal in-depth insight as to how they may affect social-ecological resilience and generate NCAs and also point to knowledge gaps in our understanding of this process. Finally, we discuss future applications of the framework and draw conclusions.

Our conceptual framework is designed to be applicable in any SES context. However, in this review we focus on NbS involving forest SES. Forest NbS provide essential adaptation benefits to communities worldwide, yet there are serious concerns about their effectiveness under future changing conditions (1). Indeed, they are facing a myriad of threats that may be undermining their capacity to withstand climate change hazards (39). Thus information as to the extent to which these concerns are or can be addressed is urgently required.

2. CONCEPTUAL FRAMEWORK OF THE CONTRIBUTION OF NATURE-BASED SOLUTIONS TO SOCIAL-ECOLOGICAL RESILIENCE FOR CLIMATE CHANGE ADAPTATION

We present a two-part framework to understand how NbS contribute to social-ecological resilience and the sustained supply of NCAs (see **Figure 1**). This two-part framework is in line with how Biggs et al. (23, 25) conceptualize the pathways through which resilience can be built in SES as well as work by Lavorel et al. (26, 31) and Colloff et al. (27) on NCA co-production by SES. We bridge these concepts while also drawing on other relevant research. The first part of the framework captures how NbS affect different underlying mechanisms within the SES that influence its resilience. To do this, we develop a typology of such mechanisms. The second part captures the resultant adaptation outcomes in the form of NCAs that are enabled by effects of NbS on resilience mechanisms.

To put the framework into context, however, it is important to clarify resilience-of-what and resilience-to-what (40) that the framework aims to capture. The former question refers to whether it is a particular aspect of a system that is of interest or whether it is the resilience of the system as a whole. In our case, we are interested in whole system resilience. The latter question refers to what types of disturbances or changes the system is building resilience toward. Although the framework includes elements that may be relevant to building resilience to a wide range of disturbances and changes, we focus on resilience to climate change. However, we are interested in considering resilience to any potential climate hazard as well as the uncertainty expected in which hazards and how they arise.

More recently, a third essential question has been stressed, resilience for whom (41). This is because people that make up an SES are not homogeneous and have differential power, agency, held values, and knowledges (42). These differences drive variation in resilience among people and how they are affected by resilience-building actions; however, such factors are rarely considered in resilience assessments (43–45). This can mask situations in which resilience for some is built at the expense of others, especially those afforded less power (46). We emphasize the need for equitable resilience (43) where such differences are accounted for to ensure the differential needs of all people are supported.

Lastly, we adopt the view that resilience may involve persistence, incremental adjustments, or complete transformation of its internal structures and functions (17, 22, 25, 47–49). Resilience is not just about resisting change or "bouncing back" to a previous state but also about "bouncing forward" to a new desirable state (17, 47). A distinction of resilience through transformation is

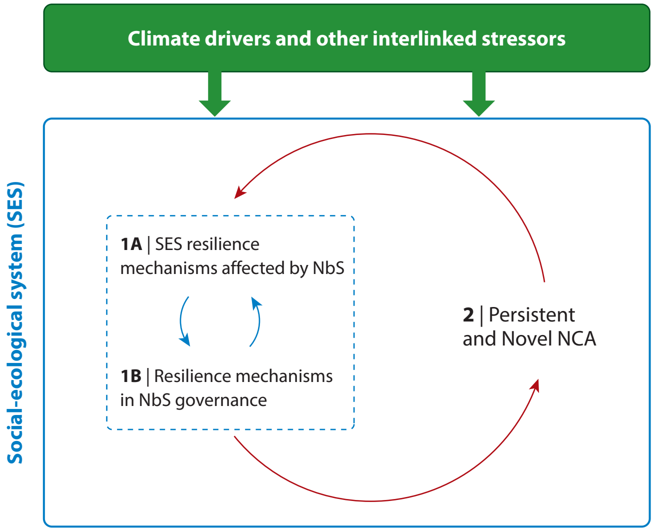

Figure 1

Conceptual framework of a nature-based solution (NbS) to support the resilience of its embedded social-ecological system (SES), in turn enabling climate change adaptation. The SES in which the NbS sits continuously experiences shock, stress, and change induced by climate or other interacting external stressors to which the SES must respond. The framework is divided into its two key parts: (1) Effects of the NbS on mechanisms that influence and underpin resilience, including (1A) generic mechanisms in the SES that are influenced by NbS governance and (1B) mechanisms that act in the NbS governance system or decision-making process. **Table 1** provides a typology of such mechanisms. These mechanisms, on their own or through interaction (represented by the arrows between 1A and 1B), ensure the supply of (2) desired nature's contributions to adaptation (NCAs). NCAs are benefits produced from social-ecological interactions that support human adaptation. NCAs may be persistent, meaning they were pre-existing, or novel, meaning they provide new ways of enabling adaptation. Mechanisms underpin the supply of NCAs at any given time but also ensure the supply of NCAs in the future. In turn, NCA supply can feed back to influence the resilience mechanisms themselves, both positively and negatively. Figure modified from Biggs et al. (23) with permission from the Annual Review of Environment and Resources, Volume 37 © 2012 by Annual Reviews, **http://www.annualreviews.org**.

critical because in some cases the current SES may be in an unsustainable, inequitable, or other undesirable state; thus, building resilience enabling its persistence would also be undesirable (47). Our framework, including the resilience mechanisms we have compiled, may be applicable to understand resilience regardless of whether the system is being modified more incrementally in order to persist or whether it is transforming.

2.1. Resilience Mechanisms

Conceptualizing NbS contribution to resilience entails understanding how NbS affect different elements within their embedded SES, which influence social-ecological resilience. We refer to these as resilience mechanisms. Assessing effects on resilience mechanisms is an indirect means of assessing resilience, inferring its potential to be so rather than identifying definitively whether a system is or will be resilient (50). At the same time, looking at effects on specific mechanisms provides information on how exactly an intervention may affect resilience, which can be informative for where future changes can be made to increase its effectiveness (51). Lastly, which mechanisms are promoted can provide insight as to whether an intervention is promoting resilience to present, known threats that ensure short-term benefits or promoting resilience to future known and unknown threats (i.e., managing for uncertain futures) to ensure long-term benefits. This is because certain mechanisms can be more important for one than the other (24).

