Contributions of nature-based solutions to reducing people's vulnerabilities to climate change across the rural Global South

Authors: Stephen Woroniecki[1,2], Femke A. Spiegelenberg[1], Alexandre Chausson[2], Beth Turner[2,3], Isabel Key[1,4], Haseeb Md. Irfanullah[5], Nathalie Seddon[2]

1. Linköping University, Department of Thematic Studies, Environmental Change Unit, Sweden
2. Nature-based Solutions Initiative, Department of Zoology, University of Oxford, Oxford OX1 3PS, United Kingdom
3. Centre d'Étude de la Forêt, Département Des Sciences Biologiques, Université Du Québec à Montréal, Montréal, QC, Canada
4. Changing Oceans Group, School of GeoSciences, University of Edinburgh, Edinburgh, UK
5. Center for Sustainable Development, University of Liberal Arts Bangladesh (ULAB), Dhanmondi, Dhaka, Bangladesh

Corresponding author email: stephen.woroniecki@liu.se

Postal Address: Linköping University, Department of Thematic Studies/Environmental Change, 581 83 Linköping, Sweden

Abstract

Nature-based solutions (NbS) - working with and enhancing nature to address societal challenges - are increasingly being featured in climate change adaptation policy and plans. While there is growing evidence that NbS can reduce vulnerability to climate change impacts in general, there is a lack of understanding on the mechanisms through which this can be achieved, particularly in the Global South. To address this, we analyse 85 nature-based interventions in rural areas across the Global South, and factors mediating their effectiveness, based on a systematic map of peer-reviewed studies encompassing a wide diversity of ecosystems, climate impacts, and intervention types. We develop and apply an analytical framework of people's social-ecological vulnerability to climate change, in terms of six pathways of vulnerability reduction: social and ecological exposure, sensitivity, and adaptive capacity. Most cases (95%) report a reduction in vulnerability, primarily by lowering ecosystem sensitivity to climate impacts (73% of interventions), followed by reducing social sensitivity (52%), reducing ecological exposure (36%), increasing social adaptive capacity (31%), increasing ecological adaptive capacity (19%) and/or reducing social exposure (14%). An analysis of mediating factors shows that social dimensions are equally important as technical factors in NbS to achieving equitable and effective outcomes. Attention to the distinct social and ecological pathways through which vulnerability is reduced helps to harness the multiple benefits of working with nature in a warming world.

Keywords: Nature-based solutions; climate change adaptation; climate change vulnerability; social-ecological systems

1. INTRODUCTION

As the climate warms, people around the globe are increasingly suffering from the impacts of climate change (IPCC AR6WGIISPM, 2022), with the poorest communities being worst hit and sustainable development severely limited (Paavola and Adger, 2006; Olsson et al., 2014; Roy et al., 2018; IPCC AR6WGIISPM, 2022). There is a large and growing gap between needs and action on climate change adaptation, especially in the Global South, and hence an urgent need to develop and scale up effective approaches to address climate impacts especially for those most at-risk.

Nature-based solutions (NbS) offer the potential to help bridge that gap, by providing affordable, long-term solutions that can support adaptation to climate change. NbS involve working with nature, including through its protection, restoration, or sustainable management, to address societal challenges whilst providing local benefits for people and biodiversity (Seddon 2022). NbS represent a range of interventions, such as ecosystem-based adaptation (EbA), ecosystem-based disaster risk reduction (Eco-DRR), locally managed marine areas (LMMAs), or agroecological methods that harness ecological interactions and biodiversity, such as agroforestry (Vignola et al., 2015). There is a substantial body of evidence demonstrating the potential of NbS to support adaptation to climate change, such as through reducing the effect of climate impacts such as floods, water scarcity and wildfire (reviewed in Chausson, Turner et al. 2020). Importantly, NbS can address a range of other societal challenges, including climate change mitigation and food and water security. Furthermore, well-designed NbS can be more holistic and integrative than analogous infrastructural adaptation options; they have the capacity to address interacting societal challenges simultaneously, and reduce trade-offs between these outcomes (Smith et al., 2021; Seddon et al., 2022; Woroniecki et al., 2019; Chausson, Turner et al., 2020, Portner et al., 2021)[1].

It is widely recognized that NbS have particular relevance for climate change adaptation in the Global South (Jones et al., 2012; Munang et al., 2014; IPCCSRCCL, IPCCSR1.5; IPBES, 2019; Seddon et al., 2020b; Seddon et al., 2021; IPCC AR6WGIISPM, 2022). In many parts of the Global South, people have

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[1] As the Secretariat of the Convention of Biological Diversity states: "EbA and Eco-DRR have gained traction because they provide multiple benefits for people, ecosystems and biodiversity, enable planning for CCA and DRR on longer time scales, are cost-effective compared to traditional engineered infrastructure, and emphasize community participation and the use of traditional and local knowledge systems. Due to their participatory nature and cross-sectoral approaches to adaptation and disaster risk reduction, EbA and Eco-DRR can achieve multiple policy objectives, including local, regional and national strategies for climate change, disaster risk reduction, and sustainable development, among others." (CBD, 2019)

been working with nature to address climate variability for millennia (Smith et al. 2021). Furthermore, NbS may be particularly relevant in lower income countries, given high dependency on local ecosystems for basic needs and livelihood strategies, and a lack of finance for technological or infrastructural approaches (Mercer et al., 2012; Munang et al., 2014; Doswald et al., 2014; Fedele et al. 2021).

A recent study of the first round of nationally determined contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC), lower income nations were found to disproportionately include NbS as part of adaptation plans compared to the global average (Seddon et al., 2020a), due in part to the long traditions of working with nature across lower income countries, and the influence of the Development and Conservation sector across these (Seddon et al., 2020b; Smith et al., 2021). Yet, recent analyses have demonstrated a bias in research on NbS effectiveness towards the Global North, including for disaster risk reduction and climate change adaptation (Sudmeier-Rieux et al. 2021). For example, a recent systematic map of the evidence for NbS for addressing climate change impacts by Chausson, Turner et al. (2020) showed that only 15% of studies involving nature-based actions are from the Global South. The aims of this study are to address the lack of evidence on the effectiveness of NbS for addressing climate impacts in the Global South (which we define as Low or lower-middle income countries as defined by the World Bank country income categories (World Bank, 2020)) and understand the mechanisms and pathways through which this can be achieved.

To understand pathways for enabling adaptation, the concept of vulnerability to climate change has been frequently applied in climate adaptation research and action (Simpson et al., 2021; Singh et al., 2021; IPCC AR6WGII, 2022). Vulnerability is defined herein as the propensity of a given system to be adversely affected by climate change-related hazards because of changes to valued ecological and social functioning and processes (after IPCC, 2014). People's vulnerability is determined by three components: their exposure and sensitivity to climate change impacts, as well as their adaptive capacity to respond to (potential) damage (see Box 1 for definitions). To reduce people's vulnerability, an adaptation action needs to reduce exposure and/or sensitivity, and/or increase people's adaptive capacity. A vulnerability approach is an insightful way to explore adaptation because it is determined by and thus brings attention to the systemic conditions which influence how climate impacts affect people's lives. This approach also allows understanding the diverse ways in which nature-based solutions act to influence human adaptation as explained below. In fact, no previous study has

Concept	Definition
Nature-based Solutions (NbS)	Actions that involve working with nature, including through its protection, restoration, or sustainable management, to address societal challenges whilst providing local benefits for people and biodiversity. (Seddon 2022)
Social-ecological system	Integrated system of ecosystems and human society with reciprocal feedback and interdependence (Biggs et al. 2015)
Adaptation	The process of adjustment to actual or expected climate change and its effects on social-ecological systems, in order to moderate harm to the system or exploit beneficial opportunities. (after IPCC 2021)
Vulnerability	Propensity of a given system to be adversely affected by climate change-related hazards because of changes to valued ecological and social functioning and processes. (after IPCC, 2014)
Exposure	The extent to which either ecological attributes (i.e. species or ecosystems) or social attributes (i.e. infrastructure, assets or livelihoods) are subject to climate change impacts through their presence in a particular location. (After Seddon et al., 2020)
Sensitivity	Degree to which system attributes are affected or altered as a result of pressures. (after Seddon, 2020)
Adaptive Capacity	Ability of units that provide system functions and processes to adjust to potential damage, to take advantage of opportunities, or to respond to consequences. (after IPCC, 2014)
Global South	Low or lower-middle income countries as defined by the World Bank country income categories (World Bank, 2020)
Mediating factors	Elements that influences the outcome of the intervention, either as a barrier or as an enabler. Mediating factors can fall under different categories, including governance, land tenure security, economic aspects, and people's values. (after Seddon 2022)
Institutions	Informal and formal mechanisms that shape recurring and continuous behaviour in a social setting (Huntington, 1996), including legal rules and economic structures as well as cultural norms, religious rules, and societal systems (c.f. North, 1991; Ostrom 2006; Young, 2011; Partelow and Winkler, 2016).
Historical institutions	Those relevant institutions that have altered the social-ecological system's contextual conditions in the past. (own definition)
Contemporary institutions	Those relevant institutions active when an NbS is implemented. (own definition)
Intrinsic institutions	Those relevant institutions integral to the NbS itself, part of its constitutive character and conduct. (own definition)

outlined distinct social and ecological pathways to reducing vulnerability to climate change through NbS or otherwise.

