










Mapping the effectiveness of nature-based solutions for climate change adaptation

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Funding information

Natural Environment Research Council,
Grant/Award Number: NE/R002649/1;
University of Oxford: John Fell Fund and the
Oxford Martin School

Abstract

Nature-based solutions (NbS) to climate change currently have considerable political traction. However, national intentions to deploy NbS have yet to be fully translated into evidence-based targets and action on the ground. To enable NbS policy and practice to be better informed by science, we produced the first global systematic map of evidence on the effectiveness of nature-based interventions for addressing the impacts of climate change and hydrometeorological hazards on people. Most of the interventions in natural or semi-natural ecosystems were reported to have ameliorated adverse climate impacts. Conversely, interventions involving created ecosystems (e.g., afforestation) were associated with trade-offs; such studies primarily reported reduced soil erosion or increased vegetation cover but lower water availability, although this evidence was geographically restricted. Overall, studies reported more synergies than trade-offs between reduced climate impacts and broader ecological, social, and climate change mitigation outcomes. In addition, nature-based interventions were most often shown to be as effective or more so than alternative interventions for addressing climate impacts. However, there were substantial gaps in the evidence base. Notably, there were few studies of the cost-effectiveness of interventions compared to alternatives and few integrated assessments considering broader social and ecological outcomes. There was also a bias in evidence toward the Global North, despite communities in the Global South being generally more vulnerable to climate impacts. To build resilience to climate change worldwide, it is imperative that we protect and harness the benefits that nature can provide, which can only be done effectively if informed by a strengthened evidence base.

KEYWORDS

adaptation, biodiversity, climate change, ecosystem-based adaptation, nature-based solutions, resilience, systematic map

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1 | INTRODUCTION

Anthropogenic climate change is causing a wide array of damaging impacts across the globe, such as sea-level rise, increased climate variability, and more frequent or intense droughts, floods, and wildfires (IPCC, 2018). This is having increasingly severe social and economic consequences, especially in low and lower middle-income nations which tend to be most vulnerable to the impacts of climate change (IPCC, 2018; McKinsey, 2020; WEF, 2020). Ambitious climate change mitigation action will significantly reduce the severity of impacts that nations, societies, and ecosystems have to face, but even if measures to limit temperature increase to 1.5°C are successful, some impacts such as sea-level rise will continue to increase due to climate system feedbacks and inertia (IPCC, 2018). Adaptation to climate change is therefore necessary.

To date, prevailing approaches for addressing climate change impacts on people, built infrastructure, and economic activities have relied on hard-engineered interventions (Jones, Hole, & Zavaleta, 2012). For instance, sea walls and embankments are commonly used to reduce the impacts of coastal hazards (Enriquez-de-Salamanca, Díaz-Sierra, Martín-Aranda, & Santos, 2017). However, there is growing recognition that nature-based solutions (NbS) can complement or improve upon these approaches (Hobbie & Grimm, 2020; Kapos, Wicander, Salvaterra, Dawkins, & Hicks, 2019; The Royal Society, 2014).

Nature-based solutions are approaches that work with and enhance nature to address societal challenges (Seddon, Turner, Berry, Chausson, & Girardin, 2019). They encompass a broad range of actions that protect, restore, or sustainably manage ecosystems (including natural, semi-natural, or created) to provide benefits to people (Cohen-Shacham, Walters, Janzen, & Maginnis, 2016). NbS include established approaches such as ecosystem-based adaptation (EbA), ecosystem-based disaster risk reduction, natural infrastructure, green and blue infrastructure, and forest and landscape restoration (Cohen-Shacham et al., 2016, 2019), as well as the more recently coined "natural climate solutions" (Griscom et al., 2017). NbS harness a range of benefits that flow from healthy, biodiverse, and resilient natural systems. For example, they can support climate change adaptation through flood protection, air and water quality regulation, and urban cooling while contributing to climate change mitigation and sustaining or enhancing biodiversity (Convention on Biological Diversity, 2009; Griscom et al., 2017; Lavorel, Locatelli, Colloff, & Bruley, 2020; Maes & Jacobs, 2017; Seddon, Chausson, et al., 2020). Indeed, a large part of the appeal of NbS is their potential to address multiple sustainable development goals simultaneously.