Therefore, we compiled a comprehensive typology of SES resilience mechanisms that can be considered to assess how NbS affect this first part of the framework. The approach was deductive, relying on existing social-ecological resilience literature. From decades of empirical research, specific mechanisms have emerged as being the most important or relevant for social-ecological resilience. In one of the most comprehensive exercises to consolidate this research, Biggs et al. (23, 25) distilled these mechanisms into a set of seven principles. We used these principles as a foundation. We then referred to other sources, including more recent reviews on social-ecological resilience mechanisms. This helped to provide more specificity on mechanisms within those overarching seven principles while also expanding the types of mechanisms included. Any given SES is nested within larger SES at regional, national, and global scales, and there can be mechanisms acting at these higher levels (47, 52). However, we focus on mechanisms acting on the local level at which NbS predominantly act within an SES.

NbS governance: the exercise of deliberation and decision-making among groups of people who have various sources of authority to act (23)

Biggs et al. (25) and Quinlan et al. (50) further suggest that mechanisms can be grouped into those that relate to generic SES properties and processes that can be governed, and those that relate to properties in the SES governance process. We adopt this division, as it illustrates the ways in which NbS act within the SES. The generic SES properties (or mechanisms as we call them) are those that ensure continued SES functioning in the face of disturbance and change which NbS may affect. Yet the potential of NbS actions to positively affect these generic mechanisms is influenced by key mechanisms within the NbS governance system, or the processes of decision-making involved in designing, implementing, monitoring, and improving NbS (25, 53). Moreover, the governance mechanisms ensure the governance process itself is able to respond to change. This is akin to the concept of adaptive governance, or the form of governance needed to navigate change and uncertainty (54).

We also divided the generic SES mechanisms based on whether they were acting in the social versus the ecological subsystems. Within the ecological subsystem, we further divided mechanisms based on whether they acted at the individual, community, or landscape level, as per Oliver et al. (51). In the social subsystem, we divided them into broad types modified from Cinner et al. (55): diversity, organization, learning, assets, and agency. We added a sixth type, equity, to capture outcomes for equitable resilience. The distinction between social subsystems and governance mechanisms is that the former act within the broader social community of the SES, whereas the latter are narrowly focused on mechanisms acting in the process of NbS decision-making. **Table 1** provides the resultant list of mechanisms. **Supplemental Table 1** provides their corresponding definitions.

Supplemental Material >

2.2. Nature's Contributions to Adaptation

Resilience mechanisms interact to ensure the capacity of an SES to function and generate desired SES outcomes in the face of disturbance and change (25). As we are interested in the societal goal of adaptation, we consider NCAs a key desired SES outcome. Thus, resilience mechanisms act by contributing to or supporting the suite of social-ecological functions and interactions that generate NCAs (31) (for details on these functions and interactions, see the sidebar titled What Are Nature's Contributions to Adaptation and What Is Their Link to Nature-Based Solutions?). Moreover, NCAs can be grouped into different types. One such categorization is to divide them based on whether they are persistent or novel [based on a modified typology from Lavorel et al. (26) and Colloff et al. (27); see also the **Supplemental Appendix**]. The distinction between the two clarifies whether resilience-building enables the continued supply or emergence of new contributions to address adaptation respectively.

Table 1 Typology of social-ecological resilience mechanisms that may be influenced by nature-based solutions (NbS), categorized on the basis of whether they are generic mechanisms in the ecological or social subsystems influenced by NbS or whether they act in the NbS governance process[a]

Governance[b]	Social[c]	Ecological[d]
Type of governance system: decentralized, comanagement, or external Local community participation in decision-making: active, passive, mixed, or absent Knowledge types included in decision-making: external, local, or multiple Inclusion of local values in decision-making: present, mixed, or absent Application of adaptive (co-) management: present, or absent Understanding social-ecological systems as complex adaptive systems: Account for lag effects, cross-scalar interactions, trade-offs, and/or uncertainty.	Diversity: Livelihood Actor Knowledge and experience Social organization and capital: Knowledge exchange Bonding capital Bridging capital Attachment to place Potential for learning: Access to information Access to education Access to assets: Financial Technical Agency: Empowerment Rights and ownership Social acceptance Equity: Distributional Recognitional	Individual: Genetic diversity Phenotypic plasticity Sensitivity to environmental change Community/ecosystem: Species diversity Response diversity Functional diversity Heterogeneity (community level) Keystone species or functional groups Dominant species Strength of species interactions Habitat area Control of local threats Availability of resources Intact habitat structure Landscape level: Network structure Heterogeneity (landscape level) Ecological learning and memory

[a]Managing for feedbacks that can exist between all other mechanisms is a pervasive mechanism across the typology. Mechanisms are those that act at the local level in which an NbS acts rather than those acting at broader regional to global scales. **Supplemental Table 1** provides definitions. Key sources used to generate the typology include 23–26, 31, 42, 43, 50, 51, 55, 59, 61, 63, 85, 118, 119.

[b]Governance mechanisms require considering which particular characteristic or process is adopted by that mechanism, which we include in the table.

[c]Social mechanisms are divided into six broad types, modified from Cinner et al. (55).

[d]Ecological mechanisms are divided based on the level of biological organization in which they act, as per Oliver et al. (51).

Supplemental Material >

Long-term resilience: capacity of an SES to sustain desired outcomes in the long term in the face of future disturbance and change, including those known and unknown, enabling the capacity to navigate future uncertainty

Capturing NCA supply is important to understand the types of outcomes that resilience mechanisms can provide to enable adaptation. However, we acknowledge that NCAs as an SES outcome are limited in the sense that they are more an indication of fulfilling human-centered outcomes. This is not to suggest that the only focus of promoting resilience through NbS is to serve people nor does their supply necessarily only indicate human well-being. Because they are underpinned by supporting mechanisms within the inseparable social and ecological subsystems, their supply relies on and can indicate the integrity of nonhuman elements as well. Maintaining both subsystems and their interactions is a fundamental component of NbS (2).

Furthermore, inclusion of NCAs in the framework is also necessary to understand long-term resilience of the SES, because harnessing NCAs feeds back to influence the resilience mechanisms themselves (31). The aim should be for positive feedbacks. A key example is where human appreciation of NCAs motivates or enhances ecosystem stewardship to support ecological resilience mechanisms (56). Yet there could be unintended negative feedbacks, such as when harnessing the NCAs degrades the ecosystem in the long term, as in the case of overharvesting timber. Thus, in order to promote resilience through time, care must be taken to minimize any negative feedbacks and, rather, promote a reciprocal exchange between human and nonhuman nature (33, 56).