Box 1 - Glossary of key terms used in the study

Over the past decade, there has been a focus on unpacking vulnerability according to its social and ecological dimensions (Cinner et al., 2012; Thiault, et al., 2018; Depietri, 2020; Seddon et al., 2020a. Indeed each of its three main components can be further divided into social or ecological exposure, sensitivity, or adaptive capacity (see Box 2). Though these conceptualizations are not focused on climate change — rather vulnerability to any kind of shocks and stresses — the frameworks help contextualise people's vulnerability as the property of a social-ecological system (SES) (see definitions in Box 1) (Gallopin, 2006; Adger et al., 2009; Brink et al., 2016; Lavorel et al., 2020) and is most appropriate for capturing the diverse effects of NbS on people's vulnerability. Together and through their interactions, the social and ecological components of vulnerability determine the vulnerability of people who live in an SES. An NbS has potential to influence both social and ecological aspects of vulnerability through changes to an SES (Seddon et al. 2020; Turner et al. 2022), because each NbS intervention is embedded within a specific SES and - at least, when successful - forms a place-based partnership between people and nature (Seddon et al. 2020; Palomo et al. 2021; Tzoulas et al. 2021; Turner et al. 2022).

In turn, understanding both the social and ecological mechanisms by which these components of vulnerability are reduced across lower income countries is crucial to support the robust incorporation of NbS in climate change adaptation policy (Seddon et al., 2020b). Incorporating the often-neglected social dimensions of vulnerability and NbS, and embedding them within an SES, contributes to designing effective vulnerability reduction measures. For instance, Smith et al. (2021) showed how social factors for NbS in Bangladesh (namely government's policy support to NbS; participatory delivery; strong and transparent governance; and secured finance and land tenure) help to maximize NbS benefits and manage trade-offs.

No previous study has attempted to determine the state of the evidence of the pathways through which people's vulnerability to climate change can be addressed through nature-based adaptation actions. A recent study by Turner et al. (2022) provided an in-depth analysis of the specific mechanisms by which NbS can help SES be resilient and respond to change, helping to illuminate the sensitivity and adaptive capacity dimensions of the vulnerability framework. Yet here we provide the first analysis of all of social and ecological pathways through which NbS shape people's vulnerability, focusing on rural areas of lower income countries.

To analyze how NbS shape people's climate vulnerabilities, we elaborate a social-ecological vulnerability framework to structure evidence reported across a dataset of systematically collected

peer-reviewed studies (Chausson, Turner et al., 2020). We conceptualise effectiveness in terms of reducing people's social or ecological vulnerabilities through the pathways of exposure, sensitivity, and adaptive capacity. Using this framework, we analyse 85 interventions across 66 separate studies across rural contexts in lower income countries to understand whether and how NbS reduce people's vulnerabilities. We provide a description of the contextual diversity of the dataset according to key social and ecological variables. We also identify a set of specific social and ecological factors that mediate the reduction of vulnerability through these pathways.

With this analysis we highlight the reported effectiveness of NbS for climate change vulnerability reduction to characterize the evidence base and guide future evidence analysis. Acknowledging the diverse, context-specific ways, in which vulnerability and vulnerability reduction is co-produced and for whom, the study thus explores *how* effectiveness is mediated by social and ecological factors (cf. Colloff et al., 2020; Osaka et al., 2021), a research gap identified by Welden, Chausson et al. (2021).

Our research questions are:

1. In which rural ecological, geographical and social contexts are NbS represented in, across lower income countries?
2. What is the reported effectiveness of NbS in reducing people's vulnerability, and through which social-ecological pathways?
3. Which factors are reported to mediate the effectiveness of NbS in reducing people's social-ecological vulnerability?

2. THEORY

2.1 Conceptual Framework

Climate Change Vulnerability

We use an SES approach to construct a social-ecological vulnerability framework to reveal pathways through which NbS shape vulnerability, and factors mediating these. Outlining distinct social and ecological pathways to vulnerability reduction is a conceptual advance on previous analyses and addresses issues of critical relevance to the Global South contexts; namely the integrated character of vulnerability and the need to consider all aspects of NbS and their effects on local people.

Nature-based Solutions and social-ecological vulnerability reduction

Our conceptualisation of nature-based vulnerability reduction builds on the social-ecological vulnerability approach by making explicit i) how people are situated in, shape, and depend upon an SES; ii) how people's vulnerability to climate change depends on distinct components of social and ecological exposure, sensitivity and adaptive capacity; iii) how NbS affect these components of vulnerability, through *vulnerability-reduction pathways*; and iv) how place-based mediating factors shape these pathways.

This approach makes clear how the processes of conserving, restoring and managing SES are central to NbS (e.g., Nesshöver et al., 2017; Seddon et al., 2020a), and shape vulnerability beyond the flows of ecosystem services (Turner et al., 2022). Our conceptualisation therefore contrasts with previous conceptualisations of social-ecological vulnerability (see Thiault et al., 2018; Depietri, 2020; Seddon et al., 2020a, which focused on "social" vulnerability mainly being influenced by a stressor's impact on ecological vulnerability and subsequent ecosystem service supply. This conceptual expansion of social-ecological vulnerability was necessary to make visible non-ecological pathways through which NbS can shape people's vulnerabilities, directly or indirectly. Here, we use the term 'ecological pathways' to denote the ways that NbS act upon the vulnerability of a system's ecological attributes (systemic ecological elements which people depend on or attribute value to). In contrast, 'social pathways' denote the vulnerability of social attributes (any asset or resource in a system that are of relevance and value to people but not directly connected to an ecosystem, including people themselves).
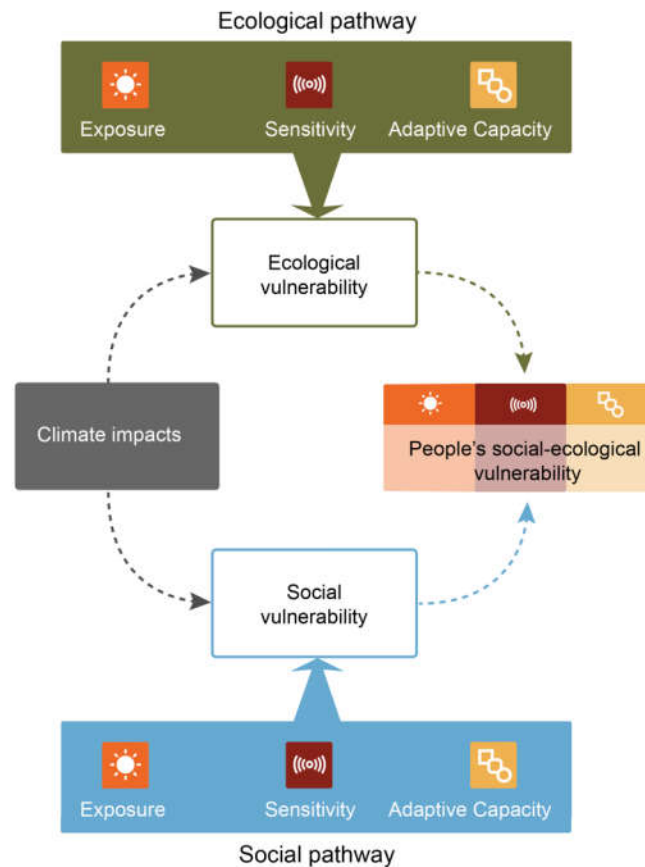
Figure 1 – Conceptual framework of people's social-ecological vulnerability to climate change. The framework accounts for six different components of people's social-ecological vulnerability; exposure, sensitivity and adaptive capacity, each of which has a social and ecological dimension. The arrows show how climate change does not impact people directly but is rather shaped through these six pathways. It is these pathways that enable NbS act upon the impacts of climate change, reducing vulnerability to climate change and ultimately reducing the effect of the impacts (Figure 2).