With increasing evidence for the many benefits for people from working with nature, NbS have become more prominent in international policy and business discourse on climate change. For example, they were highlighted in recent landmark synthesis reports by the IPCC (2019) and the IPBES (2019), have been endorsed by the World Economic Forum (WEF, 2020), and have ignited major political interest across the world (for a summary, see Seddon,

Daniels, et al., 2020). The United Nations Framework Convention on Climate Change (UNFCCC) also now emphasizes NbS, and the Paris Agreement of UNFCCC (2015) calls on all Parties to acknowledge "the importance of the conservation and enhancement, as appropriate, of sinks and reservoirs of the greenhouse gases," and to "note the importance of ensuring the integrity of all ecosystems, including oceans, and the protection of biodiversity." In response, 66% of Paris Agreement signatories include NbS in the first iteration of their national climate pledges, that is, their Nationally Determined Contributions (NDCs; www.nbspolicyplatform.org; Seddon, Daniels, et al., 2020). However, national intentions to incorporate NbS for climate change adaptation vary by level of economic development, region, and ecosystem type, and have yet to be fully translated into measurable evidence-based targets and action on the ground (Seddon, Daniels, et al., 2020).

One reason for this is a lack of synthesis of the evidence on the effectiveness of NbS for climate change adaptation, especially in comparison to alternative approaches (Seddon, Chausson, et al., 2020). Existing evidence is scattered across disciplines in the physical, natural, and social sciences and is thus not easily accessible to policymakers and decision-makers (Seddon, Chausson, et al., 2020). Nearly a decade has passed since the last major systematic attempt to consolidate global evidence on the effectiveness of NbS for climate change adaptation (Doswald et al., 2014; Munroe et al., 2012). Since this review, thousands of studies have been published on interventions relevant to NbS (Figure S1 in Appendix F).

While there have been several efforts to collate this evidence (e.g., Bonnesoeur et al., 2019; Dadson et al., 2017; Filoso, Bezerra, Weiss, & Palmer, 2017; Morris, Konlechner, Ghisalberti, & Swearer, 2018; Rowiński, Västilä, Aberle, Järvelä, & Kalinowska, 2018), most of these reviews are not systematic, and focus on a limited set of climate change impacts or types of NbS, often in a specific geographic region and/or narrow range of ecosystem types. There has been a particular emphasis on synthesizing evidence on the effectiveness of wetland or forest restoration in river catchments for flood and soil erosion reduction, or regulating water supply and quality (Bonnesoeur et al., 2019; Dadson et al., 2017; Filoso et al., 2017; Meli, Benayas, Balvanera, & Ramos, 2014; Rowiński et al., 2018), and to a lesser extent, a focus on comparing the cost-effectiveness of NbS with engineered approaches for protecting coastlines (Morris et al., 2018; Narayan et al., 2016). Existing reviews are also limited to empirical studies, omitting scenario modeling (i.e., where effectiveness is derived from temporal modeling projections), hence overlooking contexts that cannot be studied empirically. For example, scenario modeling can be useful for testing intervention effects at broader spatial scales and can evaluate their performance under different future climate change scenarios, crucial for adaptation planning. Finally, existing reviews tend not to report on social, economic, and ecological outcomes together, yet delivering multiple, diverse benefits simultaneously is central to the dominant concepts of NbS (Cohen-Shacham et al., 2016, 2019; European Commission, 2015; Hanson, Wickenberg, & Olsson, 2020).

As nations revise or prepare new climate change adaptation policies, including NDCs and National Adaptation Plans, it is particularly important that a more comprehensive understanding of the effectiveness of NbS for climate change adaptation is available (Seddon, Chausson, et al., 2020). A rigorous scientific evidence base is crucial for policy and practice on NbS, including for target setting, planning, and governance, and to achieve coherence across policy goals. This includes identifying potential synergies and trade-offs between adaptation, mitigation, biodiversity conservation, and sustainable development objectives, and how those vary across scales (Kapos et al., 2019).

To address these issues, we used a systematic mapping methodology (cf. James, Randall, & Haddaway, 2016) to consolidate and characterize the large and dispersed evidence base on the effectiveness of NbS for addressing climate impacts, including hydrometeorological hazards. "Climate impacts" were defined following the IPCC as "the effects on natural and human systems of physical events, of disasters, and of climate change" (IPCC, 2012). Our aims were to (a) identify existing evidence of the effectiveness of NbS for addressing different climate impacts on people and economic sectors, and catalogue this evidence with respect to geography, nation income group, climate impacts addressed, ecosystem, and type of intervention; (b) highlight synergies and/or trade-offs between climate impact reduction and greenhouse gas (GHG) mitigation, and/or ecological and social outcomes; and (c) highlight knowledge gaps to stimulate further research, especially on the extent to which geographic regions, ecosystems, intervention types, and climate impacts are understudied. We did not narrow our scope to studies explicitly using the terminology of NbS, nor to interventions meeting the conceptual definition of NbS, because this would have excluded many relevant studies. Hence, hereafter we refer to nature-based interventions instead of NbS.