3. CONCEPTUAL FRAMEWORK APPLICATION

We applied our conceptual framework to analyze pre-existing literature on NbS adaptation strategies in order to assess how they contribute to social-ecological resilience and NCAs in forests. Specifically, we draw on an existing database from Chausson, Turner, and their coauthors' (6) global systematic map of peer-reviewed studies investigating the effects of NbS on climate impacts or other hydrometeorological hazards.[1] It captured all relevant literature published up to April 2018 [see Chausson, Turner, and coauthors (6) for a detailed description of scope and methodology]. Since publication, it has been updated to April 2020 as part of a broader review of NbS on local development (57). We included these more recent studies, although the update focused on studies from low- or lower-middle income countries. We extracted all studies where the NbS involved at least in part a forest ecosystem, although they may also have involved other ecosystem types as well. We further refined the studies to include only those where adaptation to climate impacts or other hydrometeorological hazards was at least one of the intended goals of the NbS in order to understand how NbS specifically designed to deliver adaptation may be influencing resilience to deliver these benefits now and into the future.

Through this exercise, we captured 37 studies comprising 41 unique NbS addressing adaptation in forests (see **Supplemental Table 2**). The NbS were for the most part distributed equally across continents including Asia and the Pacific (11 NbS), North America (11 NbS), Africa (8 NbS), and Europe (8 NbS). The exception was Latin America and the Caribbean for which only two NbS were found, which may be because only studies published in English were included. The majority of NbS involved at least in part a lowland forest (29 cases). Montane forests were reported in 12 NbS and riparian forests in six. The studies captured all of the broad types of NbS [see Chausson, Turner, and coauthors (6) for definitions and examples], and 18 of the 41 NbS involved a combination of different types (e.g., the NbS involved a combination of protecting and restoring forests). Protection was reported as at least one of the types in 16 NbS, restoration in 18, and management in 25.

Supplemental Material >

A prerequisite for inclusion in the original dataset was that studies had to report effects on at least one NCA (part 2 of the framework) [see Chausson, Turner, and coauthors (6)—although they did not use the term NCA itself]. Thus, studies reporting only effects on resilience mechanisms (part 1 of the framework) would have been excluded if they did not also report NCA effects. Nonetheless, it provides a valuable resource to investigate how NbS influence both parts of the framework—showing how NbS that have reported effects on NCAs are also affecting the resilience mechanisms that underpin them.

In the following two sections, we present and discuss the findings of the framework application. Section 1 of the **Supplemental Appendix** provides details on how we applied the framework to the case studies. Although we focus on the different elements of the framework separately as we aim to look at how NbS are reported to affect each element across the dataset, we also provide

[1]We use the term NbS to describe the nature-based actions captured by the studies loosely since we did not fully appraise each action as to whether it met the more specific recent criteria emerging as to what should or should not count as an NbS. However, as a primary filter, we did exclude actions that exclusively relied on afforestation that did not explicitly promote ecological integrity [which were included in the original dataset by Chausson, Turner, and coauthors (6)] given the strong consensus that this should not be considered an NbS (5).

Supplemental Material >

Short-term resilience: capacity of an SES to sustain desired outcomes in the short term in the face of current known disturbances and changes

a set of examples to show how individual NbS affect all parts of the framework to influence SES resilience and deliver NCAs (**Supplemental Table 3**).

4. WHAT ARE THE EFFECTS OF NATURE-BASED SOLUTIONS ON RESILIENCE MECHANISMS?

We sought to understand how resilience mechanisms are reported to be affected by NbS as a means of assessing their potential to influence resilience. We looked at individual mechanisms to uncover the specific ways they may be underpinning resilience. This also helped us understand NbS potential to support resilience into the future to enable long-term adaptation effectiveness. All forest NbS except one were reported to affect at least one mechanism associated with social-ecological resilience and suggested that NbS are reported to act in ways that enable forest SES to be resilient to climate impacts. Although several mechanisms reported were important for shorter-term resilience, some important for the long term were also supported. However, our understanding of specific effects diverged between the different subsystems of the SES at a few points. We found a diverse range of social subsystem mechanisms that are associated with building resilience in both the short and long term. There is, however, an absence of reporting on social mechanisms related to equitable resilience. In contrast, in the ecological subsystem, a few mechanisms predominated, and there was an absence of reporting on key mechanisms related to long-term resilience. In the governance system, reported effects on several resilience mechanisms reflect what is needed to build resilience, yet effects on others do not. At the same time, we have limited knowledge of some of the key governance mechanisms needed to promote long-term resilience in the face of uncertainty. Importantly, absence of evidence does not imply that NbS do not affect such elements. Rather, it reflects what has been studied, thus calling on the need for future research. We expand on these key findings below.

4.1. Mechanisms in the Social and Ecological Subsystems

Generic resilience mechanisms acting in the social and ecological subsystems enable social-ecological resilience by ensuring the functioning of the SES in which the NbS sit is sustained through time. We looked at which resilience mechanisms were reported to be affected by each NbS. Of the many mechanisms known to promote resilience within the ecological subsystem, the evidence is dominated by only a few of these mechanisms. These were namely intact habitat structure, control of local threats, habitat area, species diversity, and species sensitivity to environmental change (**Figure 2**). For example, a combination of protection and restoration actions often enabled the regeneration of forest vegetation structure and increased the area covered by the forest. Local threats were controlled in instances such as in community forest management schemes that successfully eliminated or reduced illegal or overexploitation of timber or uncontrolled human-induced fires. Examples of altering species sensitivity to environmental change include assisted species migration schemes for reforestation. Here, provenances of the same species from other areas better adapted to the changed conditions of the reforested area were introduced. Other mechanisms were reported on in fewer than five (12%) of NbS, and no NbS reported effects on phenotypic plasticity, genetic diversity, or strength of species interactions (**Figure 2**).

Most effects on mechanisms were positive, meaning they were explicitly reported to either increase or be supported and maintained by the NbS. However, although there were only two negative cases, there were several mixed effects (12% of the total number of outcomes reported on ecological mechanisms), predominantly because the effect varied spatially or temporally. For example, local threats were controlled in some forest stands in the management area but not all. In other cases, for example, habitat structure, it was mixed because the NbS had a positive effect on above-ground vegetation structure, but failed to have an effect on root and soil structure.