Importantly, our conceptual framework frames vulnerability as both related to a climate hazard as well as the conditions of the system itself (see Figure 1). This focus on the contextual conditions (e.g., place-based factors, particularly local institutions) of the SES impacted by a hazard makes explicit how NbS are a function of the context (including social-ecological interactions) in which they sit (Figure 2).
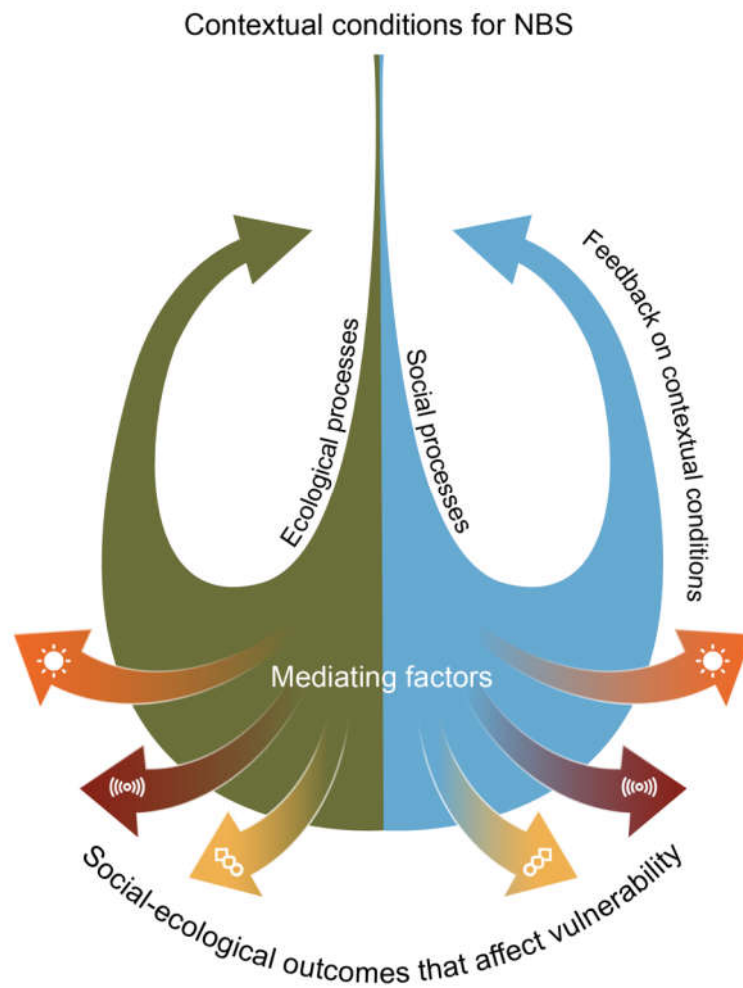
Figure 2 – Conceptualisation of NbS and its effects as part of a social-ecological system. The green and blue colors represent the ecological and social dimensions of the NbS, respectively. NbS, which, like the vulnerability that they act upon, are a function of an SES context and processes. Therefore, NbS outcomes necessarily feedback on these contexts and processes

3 METHOD

3.1 Data Collection

We draw on the dataset from the global systematic map of NbS for adaptation compiled by Chausson, Turner et al. (2020), updating it to include studies through April 2020 in Low and Lower-Middle-Income Countries (World Bank, 2020). In total, we identified 68 studies, published in English in academic journal articles and recorded on Web of Science and Scopus. These studies captured 87 interventions

in total. The data collection methodology, including the steps of scoping, searching, and selection can be found in the Supplementary Material (Appendix 1). We further excluded cases where no human subject (social group, community or otherwise) was explicitly mentioned in the relevant study and those that did not specify a scientific methodology for compiling and assessing their results. Two cases were removed from the dataset for not fulfilling these criteria, resulting in a final dataset of 85 interventions.

3.2 Data Coding

The coding strategy is based on our conceptual framework on the contextual variables of NbS, the pathways of social-ecological vulnerability, as well as mediating factors. These aspects of the framework and their definitions guided data extraction for specific intervention cases, associated with one or more climate impacts (see Supplementary Material Appendix 2). Each article could contain one or more intervention cases. We advise care in interpreting the evidence reported, as the prevalence of evidence for any category without our framework (e.g. mediating factors, or a given vulnerability pathway) is influenced by the original studies' focus.

Context variables

To describe the context, we coded this dataset according to country of study focus, income level of country, ecosystem type, climate change impact type, and type of intervention (c.f. Chausson, Turner et al. (2020) for the methodology). We also made a categorization of beneficiary groups through an inductive approach using the available information. Most commonly such groups were classed by livelihood group, which is a commonly used variable in frameworks of social-ecological interactions in SES research in the Global South (e.g., Daw et al., 2016).

Institutions

Each intervention was reviewed to examine how institutions were developed or built upon to implement NbS or how institutions directly altered the contextual conditions in which the NbS occurred. The coders firstly identified any institutions, defined as informal and formal mechanisms that shape recurring and continuous behaviour in a social setting (Huntington, 1996), including legal rules and economic structures as well as cultural norms, religious rules, and societal systems (c.f. North, 1991; Ostrom, 2005; Young, 1986; Partelow and Winkler, 2016). Those identified institutions that were relevant to the NbS operation or its context, improving/exacerbating climate change impacts and/or affecting components of human vulnerability were coded for.

We categorised these institutions as either historical, contemporary, or intrinsic (c.f. Woroniecki, 2019). Historical institutions are those relevant institutions that have altered the system's contextual conditions in the past. Contemporary institutions are mechanisms active when an NbS is implemented. Intrinsic institutions are integral to the NbS itself, part of its constitutive character and conduct. The institutional analysis allows for further exploration of the influence of institutions on NbS pathways. It is not exhaustive and limited by the extent to which study authors acknowledge and conceptualise the institutions.

Vulnerability-Reduction Pathways

Our social-ecological vulnerability framework conceptualises if and how nature-based interventions identified in the dataset intervene in a particular system to affect social-ecological vulnerability. We first categorised if the intervention was reported to have a positive, negative, mixed, or unclear effect on the vulnerability of the groups in question depending upon the outcome statements identified in the case studies (see Chausson, Turner et al. (2020) for details of the methodology). Impacts were positive when one dimension of vulnerability was reportedly reduced and no other dimensions were reported to worsen. Impacts were mixed when one dimension was reduced, and another was worsened, or when the direction of effect (+ve or -ve) on vulnerability differed between social groups. Negative impacts were recorded where dimensions were only worsened. This allows characterizing the evidence in terms of reported effectiveness, in order to guide future analyses. This should not be used to generalize effectiveness of a particular intervention type, as the heterogeneity of evidence and underpinning study methodologies precludes weighing reported categorical outcomes by strength of evidence.

The analysis of vulnerability reduction uses the IPCC's definition of vulnerability (box 1). We analyse how NbS shape vulnerability by acting upon social and ecological functions and processes (which we call attributes) through the six possible distinct pathways of social and ecological exposure, sensitivity and/or adaptive capacity of the system (Box 2). To do this we disaggregated vulnerability effects according to social and ecological pathways following definitions given in Box 1, assuming that whether social (e.g., livestock, or built infrastructure) or ecological (e.g., native mangroves), these attributes of SES are vulnerable to climate change in terms of their exposure, sensitivity and adaptive capacity. A given NbS could potentially affect vulnerability through all six pathways simultaneously.

The social and ecological pathways to vulnerability reduction are equal and distinct in terms of their placement within the vulnerability reduction framework, and do not precede or proceed from one another. If an intervention is coded for multiple vulnerability reduction pathways, these are to be understood as distinct contributions to reducing people's vulnerability. Where a pathway was assessed to transition to another pathway, such as where an intervention reduces soil erosion to protect mangroves from sea level rise (ecological vulnerability reduction), which then protect social attributes such as a village from climate impacts (social vulnerability reduction), we only included the first pathway of vulnerability reduction, to avoid double counting. We did not speculate on indirect vulnerability reduction effects not explicitly detailed in the study. When describing the evidence, we note whether pathways acted independently within the system to reduce vulnerability (additive effects), or synergistically (for example through cascading influence which overall trigger greater vulnerability reduction).

A necessary criterion is that there is a visible and direct contribution of NbS to people's vulnerability to climate-related stressors. Any study that did not show this was removed at the quality appraisal stage (see below). Vulnerability was not analysed solely in relation to specific climate change hazards, but rather to the effects of the NbS on vulnerability to climate-related stressors more broadly. We considered vulnerability as co-produced between a given SES, its people, and their interaction with environmental stressors, including climate hazards. This enabled a more in-depth analysis of what occurred in the interventions, given that they were not necessarily implemented to address climate hazards.

Box 2 Definitions of the six Vulnerability Reduction Pathways

Vulnerability Reduction Pathways	Ecological Definition	Social Definition
Exposure	Extent to which species or ecosystems, environmental functions, services, of value to people in a given system are subject to pressures (floods, droughts, landslides, fires, etc.) through their presence in a particular location. It is determined by the intensity, duration and frequency of events, geomorphology and the extent of use and management of natural resources by human societies. (Seddon et al., 2020b)	Presence of people, livelihoods, household assets, resources, infrastructure, economic, community or cultural assets in places and settings that could be adversely affected. (IPCC, 2014)

Sensitivity	Degree to which ecosystem structure and function alters as a result of perturbations. (Seddon et al., 2020b)	Degree to which these people, livelihoods, household assets, resources, infrastructure, economic, community or cultural assets are affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise). (IPCC, 2014)
Adaptive capacity	Ability of units that provide ecological functions and processes (species, ecosystems, landscapes) to adjust to potential damage, to take advantage of opportunities, or to respond to consequences. (IPCC, 2014)	Ability of the units that provide valued functions and processes (households, communities, social and cultural institutions) to adjust to potential damage, to take advantage of opportunities, or to respond to consequences (of climate change). (IPCC, 2014) *Note: In coding, we differentiated social sensitivity and adaptive capacity according to a temporal scheme. While Sensitivity relates to present effects (i.e., those that were shown to affect the sensitivity of the system now), adaptive capacity builds capacity to response to potential future changes.*

Mediating Factors

We also conducted an inductive analysis of mediating factors, i.e., elements stated to modify the intervention's social and ecological pathways of reducing vulnerability. This entailed identifying any study text passages indicating conditioning effects and variables on intervention outcomes. These passages were extracted and then through an inductive process, analyzed to produce emergent mediating factor categories and sub-categories. This coding resulted in four inductively-derived categories (i.e., social, technical, economic, political, as well as combination), which nevertheless closely align with analysis of such factors (Nalau et al., 2018). We then coded each passage by its corresponding category. Where institutions were coded as mediating the effectiveness of an intervention, these were included as a political mediating factor.