Our overarching question was "What is the state of the scientific evidence base on the effectiveness of nature-based interventions for addressing the adverse impacts of climate change and hydrometeorological hazards?" In mapping and characterizing the evidence from the literature on this question, our goal is to enable well-targeted scientific research to play a stronger role in informing climate and biodiversity policy and pledges, and to support the design and implementation of successful and resilient NbS that deliver benefits for both nature and people.

2 | MATERIALS AND METHODS

2.1 | Systematic mapping protocol

We drafted a systematic mapping protocol (Appendix A) to catalogue the evidence in a transparent and objective manner (Collaboration for Environmental Evidence, 2018). We revised the question scope (Table 1), search string, study selection criteria, and coding framework (Tables S1 and S2; Box 1; Appendix B) in early 2018 through a series of meetings and workshops with a

TABLE 1 The elements of the question scope underpinning the search string and study selection criteria

Target	Intervention
Human individuals, groups, communities and economic sectors (e.g., agriculture, water, forestry, transport, energy)	Actions in rural, semi-rural, or peri-urban settings involving management, restoration or protection of biodiversity, ecosystems, or ecosystem services, or involving ecosystem creation and subsequent management
Comparator	Outcome
Pre-intervention baselines; repeat assessments over time; quasi or experimental controls (where no adaptation action was taken); modeled counterfactuals or evaluator inference of counterfactual. Studies using non-nature-based adaptation approaches as comparators were included, but for these, overall effectiveness was not reported	Measured, observed, or ex-ante modeled outcomes (regulating or provisioning ecosystem services) affecting impacts of hydrometeorological hazards or climate change on people or economic sectors

BOX 1 Study exclusion criteria (see Table S2 in Appendix E for the full list of selection criteria)

We excluded studies on:

- Effects of nature-based interventions on stressors not associated with climate change or hydrometeorological hazards, which nevertheless could play important roles in building resilience to the impacts of climate change
- Impacts not explicitly reported as being driven (at least in part) by climate or hydrometeorological phenomena
- Effects on vulnerability (including social adaptive capacity) only arising from intervention implementation, management or governance rather than from the flow of ecosystem services
- Urban nature-based solutions, hybrid natural/engineered interventions, agricultural interventions (such as agroforestry), rangeland, or fisheries interventions not involving ecosystem restoration or protection
- Effectiveness of existing ecosystems for adaptation-relevant services, unless an intervention (e.g. protection or restoration) was involved

panel of experts from the conservation and development sectors with global expertise covering food and water security, ecosystem-based approaches to climate change adaptation, ecosystem services, sustainable development, and climate change policy (see Section Acknowledgements; Appendix A). We designed the framework to ensure relevance for policymakers and to capture

the broad heterogeneity of studies, intervention types, and outcomes associated with the NbS concept. We specifically focused on evidence on the effects of nature-based interventions on climate impacts.

We modified a previous search string devised by Munroe et al. (2012) to match the conceptual scope of NbS (Cohen-Shacham et al., 2016), and expanded the four-part search string into a five-part search string, modifying and building on the previous set of terms (Appendix A). This better targeted the search to ensure a manageable number of studies. We also included studies with GHG mitigation, ecological, or social outcomes only if the effect of the intervention on climate impacts was also reported. Hence, a large body of literature reporting solely on any of these other outcomes were excluded (e.g., Anderson et al., 2019; Busch et al., 2019; Friedlingstein, Allen, Canadell, Peters, & Seneviratne, 2019; Griscom et al., 2017, 2020; Lewis, Wheeler, Mitchard, & Koch, 2019; Roe et al., 2019).

2.2 | Searches and screening process

We ran the search string for English publications in SCOPUS and Web of Science CORE index collections (April 12, 2018), restricting the search to title, abstract content, and author keywords, and excluded reviews, proceedings, book chapters, editorials, opinions, commentaries, and perspectives. We removed duplicates in EndNote (v8.2) and exported search results into Abstrackr (Wallace, Small, Brodley, Lau, & Trikalinos, 2012) for screening using a stepwise procedure, screening first reference titles, then abstracts. Next, we progressively refined selection criteria for clarity and inter-reviewer consistency, and further refined these criteria after abstract screening to produce a manageable number of studies, based on time and team capacity constraints. At this stage, we excluded studies strictly focusing on hybrid (natural/engineered) interventions, unless the outcome from the nature-based component was explicitly delineated, as well as a set of agricultural, pastoral, and fisheries-orientated interventions that did not aim to restore or protect a natural ecosystem (see Table S2—selection criteria exclusion points 1 and 2).