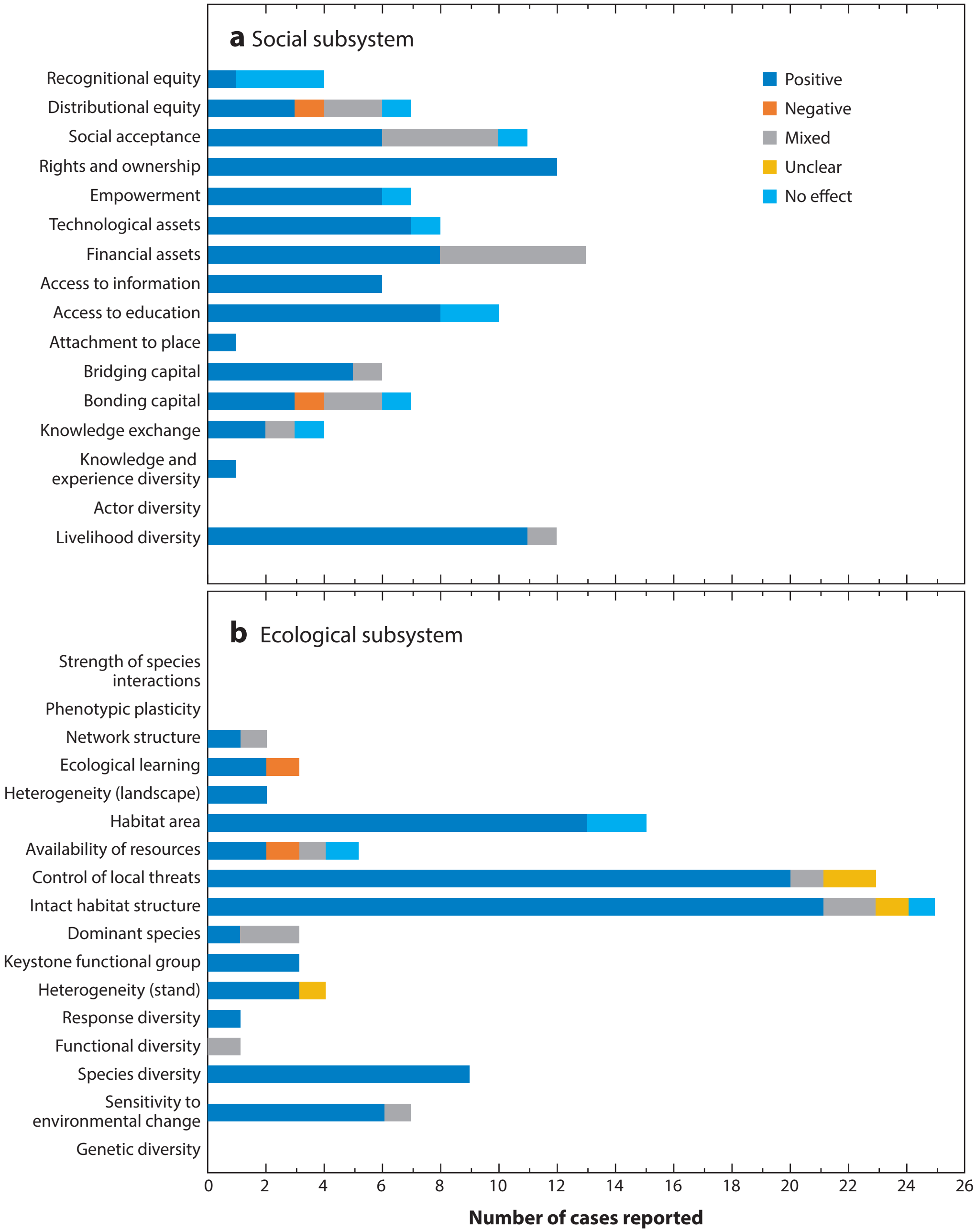

Figure 2

Number of cases that reported effects of a forest nature-based solution on each generic social-ecological resilience mechanism and whether the effect was positive (i.e., the mechanism increased or was supported), the effect was negative (the mechanism decreased), there was no effect (the mechanism was not supported), the effect was mixed (e.g., effect varied spatially or temporally), or the effect was unclear (the authors were unable to determine the effect). Mechanisms are divided based on whether they act in the social subsystem (*a*) or the ecological subsystem (*b*).

We presume that positive effects on generic social-ecological resilience mechanisms are associated with an increase or maintenance in resilience (24–26, 39, 42, 51, 55, 58–61). Thus, this predominance of positive effects suggests that NbS in forest SES are largely reported to support the capacity of their ecological subsystems to be resilient to climate hazards or changes. However, which mechanisms were predominantly reported on suggests they may be promoting resilience in the short term to known threats rather than resilience in the longer term, including resilience to unknown future threats. Particularly, intact habitat structure may be important for supporting resilience to more immediate known threats (62). For example, in several cases, it ensured forest functions of water storage and soil erosion control were maintained specifically in the face of precipitation variability. Yet vegetation intactness alone may be less able to maintain these functions in the face of other threats. Modifying species sensitivity will also likely only promote resilience to specific known threats if their sensitivity to only those threats is considered, as was the focus in the NbS cases found here. Yet effects on many mechanisms considered key for long-term resilience and dealing with uncertainty (e.g., 24, 63) were rarely or never reported on. These include response diversity, stand and landscape heterogeneity, genetic diversity, landscape structure including connectivity, and ecological memory (i.e., traits retained following disturbances that enable future disturbance response). For example, promoting a diversity of tree species that respond and recover from various disturbances differently increases the chance that at least some species will persist and preserve forest functions in the face of a range of known and unknown hazards in the long term (64). Connectivity also facilitates recovery from various and unexpected disturbances through time through dispersal from nearby forest patches less damaged by disturbance events (65). In turn, conceptual and modeling studies are showing how forest practices can be adapted to promote these mechanisms under future climate-related hazards (39, 66, 67).

Adaptation actions focusing on short-term or specific hazards are troubling, as they may undermine building longer-term resilience to future and novel threats (22, 62, 68). This will limit the capacity of NbS to be effective over time and deliver their full potential. Others who have appraised the targets of forest NbS, e.g., Messier et al. (39), have observed this focus on shorter-term known risks. For example, a review in Mediterranean forests found that strategies reflect short- rather than long-term risk management and rarely managed for genetic and species diversity as well as stand and landscape heterogeneity (69).

Importantly, however, absence of reporting on other mechanisms does not necessarily mean that NbS were not affecting them, either intentionally targeted by implementers or not. It may be more a reflection of what has been studied. For example, the most documented mechanisms can be easier or less expensive to measure. Yet because studies fail to measure these mechanisms, our knowledge as to the potential of NbS to promote long-term resilience is constrained. We also note that our dataset excluded studies reporting only on resilience mechanisms that in turn did not report effects on NCAs, which could provide additional insight on this question. For example, a recent study on community forests in British Colombia indicated increased stand and landscape heterogeneity through species diversification and uneven-aged tree management as a climate change adaptation strategy (70). Nonetheless, this knowledge gap in our understanding of forest adaptation strategies has been identified elsewhere (e.g., 71). Thus, future assessments of NbS that include outcomes on these mechanisms are needed. The few exceptional cases we did find that measure such mechanisms shed some light on how NbS in forests could be managed for long-term resilience. In one example, degraded community forests were replanted with a mix of native species that respond differently to disturbances and were planted in modular blocks; community members have already perceived that this approach helped forests deal with and constrain unexpected threats such as drought, pests, and fire (71). Moreover, the number of instances reporting increased or maintained habitat area is promising. This mechanism is predominantly known to influence resilience by promoting other mechanisms (see 51) including those for long-term resilience. The same could be said for the many cases reporting control of local threats because such threats can otherwise erode other resilience mechanisms. For example, overharvesting can cause forest fragmentation, reducing landscape connectivity.