3.3 Verification

To ensure consistency and reliability in coding of interventions/studies, all coding decisions were verified by a second coder, who checked coding extracts in accordance with the definitions of the six pathways and mediating factors. Discrepancies or uncertainties in regarding the coding and definitions were resolved through regular meetings. To improve inter-coder reliability, 48 intervention-cases

(56% of intervention-cases) were coded by both coders independently, with any identified discrepancies resolved before coding independently.

3.4 Data Analysis

Interventions were coded with both quantitative (i.e., binary and numerical) and qualitative (i.e., text-based) data extraction columns. This enabled descriptive statistical analysis and in-depth qualitative analysis to explore patterns, elucidate paradigmatic examples and explore relationships between different variables (see Supplementary Information). The evidence base was also characterised through descriptive statistics, reporting the number of studies with respect to contextual parameters (e.g., geography, climate impacts, and ecosystem types) (section 3.1). We describe the evidence base in terms of absolute numbers and percentages of intervention-cases for each category.

4. RESULTS

4.1 Contextual diversity

Research Question (RQ): In which ecological, geographical and social contexts are NbS represented across the rural Global South?

Our dataset is highly heterogeneous in relation to geography, climate impacts, ecosystem type, intervention type, and institutional diversity. In other words, few of the same configurations of country, climate impact, ecosystem type, intervention type, and institutional set-up occur more than once.

Geographic distribution of studies

The studies were found across 28 low income and lower-middle-income countries (Figure 3a). A few countries are overrepresented in the dataset, notably Kenya and Ethiopia (14 and 11 interventions, respectively), whilst most account for only one, two or three interventions (Figure 3). The top five countries with the greatest number of interventions reported countries were Kenya, Ethiopia, Nepal with six interventions, and Indonesia and Philippines with five interventions.
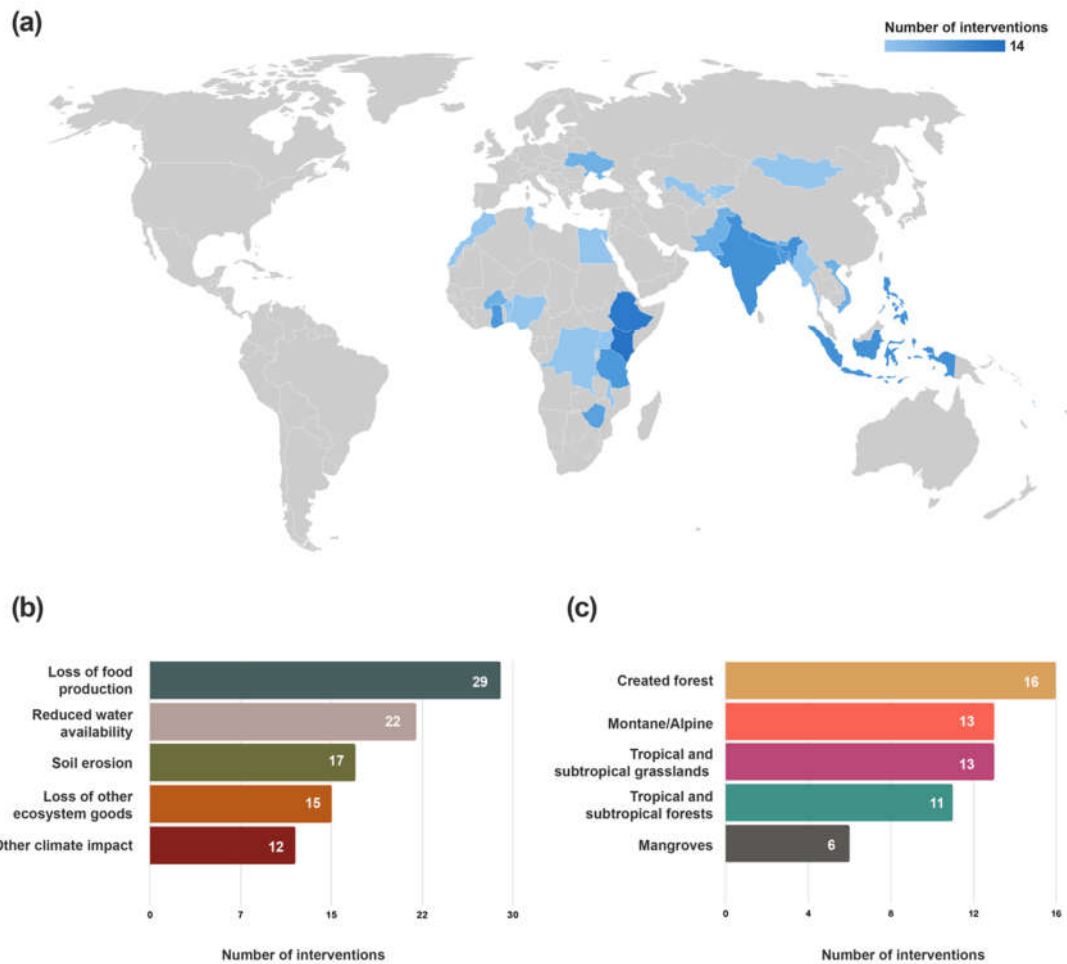
Figure 3 (a) shows the geographical distribution of countries represented in the dataset. Figure 3b shows the five most commonly occurring climate impacts and the number of separate interventions in which they occurred. Figure 3c shows the five most commonly occurring ecosystem types and the number of separate interventions in which they occurred.

The African and Asian continents were well represented, while no countries from Latin America or the Caribbean were included. Most countries in this region are upper-middle, or high income (World Bank, 2020), and for those that are lower income, including Bolivia, Honduras and Nicaragua, no studies were found. However, there are marked regional disparities: Whilst East Africa is well represented, many African countries did not have a single study. Likewise, in Asia, South Asia was often counted, with Nepal, India, Bangladesh and Pakistan all with relatively higher representation, whilst studies in countries in South-East and Central Asia were rare. Europe was covered by a single intervention in Ukraine. Only one Small Island Developing State (SIDS) (Vanuatu) was recorded (despite other SIDS being captured in the Systematic Map, these were not low or lower-middle income countries).

Climate Impacts

Eighteen climate impact types were identified, with most interventions addressing one impact, up to a maximum of 9 (mean = 1.6). The representation of climate impacts across the dataset is skewed, with 11 climate impacts found in five or more cases (Figure 4), and four climate impacts represented in 10 or more (the category 'other climate' impact refers to all other kinds of impact that were not represented in one of the coded categories) (Figure 3b).

Ecosystem Type

We found interventions across 22 ecosystem categories (including combinations of different types addressed in a single intervention). Most intervention cases (68%) were in created forest (16), followed by several terrestrial and coastal ecosystems (Figure 3c). The strong presence of sub-tropical or tropical grasslands, forests and mangroves in the dataset coincides with the presence of most cases in lower latitudes.

Intervention Type

Most interventions (35 interventions, 41%) involved a combination of actions in natural or semi-natural ecosystems, followed by interventions in novel ecosystems (21, 25%)[2]. Few interventions involved protection (11), management (6), restoration (6), or the use of a mix of novel and non-novel ecosystems (4).

Institutions

Intrinsic institutions were identified in 52% of cases (44 interventions), historical institutions in 49% of cases (42 interventions) and contemporary institutions in 32% of cases (27 interventions).

Historical institutions

Where reported, historical institutions most often mediated the vulnerability reduction efforts for different groups by shaping social-ecological interactions of the context in which NbS intervene. For example, in a case involving land exclosures to foster grassland regeneration, historical conflict

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[2] Note: Novel ecosystems do not include interventions directly occurring on the agricultural matrix (e.g., agroforestry) since these were excluded from the dataset (see Chausson, Turner et al. (2020) for exclusion criteria). The dataset did however include interventions harnessing surrounding ecosystems (through protection, restoration, or other forms of management) to reduce vulnerability of agricultural systems to climate change (such as, vegetation bunds or wind breaks).

management structures continued to favour sedentary communities over nomadic groups, marginalizing the nomadic community and increasing their vulnerability to climate change impacts (Ahmad et al., 2012). Their marginalisation led to more intensive grazing on limited available areas outside the exclosures. This illustrates how historical institutions shape the context in which the NbS is set, consequently shaping intervention design in relation to the exclosures, and the distribution of outcomes across social groups.