Decisions at each stage of screening were conservative; we assessed studies for which inclusion eligibility was unclear at the next stage. We randomly selected at least 10% of references to check for inter-reviewer coding consistency with a Kappa test. If the Kappa coefficient was below 0.6 (the threshold at which inter-reviewer coding consistency is deemed sufficient; Cohen, 1960), we reviewed any emerging inconsistencies and revised the screening strategy and selection criteria for clarity. We carried out single reviewer screening cautiously, that is, checking screening consistency throughout the process. Approximately 25% of all screening decisions at the abstract and full-text stages were made by at least two reviewers. Studies excluded during full-text screening, and reasons for their exclusion, are available in Appendix D. Inclusion decisions were

guided by whether the study reported outcomes stemming from nature-based interventions relevant for assessing the effect on an existing, or predicted climate impact, regardless of the aim of the intervention.

2.3 | Coding strategy

The extraction of evidence from studies was guided by a coding framework (Appendix B) and recorded through an entry form feeding into an online evidence map (naturebasedsolutionsevidence.info). We adapted a typology of 29 climate impacts from Munroe et al. (2012). Climate impacts can be interrelated—for example, drought can affect water availability and food production. To standardize coding, we categorized the study under the climate impact most closely corresponding to the outcome measure. For example, if water flows were measured, we coded for water availability, even if the impact was characterized as drought. We defined effectiveness as the extent to which an intervention affected a climate impact in comparison to the comparator reported in the study (see Table 1).

To explore the comprehensiveness of intervention effectiveness assessments, we also coded for reported social and ecological outcomes, beyond those directly related to climate impacts (hereafter “broader outcomes”; refer to Appendix B for full definitions). Reported ecological outcomes were defined as outcomes associated with species conservation, habitat quality, diversity (e.g., species richness), or resilience of natural ecosystems, and were either measured or indirectly reported (e.g., from local knowledge). We defined social outcomes as any outcomes reported that were framed by the authors as relevant to a specific group of people. Social outcome measures sometimes overlapped with the outcome measure for the climate impact, such as if the measure was the number of people of a community protected from coastal storms. In other instances, social outcomes were not linked to climate impacts, such as in studies addressing equity or empowerment. We also recorded whether the study reported monetized implementation and maintenance costs, or economic outcomes (thereafter economic costs/benefits) stemming from the intervention; whether these were reported in the context of economic appraisals (including ecosystem service monetary valuations); and whether the implementation and maintenance costs were compared to those of alternative interventions. For studies reporting economic outcomes, we did not code for the overall direction of economic effect, focusing instead on whether the study reported cost comparisons and economic appraisals.

We grouped nature-based interventions into six categories: (a) protection; (b) restoration; (c) other forms of management of natural or semi-natural ecosystems (hereafter management); (d) combination (a combination of protection, restoration, and/or management); (e) creation or management of created ecosystems (hereafter termed “created ecosystems”); and (f) combination of actions in created ecosystems and natural/semi-natural ecosystems (hereafter “mixed

BOX 2 Coding definitions for nature-based interventions

Restoration: Active or passive restoration of natural or semi-natural ecosystems including approaches characterized as follows: ecological restoration; functional restoration; habitat restoration; structural restoration; intervention ecology; reclamation; reforestation; rehabilitation; reconstruction; revegetation. Lab-based experiments (e.g., flume experiments) mimicking restoration were coded as such. Ecological, ecosystem, or nature-based engineering approaches were coded as created ecosystem interventions if there was no clear intent to restore or recover a natural or semi-natural ecosystem.

Protection: Marine, freshwater, and land site-specific protection of natural or semi-natural ecosystems, including protected areas and their management, land exclosures, private land conservation measures, reserves, conservancies, and locally managed marine areas with specific set-aside "conservation zones."

Management: Natural or semi-natural ecosystem management interventions other than restoration or protection. This includes forest management (e.g., close-to-nature approaches) and ecosystem-based fire management strategies. We excluded agricultural, fisheries, and husbandry approaches, including pastoralism, that do not aim to restore or protect a natural or semi-natural ecosystem to provide supporting, regulating, or provisioning services for climate change adaptation.

Combination: A combination of two or more approaches in natural or semi-natural ecosystems, including interventions where land can regenerate through protection.