Furthermore, most of these mechanisms are those that act at the community or ecosystem level, with very few acting at the individual or landscape level. This is despite the fact that NbS are often implemented at a landscape scale (6). The lack of measures at the landscape level such as forest connectivity is troubling, as the resilience of any given forest stand is dependent not just on its own properties but also its connection to and condition of the surrounding landscape (39, 72).

As opposed to the ecological subsystem, the evidence in the social subsystem was more evenly spread across different types of mechanisms. The most common were livelihood diversity, financial assets, rights and ownership, social acceptance, and access to education and information (**Figure 2**). There were also several cases reporting on technological assets, empowerment, bonding capital (including trust, social cohesion, and sense of community), and bridging capital (including stakeholder connectivity) (**Figure 2**). For example, rights and ownership were often supported where forest restoration or management initiated by governments handed over land ownership to local people and/or rights to make decisions on how forests should be managed. Livelihood diversity was enhanced where protected and sustainably managed forests provided a range of income sources from timber or other nontimber forest products. Access to education and information increased through training programs on new forestry techniques. Bridging and bonding capital such as the formation of stakeholder networks, trust-building, and community cohesion resulted from setting up community forest user groups where community members started meeting regularly to make management decisions.

Most reported effects on mechanisms were positive (72% of the total number of outcomes reported on social mechanisms) and, thus, these studies capture a diverse range of ways in which NbS in forests affect elements in their embedded social subsystems to support resilience. Interestingly, unlike the evidence for the ecological subsystem, more short-term and long-term resilience-oriented mechanisms were reported on. More short-term mechanisms included, for example, several cases reporting effects on assets including technological and financial. In many such cases, these mechanisms were essential for initially establishing the NbS to respond to immediate challenges, for example, external organizations providing funding or technical resources. Moreover, there were several outcomes for the broad categories of social organization, agency, and learning—all important for long-term resilience and dealing with uncertainty, although they may also be important for short-term resilience as well (73–77). For example, a community forest in Nepal promoted social connectivity and learning that increased resilience to both immediate and future unknown risks (78). This was done through a user group platform to collectively decide how to respond to current forest threats and to meet regularly through time to enable responses to new risks as they emerged.

Moreover, out of the six broad categories of resilience mechanisms in the social subsystem, it is notable that agency had the most number of reported outcomes. This dimension is often not considered in resilience assessments (55). Cinner et al. (55) emphasize that although many mechanisms provide the necessary tools or enabling conditions to support resilience, these can only be put into action if people have the confidence or willingness to make use of them. This was highlighted in an example from Ethiopia where an international NGO provided training on new forest restoration strategies. Land rights were granted, which increased agency by increasing people's willingness to take part, thus enabling them to make use of such financial and technical mechanisms provided (79).

Although most cases reported positive outcomes, there were a number of mixed outcomes (14% of social mechanism outcomes) or instances where the NbS was not able to have an effect on the mechanism (10%). Both types of effects were mostly associated with issues of equity, as explained below.

The few notable knowledge gaps included effects on social diversity beyond livelihood diversification and effects on equity (particularly recognitional). Lack of reporting on NbS equity outcomes has also been highlighted elsewhere, such as in a review of NbS in mountain regions (20). These gaps in social diversity and equity also reflect a consideration often absent in resilience and adaptation assessments in that communities are not homogeneous but vary across many dimensions including level of power, age, gender, knowledge, background and experience, and values (43, 80). This diversity influences whether and how people may be affected by a local adaptation action, including who bears the costs of the intervention and who receives its benefits (80). In turn, this diversity is essential for understanding the question of resilience for whom and promoting equitable resilience (42, 43). This was highlighted in the few cases that did report on equity. For example, in a community forest in Myanmar, locals who attended regular meetings empowered themselves, built social cohesion, and bonded with other members. However, poorer households were unable to attend meetings due to the time it took away from work and thus did not gain such benefits (81). In turn, it was these cases of negative equity effects that were associated with mixed outcomes for other social mechanisms because the NbS had positive effects on some social groups but not others. These cases were also associated with most cases of no effect because they failed to acknowledge recognitional equity. Indeed, Woroniecki et al. (8) identified such socially differentiated outcomes as a key issue in understanding how NbS affect social vulnerability more broadly. Unequal distributions of costs and benefits have also been reported from other reviews of NbS in forest SES (e.g., 82). The lack of reporting on equity in other NbS cases means we do not know the extent to which this may have been at play in these cases as well. It moreover implies that the positive results for other resilience mechanisms from these NbS need to be interpreted with some caution, as uneven distributions within the community may have remained hidden.

An important point, however, was that several NbS cases only reported outcomes within the ecological subsystem, and none within the social subsystem. This reflects a limited view of how NbS act, disregarding that they affect the SES as a whole (2, 20, 21). A few of the studies here captured the consequences of only considering effects on the ecological subsystems. For example, there were cases where NbS were successful in promoting ecological subsystem resilience by establishing protective no-access rules. Yet these strict rules did not consider local needs for forest products as income sources in times of need degrading social subsystem mechanisms of resilience. This echoes other cautions that gains in the ecological subsystem's resilience will fail to translate to social-ecological resilience if people are excluded from the forest (30). Not accounting for ecological mechanisms is also problematic. In our studies, this often reflected cases where there was a failure to consider that the ecological subsystem is also exposed to the climate hazards the NbS are addressing and thus there is a need to ensure their resilience is also promoted. For example, an adaptation project involved regenerating woodlots to protect homes from windstorms, but the tree species chosen could not withstand droughts and storms (83).

4.2. Mechanisms in Nature-Based Solutions Governance

There are important mechanisms in an NbS governance system, or its process of decision-making, that are key for ensuring it is able to promote generic resilience mechanisms in its embedded social and ecological subsystems, while ensuring that the process itself is able to navigate change (50).