Contemporary institutions

Contemporary institutions (i.e., those that exist in parallel to the intervention) also shape the intervention context. For example, in a case involving assisted rehabilitation (restoration) of a seafront area in the Philippines, formal institutions (land tenure and fish-pond licenses regulating access and ownership) were critical to intervention design and implementation (Duncan et al., 2016). These institutions strongly determined the rehabilitation process.

Contextual institutional change

Cases with both historical and contemporary institutions often show contextual institutional change, mostly related to changes in ownership institutions. For example, Wairore et al. (2016) highlight how communities in West Pokot County, Kenya shifted from nomadic traditional grazing and rotating systems to sedentary approaches when colonialists implemented sub-national borders restrictions, dividing land previously customarily shared by all pastoralists amongst colonial landowners. These restrictions impeded migratory patterns, forcing communities into sedentary livelihoods. This shift in livestock grazing induced by institutional change has been the main driver of land degradation in the area. The institutional change also reiterated the need for formalising land ownership systems based on customary traditions, which became part of the intrinsic institutions of the intervention that included new agreements on land ownership and management, as well as the implementation and management of exclosures.

Beneficiaries

We identified a wide range of intervention beneficiaries across the studies. Most were rural communities whose livelihoods are directly dependent on and shaped by their local ecosystem. The most common livelihood identified was arable or mixed sedentary farming, often small-scale, located in regions characterized by riparian, savannah, montane or forest ecosystems. Most target groups also held livestock, relying on agro-pastoralist systems. Nomadic pastoralists were also represented in some studies but were generally studied only in relation to sedentary communities, rather than on

their own. We also identified coastal or river community beneficiaries, whose main livelihood was fishing.

4.2 Vulnerability reduction outcomes

RQ: What is the reported effectiveness of NbS in reducing people's vulnerability, and through which social-ecological pathways?
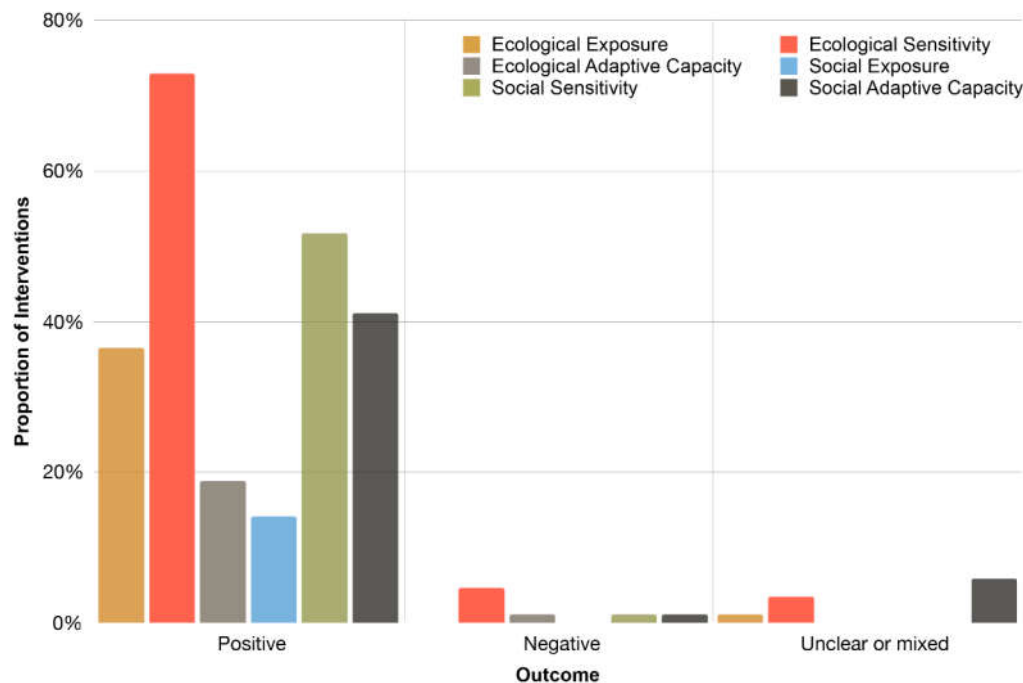
Figure 4 – Proportion of interventions displaying the three kinds of outcomes across the six vulnerability-reduction pathways.

Figure 4 shows the proportions of reported positive, negative, and unclear or mixed outcomes of NbS interventions in reducing vulnerability. Most of reviewed interventions (95%) reported positive outcomes in distinct vulnerability pathways. These are discussed in detail in section 4.2.1.

We found nine instances of unclear or mixed outcomes in distinct vulnerability pathways, with mixed cases often illustrating the importance of disaggregating intervention outcomes by social groups. For example, in the case of a land degradation project in Gilgel-Abay watershed of northwest Ethiopia, the outcomes of the implemented exclosures in the watershed differed between social groups (Crossland et al., 2018). Poorer, marginalized farmers with little or no land, relying heavily on communal grazing areas, were now excluded from using the land, forcing them to reduce livestock

ownership and turn to other livelihoods. In contrast, richer, land-owning farmers perceived exclosures as positive as the soil in the area regenerated and provided fodder.

In seven instances across five cases, interventions were reported to negatively affect distinct vulnerability pathways (two interventions reported two distinct negative outcomes each). For example, in an intervention funded by a Norwegian forestry company, in Dokolo district, Uganda, forest protection and afforestation for carbon offsetting increased vulnerability in several ways and yielded no positive outcomes for the community (Edstedt & Carton, 2018). First, it reduced the area for potential cultivation, resulting in intensified agriculture and further degradation of available land outside the offset sites. This led to loss of soil fertility and food production exacerbating the area's ecological sensitivity. At the same time, water-demanding Eucalyptus trees used in the offset project depleted water resources in proximity to the village, forcing local people to travel further for freshwater. Moreover, forest protection reduced firewood availability, making the community more exposed to price fluctuations of wood on the market while removing a stream of local income, ultimately increasing social sensitivity.

4.2.1 Pathways of vulnerability reduction

The most common pathway for vulnerability reduction was through reducing ecological sensitivity (62 interventions, 73%) (Figure 4). The next two highest categories were social sensitivity (44, 52%) and social adaptive capacity (31, 36%). Ecological exposure was the next most represented pathway (26, 31%), whereby the intervention reduces the exposure of the system's ecological attributes to a hazard. Ecological adaptive capacity and social exposures were the least represented pathways of vulnerability reduction (16, 19% and 12, 14% cases, respectively). Importantly, these results show NbS influenced social-ecological vulnerability through distinct ecological and social pathways (See Box 3 for paradigmatic examples and full list of cases attributed to each pathway).

Ecological Pathways

The analysis showed that in most cases (88%) NbS influenced people's vulnerability through the ecological pathways.

Ecological exposure

Nature-based Interventions addressed ecological exposure in different ways, mostly by establishing natural barriers shielding ecological attributes to the climate hazard. For example, in Kutubdia Island, Bangladesh, the creation of new oyster reefs on a tidal mud threatened by coastal erosion acted as a

wave break, significantly reducing coastal hydraulic load, and ultimately reducing exposure of the mudflat and salt marsh behind the reef to coastal erosion (Chowdhury et al., 2019). This facilitated habitat restoration, boosting fish population, and in turn food production and income for the local population, further reducing their vulnerability.

Ecological sensitivity

Most of the intervention cases indicated reduced ecological sensitivity, whereby regulating and supporting ecosystem services were improved or restored, consequently decreasing the propensity for damage of ecological attributes to stressors. This is highlighted in an intervention in Northwestern Ethiopia involving exclosures to restore degraded land and soils in a montane ecosystem where people mostly depended on agriculture and livestock farming (Mekuria et al. 2015). The intervention involved seasonal protection of the lands from livestock grazing and harvesting grasses and roots, and spatial zoning of communal grazing lands. It thereby shaped ecological sensitivity by reducing soil degradation and improving vegetation cover. The soil became less sensitive to climate-related-soil erosion as the vegetation cover reduced the impact of stressors like wind or water run-off. Further, the intervention rehabilitated water gullies, reducing soil erosion due from environmental stressors. As the soil improved, indigenous trees regenerated, vegetation cover improved, and fodder supply increased, reducing the vulnerability of livestock farmers dependent on soils for fodder and water.

Ecological adaptive capacity

In a small subset of cases, NbS improved ecological adaptative capacity, often through the planting of species that are more resilient to extreme weather conditions. For example, in Koyra sub-district, Bangladesh, a village affected by coastal erosion and saltwater intrusion, a mangrove forest comprised of salt tolerant species was planted to address these impacts (Imam et al., 2016). Mangrove trees improved the overall ability of the system to adjust to damage from saline intrusion.

Social Pathways

In a smaller but still sizeable proportion of cases (65%), we found that NbS influenced vulnerability through the social components of people's vulnerability.