Created ecosystems: The establishment, protection or management of created ecosystems, including the creation of a new ecosystem type in place of a naturally occurring one (e.g. afforestation of former grasslands, or constructed wetlands) or where the ecosystem is modified such that it does not resemble its natural ecological state (e.g. rehabilitating degraded land with exotic species or reforesting an area with a single species where a diverse forest used to stand). This category also includes interventions for which it could not be determined whether the established habitat is created, natural or semi-natural, and afforestation conducted to facilitate natural habitat restoration, provided the climate impact outcomes resulted at least in part from the afforested (created) habitat.

Mixed created/non-created: Approaches involving both natural/semi-natural and created ecosystems.

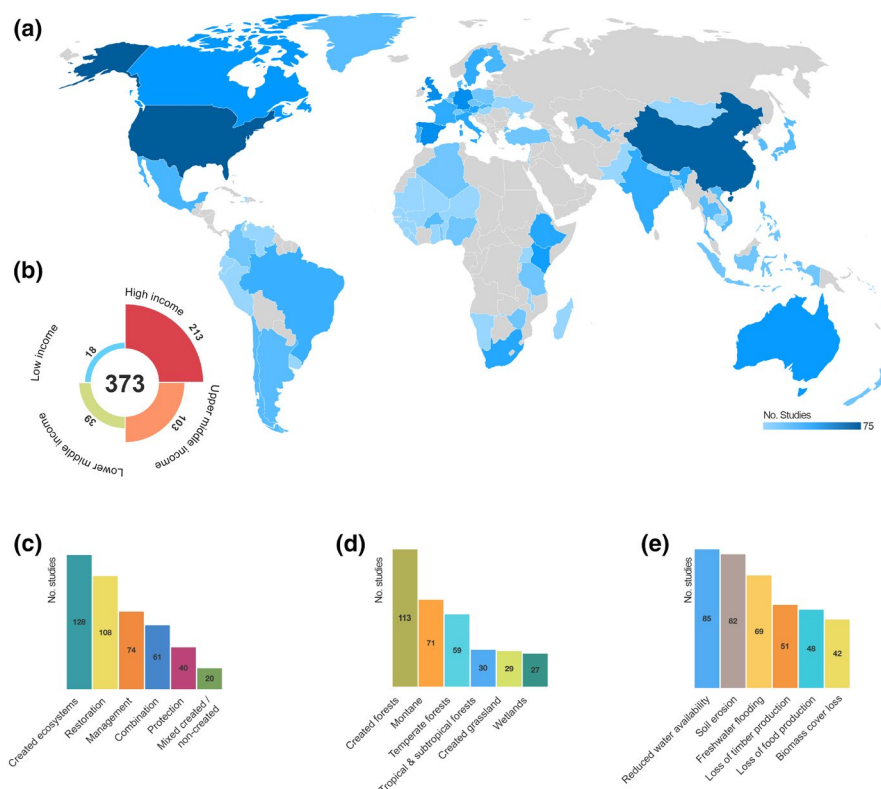


FIGURE 1 (a) Global distribution of studies examining the effectiveness of nature-based interventions to address climate impacts, and how this varies across: (b) income groups defined by the World Bank, (c) broad types of nature-based interventions, (d) the six most represented ecosystem types, and (e) the six most common climate impacts addressed by the interventions. Numbers of studies (including both empirical and scenario modeling) for each category are indicated on the plots. Note that the number of studies for climate impact, intervention type, and ecosystem type may sum to more than the total number of studies reviewed because individual studies sometimes reported findings from more than one category of each variable

created/non-created"; see Box 2 for definitions). We grouped the ecosystems in which interventions took place into 28 categories, drawing on the typologies of Munroe et al. (2012) and the IUCN

habitat scheme (v3.1; IUCN, 2015), adapting them to accommodate the range of ecosystems encompassed in our evidence database (specifically, adding explicit categories for created forests, created

grasslands, and created “other”). The nations in which interventions took place were classified with respect to broad geographic regions and income groups following the World Bank regional classification scheme (2020). For full details, see the Supporting Information available online (Appendix B).

2.4 | Data analysis and mapping

The evidence base was characterized through descriptive statistics, mapping the number of studies with respect to methodology (Section 3.1), geographic region, type of intervention, spatial scale of implementation (site specific or landscape-scale), type of ecosystem, and climate impact addressed (Section 3.2). We then reported on empirical assessments, focusing on the linkages between intervention type and climate impact (Section 3.3), reported intervention effectiveness in reducing climate impacts (Section 3.4), effectiveness comparisons with alternative approaches, extent of reporting of broader outcomes and the reported effects of the nature-based intervention on these, and the relationship among

reported climate impact outcomes of a given intervention. Critical appraisal of study quality was not conducted because this is beyond the scope of a systematic map, and is generally done to synthesize smaller subsets of studies (James et al., 2016) where quality can be appraised with reference to specific goals of the review question. Here, we summarize reported effectiveness of interventions to characterize the evidence base and guide future analyses, rather than to infer the overall effectiveness of an intervention type.