The mechanisms within the governance system for which there was the most evidence include type of knowledge included in decision-making (reported in 88% of NbS cases), governance structure (58%), and attributes of complex adaptive systems (CAS) thinking (68%). Information on the other mechanisms (adaptive management and inclusion of local values) was found in less than half of the cases (29% and 48%, respectively). Instead of coding direction of effect as with social and ecological mechanisms, it was more relevant to code the process or characteristic adopted for each mechanism to understand if reported outcomes were associated with resilience support or maintenance (see Section 1 of the **Supplemental Appendix**). In doing so, a mixed picture was found as to whether NbS governance systems are promoting resilience, as explained below.

Supplemental Material >

On the one hand, where reported on, most NbS indicated active participation of local community members in the decision-making process, and local values were explicitly taken into account (63% and 70% of NbS cases that reported on participation and local values, respectively). Similarly, the majority of forms of governance are those where community-level institutions are at the center of decision-making (i.e., most were either decentralized or comanaged) (75% of NbS cases), and there were very few that were externally controlled (20%). This predominance of inclusion of local values and engagement and more bottom-up than top-down forms of governance are suggested as essential ingredients to building resilience (e.g., 84–87). One telling example from Tanzania compared a top-down government-managed forest versus a traditionally managed forest in the same region (88). It showed the latter had active local engagement and considered local values—including both basic and spiritual needs. This maintained healthier intact forests by ensuring rules were followed and modified where necessary. In turn, the forest SES was more resistant to climate hazards. In the government scheme, rules lacked cultural relevance and were neither understood nor followed, resulting in a poorer quality and less resilient forest.

On the other hand, results of knowledge types showed few instances of inclusion of multiple forms of knowledge and a specific lack of local knowledge inclusion in the decision-making process. For those cases where knowledge was reported on, 75% of these cases relied on only external knowledge, including scientific and practitioner knowledge. Local knowledge was exclusively used in 16% of these cases and only 8% included both types of knowledge. This finding is consistent with other recent evidence of the absence of local, and more specifically, indigenous knowledge in NbS (e.g., 20, 89). The lack of knowledge diversity, and relying more on external than local sources, is counter to what is needed to build resilience for numerous reasons (76, 90, 91). It limits the understanding of the problems facing the system and the pool of potential locally relevant solutions to address the problem (36, 92, 93). At the same time, it disempowers and hinders agency of local people to respond to threats and participate in the decision-making process (94). In one example here for instance, in a communal forest in Zimbabwe, indigenous knowledge was essential in recognizing the onset of climate threats to the forest and also for creating effective solutions, in line with the cultural values of the community to ensure rules were adhered to (95). Indeed, there is a rich and strong evidence base of the resilience of indigenous communities to environmental change, of which their knowledge base, and the process of its creation and transmission, is an essential component (36, 96).

Moreover, few NbS cases provided information as to whether adaptive management was part of the process or not (29% of NbS). This type of management involves an iterative learning process of monitoring and evaluating for continual management improvement. Thus, we have limited knowledge as to the extent to which this process is included in these forest NbS and in what regard. Lastly, we looked at whether or not NbS cases adopted CAS thinking. CAS have interconnected components that enable self-organization and adaptation and also emergent outcomes that are often unpredictable (23). SES have been generally assumed to be an example of a CAS (97). Thus, CAS thinking is defined as "a mental model or worldview that views SES as CAS and appreciates the resulting implications for management" (25, p. 146). Although adopting CAS thinking may not itself necessarily support resilience, it is theorized to enable decision-makers to take a more holistic approach to management that results in the promotion of other resilience mechanisms that do directly support resilience (25, 63). We looked at whether NbS considered four different attributes of CAS thinking: accounting for lag effects, cross-scalar interactions, trade-offs, and uncertainty. Although most cases (68%) reported that at least one of these attributes was considered, they rarely reported on more than two (mean 1.5). Thus, more research is needed to understand the extent to which NbS are accounting for CAS attributes within their governance models. The limited evidence for adaptive management and CAS thinking also constrains our understanding of whether the NbS governance processes are in line with what is needed for long-term resilience, as these are key elements needed to navigate change and uncertainty. CAS thinking enables challenges to be embraced rather than avoided, and adaptive management, through iterative monitoring and evaluating, ensures interventions can be modified in light of new information and to adapt to changing conditions (25, 74–76). One telling example we did find came from farmers in Peru who acknowledged that their landscape and the threats facing it (both climate and other) were constantly changing and thus they were continually experimenting with new approaches to address these threats. Through the process, they started incorporating more forest patches to restore and protect long-term soil health (98).

It should also be noted that, as mentioned previously, literature that did not report outcomes on NCAs was excluded, which would include literature focused exclusively on governance attributes of NbS in forests. From this body of literature on governance we missed, further examples could be drawn on to show how forest NbS have incorporated resilience governance mechanisms (see, e.g., 70, 99–101 for a few recent examples). Nonetheless, how often these mechanisms are supported or not across NbS adaptation strategies in forests is unknown.

5. WHAT ARE THE EFFECTS OF NATURE-BASED SOLUTIONS ON NATURE'S CONTRIBUTIONS TO ADAPTATION?

Supplemental Material >

Resilience mechanisms underpin the supply of NCAs in the face of change and disturbance. As such, assessments of NCAs can show the different ways that building resilience through NbS can support adaptation outcomes. We reported on all NCAs influenced by each NbS and characterized whether they were persistent or novel. This was to give an overview and initial insights about these types of outcomes. The forest NbS here reported effects on a range of NCAs, the most common being water supply, soil erosion control, timber provision, and flood protection (for a complete list, see **Supplemental Table 4**). However, outcomes were largely through the supply of persistent, previously valued NCAs rather than novel types for which more evidence is needed. Moreover, the majority of NbS reported positive outcomes for NCAs, although there were some instances of trade-offs and lack of reporting on multiple NCAs simultaneously. We noted that authors made at least one explicit link between mechanisms and the NCAs reported in all but two cases. Yet we were not able to capture the full extent to which mechanisms affected by NbS enabled these NCAs across all cases. However, we expand on these findings below through examples that illustrate how resilience mechanisms can underpin NCAs. We also discuss how the NCA outcomes on their own have implications for understanding whether an NbS may be supporting long-term social-ecological resilience.