Social exposure

Several interventions used natural barriers to reduce the exposure of social attributes to climate hazards. For example, a rural community in Northern Ghana affected by fire and wind in a tropical grassland ecosystem established fire belts and planted small patches of tall vegetation around their village (Ngwese et al., 2018). The fire belts (vegetation free corridors) prevented bushfires from

reaching the village, whereas planted tall plants protected rooftops against heavy winds. Reduced exposure of material possessions and infrastructure thus reduced the vulnerability of the community.

Social sensitivity

In most cases of reduced social sensitivity, interventions strengthened social cohesion or diversified livelihoods, minimising the impact of environmental stressors. For example, in the Panchase mountain region in Nepal, the establishment of community forest management increased social cohesion and inclusion through a social network, improving villagers' access to community support in times of difficulty (Adhikari et al., 2018). Furthermore, the community forest improved access to firewood and timber, and diversified livelihoods by generating employment and income from improved ecosystem goods. An education programme also improved capacities for ecosystem management and strengthened community-based institutions, such as mechanisms to manage forest services, platforms to discuss issues relating to their livelihoods, and participatory decision-making. Increased cohesion, strengthened institutions, and increased streams of income provided the community with the knowledge and material capacities to deal with climate change impacts locally.

Social adaptive capacity

Social adaptive capacity is often closely linked to social sensitivity. Where social adaptive capacity improved, communities were better able to cope with and adjust to environmental change. For example, in the Lenche Dima watershed in Ethiopia in a montane ecosystem, a multi-faceted intervention established rangeland exclosures, multi-purpose tree plantations, and management, education, and institution-building projects to foster community participation to address reduced water availability and loss of food production (Descheemaeker et al., 2010). Beyond directly addressing reduced water availability and food production, the intervention empowered the local community, which was crucial to improve adaptive capacity. Education in natural resource management, strengthened local institutions and generated new forms of income generation enables people to adjust to change and and make more strategic adaptation decisions, by identifying problems and potential solutions early, thereby reducing their vulnerability.

Box 3- Nature-based Interventions associated with a particular vulnerability pathway, and a paradigmatic example of each pathway

Pathway	Paradigmatic Example	Case identifier (see SI Appendix 2 for case studies, and

		Appendix 3 for full study references)
Ecological Exposure	Created oyster reefs reduced hydraulic load on the coast by reducing exposure to large waves and coastal erosion. The community's vulnerability improved as a result as organism populations restored and the shoreline remained intact, allowing the population to maintain their livelihoods on the island rather than migrating to the mainland. Chowdhury et al., 2019	2, 3, 4, 8, 14, 18, 19, 20, 25, 36, 42, 44, 46, 47, 48, 49, 50, 51, 54, 57, 58, 60, 66, 68, 75, 76, 77, 78, 80, 82, 84, 85
Ecological Sensitivity	Exclosures and the limited harvesting of grasses and roots restored land degradation, making the soil less sensitive to climatic stressors. This reduced local people's vulnerability as the increased vegetation provided cheap fodder and restored water gullies which increased fresh water supply. Mekuria et al., 2015	2, 3, 5, 7, 8-19, 23-30,31-38, 43-45, 47, 49, 51, 53-55, 57-62, 63-79, 81-85
Ecological Adaptive Capacity	Planting of salt-tolerant mangrove trees improved the system's resilience to saline intrusion, provided constant shade for under-story plants, and reducing wave height in cases of extreme weather, increasing the system's ability to adjust to changing environmental conditions. This reduced people's vulnerability as the community's fresh water was less affected by saline intrusion and the resilient trees provided a stable supply of firewood. Imam et al., 2016	11, 15, 16, 30, 31, 34, 38, 44, 52, 53, 59, 68-71, 76, 81
Social Exposure	The creation of natural barriers like fire belts and tall vegetation reduced the exposure of the village to climate hazards like fire and wind. By protecting the social attributes, the intervention reduced the vulnerability of the community. Ngwese et al., 2018	4, 7, 8, 20, 31, 42, 49, 55, 60, 80, 82, 84

Social Sensitivity	Landscape restoration and the implementation of a community-managed forest diversified livelihoods, increased social cohesion, and provided natural and human capital. This made the community less sensitive to the local effects of climate change and reduced their vulnerability. Adhikari et al., 2018	1, 3, 4, 6, 8, 9, 13, 17, 18, 23, 26, 27, 29, 31-33, 38-41, 44, 45, 48, 52-57, 59, 60, 62, 64-66, 68-71, 76, 79, 80, 82, 83, 85
Social Adaptive Capacity	Rangeland exclosures and the plantation of multi-purpose trees were used as the basis for institution-building and education of the local community. This empowered the local community to make strategic decisions about the changing environment and gave the local the tools to adjust accordingly. Descheemaeker, 2010	1, 3, 4, 6, 7, 9, 10, 12, 13, 17-19, 23, 26, 27, 29, 31-33, 39-43, 45, 48, 52-54, 56, 57, 59, 60, 62, 65, 68-71, 76, 79, 83

4.2.2 Vulnerability reduction through multiple pathway interactions

Multiple ecological pathways

Interventions were often reported to reduce vulnerability through multiple ecological pathways simultaneously, either stemming from one or more intervention components addressing multiple pathways. For example, in an intervention involving the creation of mud piles and flood barriers to reduce exposure of agricultural land to flooding, the protection of native plants also provided a source of natural pesticides, reducing the sensitivity of crops to disease.

In a case involving exclosures in Ethiopia, multiple ecological pathways synergized, creating cascading impacts that increasingly reduced vulnerability (Crossland et al., 2018). Specifically, exclosures reduced land degradation and increased soil biodiversity, thereby reducing soil sensitivity, while improved soil conditions allowed for increased vegetation cover, providing shade and reduced runoff, reducing ecological exposure to heat and flooding. The overall improved conditions of soil biodiversity, landscape greenness and moisture levels improved the soil's adaptive capacity to future environmental stressors.

Multiple social pathways

In most cases where vulnerability was shaped by social pathways, multiple pathways were involved. Social sensitivity was primarily addressed in combination with social exposure or adaptive capacity.

For example, in an intervention involving the establishment of community-forests in Ethiopia, medicinal plants and enhancement of recreational and aesthetic values improved local people's well-being while fostering communal participation (Woldie & Tadesse, 2019). In addition, the forest diversified livelihoods, producing extra income streams to cope with drought-induced loss of food production and of income, thereby increasing social adaptive capacity.

Multiple ecological and social pathways

Most interventions reduced vulnerability through ecological and social pathways simultaneously, with pathways shaping vulnerability independently, or synergising. An example of a case where social and ecological pathways complemented one another was an intervention of mangrove reforestation in the Mekong Delta in Vietnam, combining training for local people and employment (McElwee et al., 2017). The mangrove plantations functioned as shelter belts against waves and cyclones, thereby protecting the coastal system against waves and cyclones. The intervention also provided vocational training, thereby increasing local capacities to harness nature's contributions and develop coping strategies to environmental stress. Therefore this intervention reduced vulnerability through separate ecological and social pathways, reducing vulnerability in complement rather than through interaction and synergy.

In contrast, in an intervention involving exclosures to restore soil health in a tropical grassland ecosystem in Ethiopia, social and ecological pathways interacted and synergised (Crossland et al., 2018). A short period of protection reduced erosion, groundwater recharge, and increased grassland vegetation cover, reducing the area's ecological sensitivity to climatic shocks. Simultaneously, exclosures brought farmers together through grassland restoration as a shared objective, reducing land use conflict through cohesion and cooperation, and ultimately reducing farmers' social sensitivity to stressors. Reduced land-use conflicts and improved cooperation diminished pressure on the lands leading to more sustainable ecosystem service management, facilitating ecological recovery. A positive, reinforcing feedback loop was evident, as ecological recovery reduced communal conflicts over now more abundant water, food, and land for cultivation. This demonstrates how an intervention component (exclosures) can reduce vulnerability through reinforcing social and ecological pathways.