We describe the evidence base in terms of absolute numbers and percentages of studies or cases within the categories of the map (e.g., regions, ecosystem types, climate impacts). Interventions reported in scenario modeling studies were only coded at the study level, whereas for empirical studies, interventions were disaggregated into cases (each combination of intervention type, location, and ecosystem was recorded as a distinct case). Where absolute numbers of studies or cases are shown in Figures 1–4, we only report percentages in the text. Both numbers and percentages are found in Tables S3–S8. Evidence heatmaps, other visualizations, and a full list of studies identified are available online (www.naturebasedsolutionsevidence.info).

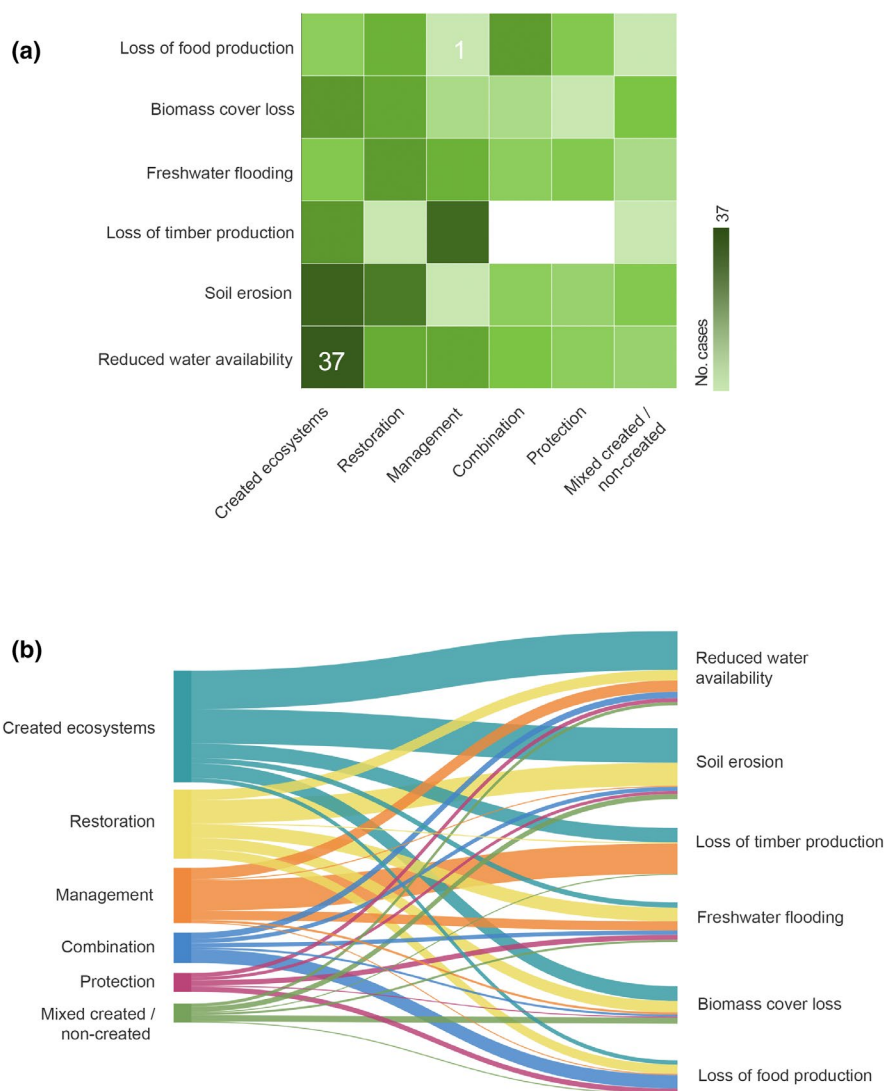


FIGURE 2 Systematic map of the six most reported climate impacts addressed by each of the six broad intervention types illustrated (a) as a heatmap showing the distribution and frequency of cases, and (b) as a Sankey diagram, where the thickness of each band corresponds to the number of cases involving the linked intervention type and climate impact. Data are from empirical studies only