Indeed, there is a dominant focus on persistent NCAs (found in 81% of NbS)—meaning that benefits had already been supplied by the SES in the past. Persistent NCAs were often those that had previously supported adaptation to climate hazards, such as erosion or flood control, but had become lost due to forest degradation. Reforestation, that recovered resilience mechanisms such as intact habitats, enabled these NCAs' recovery and persistence. However, there is less evidence on how novel NCAs may be supplied (found in 29% of NbS), and only 10% of NbS cases reported outcomes for both types of NCAs. Novel NCAs are those that arise because of new ways that people interact with ecosystems and/or because climatic changes have transformed the ecosystem itself such that it can now supply different NCAs. For example, through resilience mechanisms such as learning and access to assets, NbS enabled people to think of and be able to harness new uses of forest resources to substitute their other forms of income that were more sensitive to climate shocks. Such a case occurred in a community forest user group that provided poorer households with livestock that could graze sustainably in the forest to provide a new source of income (78). There were also instances where forests were now managed to ensure they provided the key role of protecting water sources as droughts became more severe, such as in the Mediterranean (102). The focus on persistent NCAs may reflect a knowledge gap in what is researched and/or a bias of NbS adaptation strategies to more often consider nature's contributions that are already recognized. The latter may be because changes experienced were not great enough for the need to consider novel benefits (in that persistent benefits are still sufficient and important) and/or to transform the ecosystem. However, ecosystem transformation may have occurred but was still able to support the same NCAs. Yet it may also reflect a limited capacity of an NbS to consider and support novel values as options for adaptation benefits. In turn, this knowledge gap constrains our understanding of whether these NbS in forests may be building resilience for the long term. It may be more often novel values that are supported from a long-term approach that considers whether persistent values are no longer attenable under changing conditions (26).

The predominance of positive NbS effects on NCAs (64% of all NCAs reported on) reenforces previous reviews on the benefits of forest NbS in human adaptation (6, 103). However, we did identify some trade-offs between NCAs, reported in 19% of all cases. For example, natural regeneration of forest slopes in the United States restored resilience mechanisms such as dominant tree species, but this had variable effects on flood protection and water supply during droughts (104). Moreover, we found that most cases reported effects on only one or two types of NCAs (80% of all NbS), meaning other trade-offs could have gone unreported. This also constrains insight as to how multiple NCAs could be supported simultaneously. As with a lack of reporting on novel NCAs, these findings also restrict understanding of whether these outcomes are stemming from a long-term resilience approach. The example above emphasizes the key fact that some efforts to build resilience may not support all potential NCAs (105). A long-term resilience approach will be one that aims to learn about and minimize such trade-offs to support a range of NCAs (106).

6. DISCUSSION

We have provided a two-part framework in order to understand how NbS may contribute to social-ecological resilience to support climate change adaptation. It first identifies which mechanisms an NbS affects that underpin an SES's resilience. Second, it characterizes adaptation outcomes in the form of NCAs that are supported by building resilience. We applied the framework to a set of studies on NbS in forest SES to assess the evidence of these NbS on this process.

In assessing the first part of the framework, we found forest NbS are influencing a range of resilience mechanisms across its embedded SES. These include those that act within the ecological and social subsystems and also within the NbS governance system. Most effects suggested NbS are acting in ways to support or increase resilience. However, there were a few exceptions such as a lack of including multiple forms of knowledge in NbS decision-making and some evidence that positive social mechanism outcomes are unequally distributed.

Although the prevalence of resilience-building outcomes reported is encouraging, we found that it remains unclear if particular efforts needed for long-term resilience, rather than just short-term, are occurring. Different mechanisms can be important for resilience under different timeframes. It appears that NbS are supporting several mechanisms within the social subsystem important for resilience on both time horizons. For example, they promote human agency that can enable people to take charge of their own circumstances to respond to present and future changes. However, there is a lack of reporting on mechanisms in the ecological and governance subsystems that are important for long-term resilience. Thus, overall, existing evidence is still incomplete and more research on long-term mechanisms is needed. These findings add to growing concerns about the uncertainty of whether forest NbS will be resilient enough to be able to continue delivering adaptation and other benefits under future climate changes (1). A few examples we have found here, however, point to how such challenges can be addressed.

The findings of the second part of our framework showed that NbS were reported to influence a range of NCAs, mostly positively. These results demonstrate the variety of ways that NbS can contribute to adaptation. They also show the types of outcomes that social-ecological resilience can sustain. However, evidence was mostly for sustaining already valued NCAs rather than by generating novel NCAs. They also often did not consider effects on multiple NCAs simultaneously, constraining insight on potential multifunctionality as well as trade-offs. A long-term resilience approach for a changing future will be one that considers where previously valued NCAs may no longer be attainable. It is also one that aims to promote a range of NCAs with minimized trade-offs. Thus, future research is needed to explore NbS potential to provide novel NCAs and NCA multifunctionality.

Our aim was to report on and better understand NbS effects on each dimension of the framework. However, there were a few aspects of the framework that our analysis did not capture that provide grounds for future work. First, our framework shows that resilience mechanisms enable NCAs. We did not aim to capture the full extent to which resilience-building enabled the reported NCAs in each case. We reported on mechanisms regardless of whether they were linked to reported NCAs because they nonetheless may be important for other NCAs not reported in the study, for supporting resilience beyond NCA delivery, or for ensuring resilience and NCA provision into the future. Likewise, we reported on all NCAs regardless of the extent to which mechanisms supported them, because such attribution may not have been made by studies. Examples from other research on specific case studies have sought to identify these links (e.g., 12–15). We have also provided numerous illustrative examples. However, further work on this is needed to more systematically map these relationships and understand these complex dynamics.

Second, we did not aim to make any conclusions as to whether each individual NbS was definitively supporting social-ecological resilience or not. This was not possible for several reasons, given that we were applying the framework to published studies that did not necessarily aim to assess resilience. First, increasing and/or supporting a resilience mechanism is predominantly associated with increasing and/or supporting social-ecological resilience. However, this may not always be the case (25). Second, we recognize that which mechanisms actually translate into resilience, and which are more important than others, depends on the local context (107). Therefore, an effect on any one mechanism reported by an NbS may not be relevant for supporting resilience in that particular situation. Related to this, we only have information on the mechanisms reported by the study. However, others not reported on may be as or more important in a particular case. Third, in order to understand how an individual NbS influences resilience, effects on each part of the framework and its interactions need to be analyzed together, as explained below.