4.4 Mediating Factors

RQ: Which factors are reported to mediate the effectiveness of NbS in reducing people's social-ecological vulnerability?
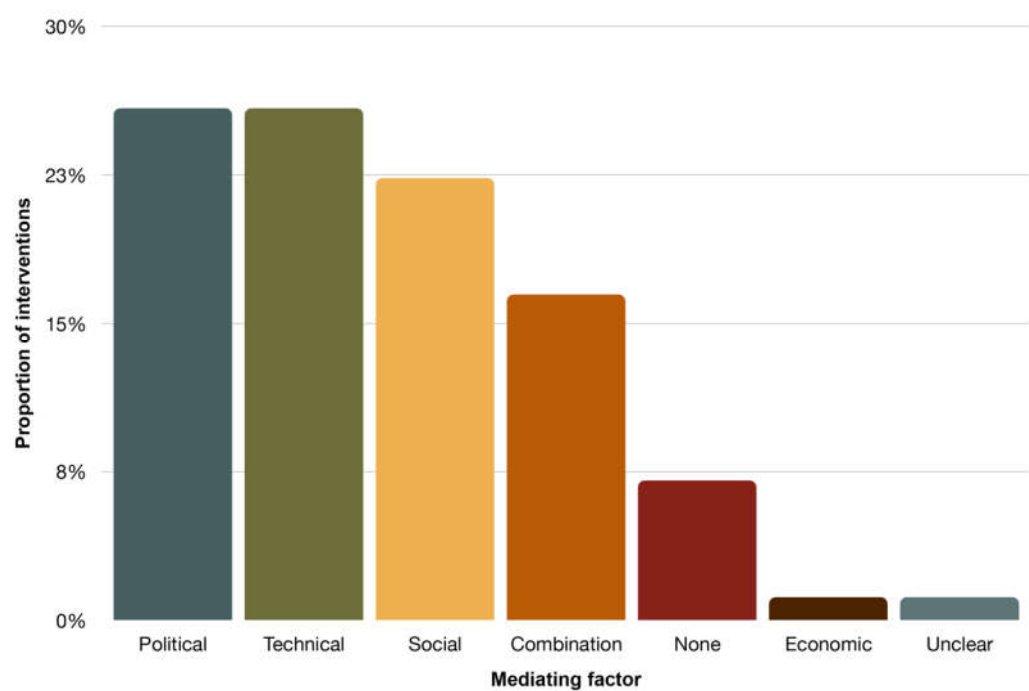
Figure 7 - Mediating factors Identified by type for the vulnerability reducing pathways, including combinations of types, where no mediating factor was identified, and where the mediating factor was unclear.

We found that 92% cases were reported to be associated with one or more mediating factors, classed as technical (pertaining to intervention design specifics), social (pertaining to education and inclusion of knowledge, values, and community members), economic (pertaining to income, inequality, and poverty levels), or political (related to historical, contextual, and intrinsic institutions and pertaining to issues of empowerment, ownership and access, conflict management). Sub-categories and paradigmatic examples of each are shown Box 4. As Figure 7 shows, the most common mediating factor types were political (including institutional factors), technical, and social, each mediating outcomes in various ways. Only 16% of cases mentioned more than one type of mediating factor.

Box 4 - Specific mediating factors for the effectiveness of NbS in reducing vulnerability, and sub-categories, with a paradigmatic example to explain each one.

Mediating Factor	Sub-category	Paradigmatic Example

Technical	Specific Design	Specific resting period length to restore rangelands in Tunisia was crucial to the level of success. Belgacem et al., 2019
Social	Education	Levels of education of the community prior to the intervention proved to be key for intervention component uptake. Formal education, for example, increased the changes of accepting the new system of land management. Safari et al., 2019
	Inclusion of community	Community inclusion supported positive social outcomes as the empowered community and its cohesion reduced social sensitivity. Community participation also allowed for community-wide adoption of measures, which mediated ecological outcomes. Descheemaeker et al., 2010
	Inclusion of local knowledge	Local knowledge of environmental conditions and local community dynamics were essential in avoiding inequity in the community. Woldie & Tadesse, 2019
	Inclusion of values	Understanding the values that local people attach to local ecosystems increased the sustainability of a mangrove plantation in India. Badola & Hussain, 2005
Economic	Income creation	Outcomes of a community forest in Myanmar were limited because people were unwilling to volunteer, i.e. they required payment for their time. Lin et al., 2019
	Poverty levels	High levels of poverty in Myanmar constrained the intervention because the poorest did not have resources to spend time volunteering in management and decision-making. Outcomes of vulnerability reduction were, therefore, not necessarily community-wide. Lin et al., 2019
Political	Conflict management	Tribal conflict in Morocco was recognised as a constraint on implementation, requiring the intervention to build on tribal organisations to increase legitimacy. Derak et al., 2018

	Access and Tenure	Clashing customary ownership and formal institutions forced local people off their lands under an afforestation project implemented in a top-down way, increasing people's vulnerability. Edsted & Carton, 2018

Technical Factors

Technical factors of intervention design were mostly reported to mediate positive outcomes. For example, Belgacem et al. (2019) highlight an intervention reintroducing a traditional form of grazing, resting, and rotating to restore rangelands in Southern Tunisia. Through different resting period lengths, the intervention showed how the technical element of time mediated ecological pathways outcomes in terms of degree of vegetation cover, density, and productivity and showed how resting period should be adapted to precipitation and temperatures regimes.

Social Factors

Social factors identified by studies as mediating outcomes included education and inclusion of knowledge, values, and community members. Here, education refers to either external factors where prior level of education mediated the outcome (e.g., Safari et al., 2019), or internal factors, where education was part of the intervention itself (e.g., Koutika, 2019). Some studies recognised the importance of including local knowledge in intervention design for vulnerability reduction (Woldie & Tadesse, 2019). Incorporation of local values in project implementation increased intervention acceptance (Badola & Hussain, 2005; Descheemaeker et al., 2010), which in turn is crucial for its adoption and overall success, thereby mediating vulnerability pathways that the intervention addressed. Descheemaeker et al. (2010) also highlight how community inclusion and engagement facilitated a watershed management intervention in Ethiopia. This strengthened social adaptive capacity, building people's capacity and confidence to deal climate change impacts as a community while managing land ownership issues. High level of social acceptance facilitated community-wide adoption of intervention, including watershed management, ultimately influencing ecological pathways to vulnerability in terms of improved water flow and decreased soil degradation.

Economic factors

Economic mediating factors were less commonly reported, but had substantial influence when they were. Such factors were either internal to the intervention, such as level of income generation of the intervention (e.g. Lin et al., 2019; Baba & Hack, 2019), or external; relating to the economic status of community members prior to NbS implementation (e.g. Lin et al., 2019; Ali & Rahut, 2020).

For example, in an intervention involving new community-based forestry institutions in Myanmar, Lin et al. (2019) highlights how high levels of poverty (external economic circumstances) hindered participation and inclusion in decision-making of poorest households. In turn, decision-making for forest management and income generation and allocation were biased towards wealthier households, creating a differential effect on vulnerability reduction. Furthermore, most forest activities were voluntary, excluding economically marginalized households who could not afford to participate, in turn hindering the intervention's implementation and limiting potential to reduce vulnerability.

Political factors

Political mediating factors, including the historical, contextual, and intrinsic institutions, include issues of empowerment, ownership and access, conflict management, and management of land and ecosystem services (including who manages and how management occurs). Ownership and access refer to issues of rights, often over land tenure, and clashing systems of ownership. Institutions mediated both positive and negative vulnerability outcomes. For example, Edsted & Carton (2018) report how the history of a reserve in Uganda was dominated by instability, where colonial institutions clashed with customary land tenure systems. These conflicting institutions formed the intervention backdrop, allowing afforestation for carbon sequestration on the lands of local people, despite their customary land rights. These rights were not recognised in the intervention's intrinsic institutional mechanisms, namely the top-down management driven by the Ugandan government and Norwegian forestry company. As a result, local people lost their lands and livelihoods, compromising their adaptive capacity. Meanwhile Derak et al. (2018) showed that the lack of a conflict-mediation mechanism in an intervention involving forest restoration in Northern Morocco negatively influenced vulnerability outcomes by allowing inter-tribal competition to prevent different groups from accessing benefits and reducing the legitimacy of the intervention in the eyes of tribal organisations.

Some studies also recognised the influence of intrinsic institutions on social and ecological vulnerability pathways in a wide range of NbS, particularly those focused on ecosystem management and protection. Those mediating ecological pathways often focused on informal agricultural institutions or influenced historical institutional change to shape social-ecological vulnerability. Both aspects are illustrated in (Belgacem et al., 2019), where historical institutional change from traditional pastoralism to modernised agriculture in Tunisia led to extreme land degradation. The intervention focused on addressing land degradation through periodic rangeland exclosures and implementation

of traditional pastoralist techniques and management. Restoration of traditional institutions in combination with periodic exclosures, rather than exclosures alone, promoted intervention longevity, reducing the risk of regressing back towards unsustainably intensive land use and land deterioration.

In a similar way, several studies highlighted the influence of intrinsic institutions on social pathways. Strauch et al. (2016) showed how historical institutional change from customary institutions to formal government institutions conflicted with social and cultural practices, thereby disempowering the community. The intervention, aiming to restore traditionally managed forests in Tanzania, focused on remediating ecological damage, while addressing issues of ownership and empowerment. Through joint ownership, co-management and land tenure rights, the intervention institutional mechanisms strengthened social, human, and economic capital. These effects directly shaped social pathways as institutional empowerment enhanced social adaptive capacity and reduced social sensitivity.

5. DISCUSSION

This study reveals the diversity of social-ecological contexts in which NbS play a role and the various social and ecological pathways through which NbS affect people's vulnerability in the rural Global South. Cases gathered through the systematic mapping method reported overwhelmingly positive effects on reducing people's vulnerability. Few studies reported negative, mixed, or unclear effects on people's social-ecological vulnerability. Some studies reported varied outcomes for different social groups (such as wealthier, land-owning groups at the expense of poorer, landless groups) demonstrating how social and political processes influence who gains from efforts to reduce vulnerability by implementing NbS (Seddon, 2022). Care should be taken when interpreting aggregated effectiveness results given gaps in the dataset (e.g., geographical cover), and limitations to weighing effectiveness outcomes by study quality (see Methods).