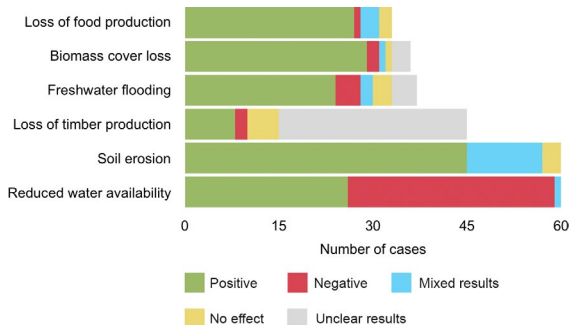


FIGURE 3 Reported effectiveness of nature-based interventions for addressing the six most reported climate impacts. A positive effect indicates where authors reported the nature-based intervention to have reduced the climate impact (e.g., improved water availability or decreased soil erosion); a negative effect indicates where authors reported the nature-based intervention to have exacerbated the climate impact (e.g., increased loss of timber production or increased flooding); mixed indicates where authors reported interventions to have had both a positive and negative effect on the climate impact (e.g., where results varied spatially or over time); unclear indicates where it was not possible for authors to determine effectiveness; no effect indicates where authors showed the intervention to have had no effect on the climate impact. Data are from 293 cases reported from 194 empirical studies. Note that the number of cases for climate impact may add to more than the total number of cases reviewed because individual cases sometimes reported findings for more than one climate impact

3 | RESULTS

3.1 | Studies identified and methodological approaches adopted

The search of the scientific literature on the effects of nature-based interventions on climate impacts identified a total of 21,995 references, of which 386 met our selection criteria (Table S2). A schematic showing the process involved in this systematic map and numbers of articles moving between stages is shown in Figure S2. The studies were published across 168 academic journals, from 1988 to 2018, with the rate of publication rapidly increasing after 2004 and 65% of articles being published since 2012 (Figure S1). Of these 386 studies, 376 reported on the effect of the nature-based intervention on climate impacts (195 empirical and 185 scenario modeling studies, with 4 studies including both). The remainder only reported on the implementation and maintenance costs or economic outcomes and therefore were not included in this analysis. The 195 studies reporting evidence from empirical assessments reported 293 intervention cases, providing 406 distinct outcome assessments (i.e., the effect of the intervention on a climate impact). Of these, most assessments were quantitative (260, 89%); 19 (6%) were qualitative and 14 (5%) involved mixed-method approaches. Most (189, 65%) were non-experimental; the rest (104, 35%) were experimental or quasi-experimental approaches (i.e.,

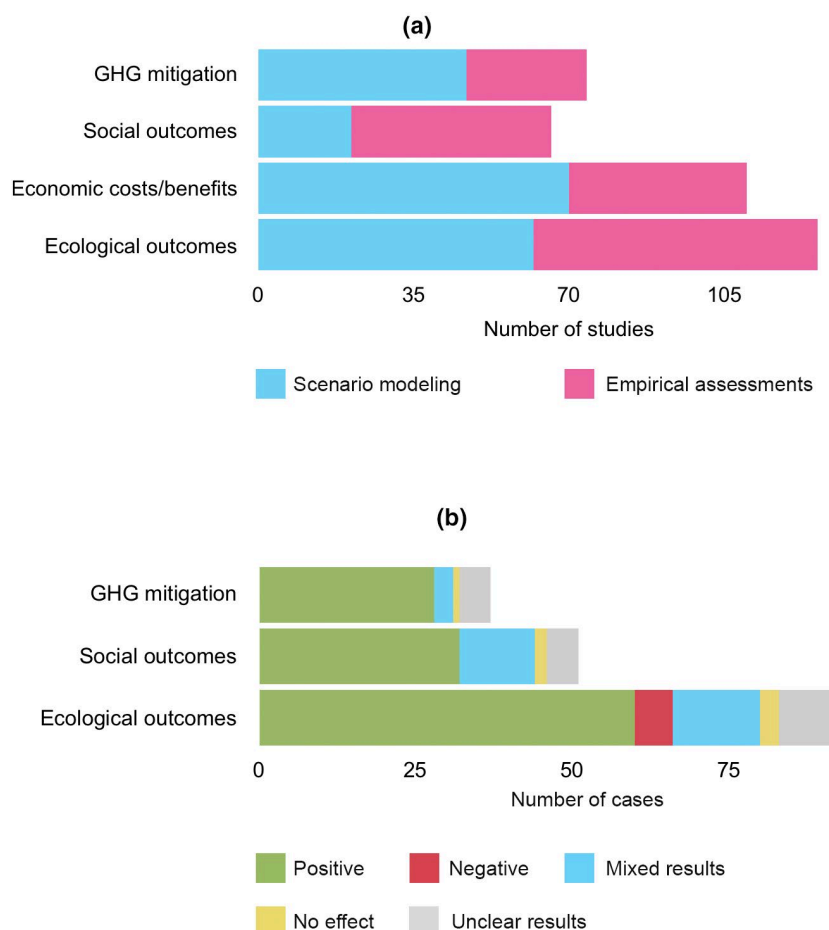


FIGURE 4 (a) Number of studies reporting on greenhouse gas (GHG) mitigation, social and ecological outcomes, and economic costs/benefits of interventions (scenario modeling and empirical assessments). (b) Number of cases from empirical studies that reported positive, negative, mixed, unclear, or no effect for GHG mitigation, social, and ecological outcomes only; the overall direction of effect was not coded for economic outcomes