Our framework emphasizes that resilience mechanisms do not act in isolation to generate effects on social-ecological resilience. Instead, they act through interactions and feedbacks with other mechanisms (25, 55). Indeed managing for such feedbacks to ensure they unfold in such a way that their outcomes support resilience is itself a key resilience mechanism (23, 56). Although we did not map all such interactions, we noted that at least one interaction or feedback was reported in all studies that reported outcomes for each of the social, ecological, and governance mechanisms. For example, in community forests in Nepal, taking local values into account (a mechanism within NbS governance) resulted in planting a diversity of tree species (ecological subsystem) (71). This was because this diversity supported the range of forest products they wished to harvest. In another case, women empowered themselves by having access to education in the form of forest management training (social subsystem) which enabled them to take an active role in decision-making (governance) (81). However, not accounting for all local values (governance) in the case of managing a riparian buffer zone led to a lack of trust from the neglected stakeholders and reduced social cohesion (social subsystem) (108). In turn, management actions these stakeholders were responsible for decreased, and there is evidence that habitat intactness (ecological subsystem) is degrading as a result.

Moreover, the framework emphasizes that harnessing NCAs can feed back to affect the mechanisms. Other research has emphasized the potential of a positive feedback loop, or a virtuous cycle, where perceived benefits of NCAs can motivate ecological stewardship and thus the promotion of ecological subsystem mechanisms through time (56). Although we could not capture these feedbacks across all studies, we did identify examples of this. For instance, people were reluctant at first to participate in reforestation schemes, yet after seeing neighbors' success in climate-adapted livelihoods generated from restored forest resources, they were convinced to join and the area of forest increased. Future studies that more rigorously explore these connections across the framework are needed to better understand the net effects of NbS on resilience through time. As with SES research in general, this will require interdisciplinary approaches and teams to bridge and integrate social and ecological phenomena (109).

These examples of feedbacks and interactions both between mechanisms and between mechanisms and resultant NCAs show clearly the complexity of SES and the pathways of building or inhibiting resilience. They further illustrate the inseparability and interdependence between people and nature. Although this has been appreciated and embraced by people throughout history, notably many Indigenous Peoples (110, 111), it is crucial that all NbS recognize this in tangible ways. Our framework provides one entry point to better understand how NbS can promote these relationships. Indeed it emphasizes a holistic NbS approach, not narrowly focusing on providing human benefits such as NCAs but one that accounts for underlying resilience mechanisms across its embedded SES.

In order to more accurately capture SES resilience and NCA outcomes within an NbS, the framework could be applied to case studies on the ground. To this effect, to ensure its accuracy in capturing local dynamics, assessments should be implemented in partnership with the people living in the target SES (107, 112). Such cocreation and application can also help identify additional resilience mechanisms that we did not capture from the academic literature, especially where knowledge from local worldviews is harnessed (113). It can also reveal how such a framework based on theory can be amended to better understand each unique SES context and reflect local conceptualizations of resilience.

In addition to general knowledge generation on how NbS operate, future on-the-ground framework applications could also be used to guide improvements in NbS or inform initial NbS design. The framework is based on mechanisms that can be actively modified. Therefore, the assessment can reveal where exactly actions could be directed to increase resilience. We acknowledge, however, that there may be many challenges to altering mechanisms and increasing resilience. One key example are power asymmetries. These can be a barrier to promoting inclusive and multi-knowledge decision-making, as well to ensuring benefits are distributed across communities in order to ensure equitable resilience (44, 94, 114). Moreover, we have focused on mechanisms at the local level in which NbS act. Yet any SES are nested in broader SES at regional to global scales, and mechanisms at these levels will also need to be considered (47). For example, we focused on local-level governance types, but polycentric governance, which has governance units at multiple linked and nested scales, is also argued to be a key resilience mechanism (23). Trade-offs with how such changes to promote resilience may affect other SES objectives must also be navigated (15). Understanding all of these factors is an area of active research (44, 48, 115). These will need to be integrated to better inform how NbS can support resilience.

7. CONCLUSIONS

Although NbS are increasingly gaining traction in adaptation policy and practice around the world, it is critical that they are designed and implemented to ensure they are able to continue functioning in the long term under a changing climate. In other words, these actions and the SES they support must be resilient to climate change. This, in turn, will enable NbS to sustain adaptation outcomes such as NCAs. This review has clarified that NbS in forest SES are helping to build their resilience and in turn provide a range of adaptation outcomes. However, there is an incomplete picture of whether these NbS will enable long-term resilience rather than resilience only in the short term. Addressing this critical evidence gap by applying our framework to a diverse range of social-ecological contexts will help clarify and strengthen this understanding. To fulfill these research avenues, we add to calls for more interdisciplinary, participatory NbS research (33) to ensure sustainable and equitable contributions of NbS to address adaptation and other societal challenges.

SUMMARY POINTS

1. Understanding how nature-based solutions (NbS) contribute to resilience for climate change adaptation requires conceptualizing NbS as social-ecological systems, investigating NbS effects on underlying mechanisms that support resilience, and investigating NbS effects on nature's contributions to adaptation (NCAs).
2. Existing evidence of NbS adaptation strategies in forests suggests that these NbS positively affect numerous different underlying mechanisms and may thus support social-ecological resilience.
3. Whether NbS will enable resilience in the long term rather than just in the short term remains unclear based on current evidence. On the one hand, NbS positively affect specific social subsystem mechanisms that are needed to build long-term resilience. Examples include promoting human agency and connectivity. However, there is some evidence that such benefits are not distributed equally, jeopardizing long-term equitable resilience. At the same time, several long-term mechanisms acting in the ecological subsystem (e.g., species connectivity and disturbance response diversity) and in the governance subsystem (e.g., adaptive management) had limited evidence.
4. NbS in forests mostly are reported to deliver positive effects on NCAs such as flood, erosion, and wildfire control. However there are some instances of trade-offs such as between water supply and flood and erosion control.
5. NbS are mainly reported to supply NCAs that are already of value such as restoring the capacity of a degraded forest to regulate flooding and erosion. However, there is also some evidence that NbS can provide novel contributions as well such as new income sources that are more suitable than previous sources under changed climate conditions.

FUTURE ISSUES

1. What are the effects of nature-based solutions (NbS) on key mechanisms that support long-term resilience within NbS ecological subsystems as well as within their governance processes?
2. How are the effects of NbS on resilience mechanisms within social subsystems distributed across different groups of people?
3. How do resilience mechanisms within the social-ecological system interact and influence one another?
4. Do NbS support the provision of novel nature's contributions to adaptation (NCAs)?
5. To what extent are NbS trade-offs between different NCAs versus promoting multifunctionality?
6. How do NbS effects on resilience mechanisms translate to effects on NCAs and how can harnessing these adaptation outcomes affect resilience mechanisms?
7. By applying the conceptual framework to case studies on the ground, can we gain a more accurate understanding of NbS effects on resilience and uncover additional or context-specific resilience mechanisms?
8. How do NbS support resilience in SES contexts other than forests?

DISCLOSURE STATEMENT

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