Our analytical framework clarifies how NbS shape people's vulnerability to climate impacts in social-ecological systems. We found that NbS were most reported to reduce vulnerability by reducing ecological sensitivity, such as where exclosures and limited harvesting restored degraded land, making the soil less sensitive to climatic stressors. Reduced social sensitivity, increased social adaptive capacity, and reduced ecological exposure, were all well represented in the dataset, in a half to a third of all intervention-cases respectively, identifying these as significant pathways of vulnerability reduction. This shows how previous conceptualizations of social-ecological vulnerability focused on ecological pathways may have missed important aspects of how NbS shape social vulnerability (Cinner et al., 2012; Thiault et al., 2018).

The least represented pathways were increasing ecological adaptive capacity and reducing social exposure. While there is a growing evidence base on the role of ecosystems in reducing people's exposure to climate impacts (Seddon et al., 2020b), few cases were coded for this pathway. This is likely due to our approach. First, we operationalised social pathways as independent of ecological pathways – i.e., specifically where an action intervenes on the social attributes of a social-ecological system. Therefore, in cases where people's overall exposure was affected, our dataset reveals that NbS intervene often principally reducing vulnerability to ecological assets that people value (such as, productive ecosystems), in line with previous findings on social-ecological vulnerability (Cinner et al., 2012; Thiault et al., 2018). Finally, to avoid double counting, studies identifying indirect reductions to vulnerability of social attributes through direct reductions on ecological vulnerability were not coded for the former. We also found that intervention's influence on ecological adaptive capacity is under reported in the literature on nature-based interventions. Specifically ecological adaptive capacity pertains to the diversity, heterogeneity, and connectedness of the ecosystem and the characteristics and conditions of its component species and habitats (Seddon et al., 2020a). Thus, lack of reporting may be in part because ecological monitoring incurs high financial and labor transaction costs.

Our analysis also highlights factors mediating the extent to which NbS reduce people's vulnerability to climate change. Social and political factors were identified as frequently as technical aspects of project design. Moreover, results highlight the critical role of institutions in shaping how interventions are designed and implemented, and therefore, the pathways by which vulnerability is reduced in NbS. This corroborates research demonstrating the influence of social-ecological system attributes and dynamics on intervention outcomes (Haider et al. 2021). It also complements research exploring how NbS are shaped by people's agency and adaptation strategies (e.g., Palomo et al., 2021; Turner et al., 2022), by recognising their social characteristics, which can both constrain and enable 'nature-based' adaptation action. Our findings provide clear evidence that access and tenure considerations are paramount in understanding how particular groups of people benefit from nature for adaptation, and that understanding the process of NbS design and implementation is crucial (Woroniecki, 2019; Mouk et al., 2021).

Limitations and opportunities for future research
By combining descriptive statistics and qualitative analysis of specific intervention-cases, we can draw general patterns from the dataset, and show how NbS outcomes depend on place-based factors in a social-ecological system. Although we do not show *the extent* to which vulnerability is reduced, we

show the range of ways in which interventions can shape vulnerability in specific contexts. Specifically, we offer a deeper understanding of pathways to vulnerability reduction, helping to generate hypotheses. Further case study research and evidence synthesis could focus more specifically on these pathways, especially factors mediating their synergies, interactions, and trade-offs, and how NbS are shaped in specific regions, contribute to transformative change across landscapes, and affect different groups (Nesshöver et al., 2017). They could also be extended to the urban context and in marginalised communities in the Global North (Brink et al., 2016).

Whilst we find convincing evidence that NbS can reduce people's vulnerability to climate change, few interventions represent the same configuration of variables, limiting generalizability across contexts and quantitative meta-analysis. Some lower income regions are poorly represented, notably on the African continent, apart from a few East African countries. These patterns can partly be accounted for by language barriers, given we excluded non-English studies (see Chausson, Turner et al., 2020 for further details). They are also indications of international inequalities in the distribution of funding and capacity for scientific research (ibid). Exclusion of grey literature may result in a disproportionate limit of evidence from particular regions.

We recognise our analysis is limited by the perspectives and research designs of the studies included in the original evidence map (Chausson, Turner et al., 2020). The scope of included studies may hide other vulnerability pathways given the initial dataset's restriction to studies explicitly linking nature-based interventions with climate impact outcomes. Importantly, studies focusing exclusively on intervention implementation, management, or governance were excluded where they did not report direct effects on climate impacts. Social vulnerability pathways may therefore be underrepresented. Also, we are bound to follow causal inferences linking the intervention to vulnerability outcomes as reported in the studies. Other drivers beyond nature-based interventions may have been instrumental in delivering vulnerability reduction benefits and NbS may have affected vulnerability pathways that were not reported on. Finally, studies may not have assessed effects on all social groups in the intervention's sphere of influence. As the scholarship on equity in relation to EbA shows, it is crucial to focus on how benefits are socially disaggregated across different groups and how vulnerability may be redistributed between groups (Atteridge and Remling, 2018; Eriksen et al., 2021).

Contributions to research and practice

Using NbS as an analytical concept, we highlight ways in which people's vulnerability to climate change is mediated by social-ecological systems, and how NbS build on such systems to produce adaptation

benefits (Maru et al., 2014; Colloff et al., 2020). Our results clearly show how NbS are not synonymous with 'ecosystem services', but rather co-productions involving people and nature working towards specific societal challenges (Lavorel et al., 2019; Bruley et al., 2021; Welden et al., 2021; Turner et al., 2022).

NbS have largely been recognised for their potential to deliver social and ecological 'co-benefits' that engineered approaches may not be able to provide, such as social cohesion or biodiversity conservation. Based on our analysis, such co-benefits (e.g., Woroniecki et al., 2019) play a crucial role in reducing social-ecological vulnerability. To understand this more holistic contribution to people's vulnerability contexts means shifting attention from climate impacts per se, and more into components of vulnerability such as sensitivity and adaptive capacity (O'Brien et al., 2007; Singh et al., 2021). This highlights the need to consider vulnerability in more integrated ways, especially in the Global South, keeping in mind issues of access, equity, and the complexity of social-ecological systems (Olsson et al., 2014; Pinho et al., 2014a;b; Hoque et al., 2018). For example, Bhowmik et al. (2021) show how different shocks and stresses function in coastal small-scale marine fisheries SES of Bangladesh, demonstrating the multiple dimensions of vulnerability.

The study underlines the multi-dimensional character vulnerability and adaptation choices, including its social and ecological dimensions, in the context of climate change (IPCC AR6WGIISRM, 2022). Therefore, a narrow practical focus on technical mediating factors is likely to miss the key role of social factors in influencing intervention outcomes (Osaka et al., 2021). Similarly, narrowly focusing in project evaluations on an NbS's ecological benefits may sideline valuable social dimensions of nominally ecosystem-based adaptation actions (Diaz et al., 2018).

Our work contributes to research on adaptation pathways (c.f. Wise et al., 2014; Colloff et al., 2020) that draw attention to the ways that societies respond to environmental change over time (Colloff et al., 2020). Although lacking a temporally explicit focus, we complement this understanding by highlighting the embeddedness of NbS in social-ecological systems, focusing on how NbS for adaptation are based upon, and in turn influence a given social-ecological context. The pathways to sustainability approach (Ely et al., 2022) offers further insights into the political character of adaptation processes including the differential costs and benefits of adaptation for different groups (Ensor et al., 2019). Whilst our analysis does not comprehensively shed light on how NbS address social and political root causes of vulnerability, we highlight how vulnerability is best understood as the property of a system. An integrated approach that goes beyond narrow indicators or climate impacts

can be furthered through genuine participatory approaches with local stakeholders and rightsholders, moving beyond technical assessments of climate risk and hazards. For example, Mehta et al. (2021), have explored these issues with marginalised groups in India, exploring the key role of agency and the co-production of social-ecological knowledge in integrated adaptation and development responses.

6 CONCLUSION

NbS are called upon to address global societal challenges, such as biodiversity and climate crises. Yet a systematic appraisal of how NbS can address societal challenges has so far been lacking. Here we analysed how nature-based interventions shape climate change vulnerability across lower income nations, where nature-dependent livelihoods make people particularly vulnerable to the climate crisis (Fedele et al. 2021). We paid attention to people's vulnerability contexts, how these are shaped by social, institutional, and political factors, and in turn how these shape, and are shaped by NbS.

The analysis revealed the need to pay close attention to intervention and vulnerability contexts, including local needs and adaptation priorities, as well as the climate-driven effects on the ecosystems on which people depend. Attention to these various elements is crucial to ensure that NbS can be effective, equitable and sustainable. We found effectiveness is strongly mediated by social and political mediating factors, in addition to technical factors which speaks to the need for interdisciplinary approaches to understanding NbS and links to development processes (Schipper et al., 2016). Lastly, we hope that this study provides a useful starting point for contributions from researchers from the Global South, who are and should be at the forefront of understanding people's diverse responses to environmental change.

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