with a control) including three cases in controlled laboratory settings (all of which were wave flume experiments). Most outcome assessments (341, 84%) used biophysical measures (e.g., wave height reduction or timber production rates). Only 37 (9%) used social measures (e.g., stakeholder perceptions of intervention effectiveness), 11 (3%) provided economic measures, and 11 (3%) were anecdotal. A few (7, 2%) provided mixed outcome measures (two or more of biophysical, social, and economic indicators).

3.2 | Distribution of the evidence of the effectiveness of nature-based interventions from modeling and empirical studies

3.2.1 | Variation in numbers of studies by region, income group, and vulnerability

Evidence was reported from 85 nations with a concentration of studies in East Asia and the Pacific (29% of the studies overall, 59% of which were from China), Europe and Central Asia (26%), and North America (24%; Figure 1a; Figure S3). Overall, most studies (57%) came from nations classified as high-income (World Bank, 2020), and 27% were from upper-middle income nations. Comparatively few are from low-income and lower middle-income nations (10% and 5%, respectively; Figure 1b). The disparity was more pronounced for scenario modeling studies, of which 71% were in high-income nations, compared to 43% of empirical studies (Figure S3). Small Island Developing States (SIDS) are particularly vulnerable to climate impacts, yet only 10 studies from SIDS were identified.

3.2.2 | Type of nature-based intervention

The most studied type of nature-based intervention, accounting for around one-third (34%) of studies in our database, involved the establishment or management of created ecosystems (e.g., tree plantations or planting exotic fast-growing grasses; Figure 1c). Restoration interventions were the second most reported (29%), followed by management interventions (20%). Combination interventions were reported by 16% of studies, and most (81%) of these included some form of ecosystem protection, though only 11% of studies reported on ecosystem protection alone (i.e., marine, terrestrial, or freshwater protected areas). Table 2 provides examples of the types of actions falling under these broad intervention categories. Overall, 67.5% of studies reported outcomes from landscape-scale interventions.

3.2.3 | Ecosystem type

Most studies (284, 76%) reported on interventions in natural or semi-natural ecosystems (Figure 1d). Of these, 53% were in forests, mostly in temperate regions, with fewer studies in subtropical and tropical regions and even fewer in boreal forests and taiga. Across

other ecosystem types, montane ecosystems (any ecosystem above 1,000 m) were found in 19% of studies while only 13% of studies included coastal ecosystems (coral reefs, mangroves, seagrass, deltas/estuaries, saltmarsh, and other coastal ecosystems), followed by rivers, streams and riparian ecosystems (in 10% of studies), inland wetland ecosystems (including peatland, ponds, and lakes; 9%), and natural grasslands (9%; mostly temperate). Seagrass and kelp ecosystems were the most poorly represented, found in just one study each. Across studies involving created ecosystems (38% of all studies), most reported on interventions in forests, followed by grasslands and wetlands (Figure 1d). Of the 29 studies that reported on interventions in created grasslands, 19 (66%) also involved created forests.

3.2.4 | Climate impacts

Nature-based interventions identified through our systematic map addressed a wide range of climate impacts (33 in total). Overall, 239 (64%) studies reported effects on one climate impact, with the remainder reporting effects on 2–5 different climate impacts (mean \pm SD = 1.5 ± 0.78). However, most of the evidence concerned effects on reduced water availability (23% of studies), soil erosion (22%), freshwater flooding (19%), biomass (vegetation) cover loss (11%), and loss of timber (14%) and food (13%) production (Figure 1e). Of the 48 studies reporting climate effects on food production, 23 (48%) concerned fish production, 18 (38%) animal fodder, and 10 (21%) crop production. Meanwhile, only 39 studies (10%) focused on coastal impacts (i.e., coastal erosion, storm surge, coastal inundation, coastal saltwater intrusion, and wind damage), and 21 studies (6%) reported effects on wildfire risk. Eight studies (2%) reported effects on climate-related slope hazards (avalanches and landslides).

3.2.5 | Comparison between empirical and scenario modeling studies

There were differences between scenario modeling and empirical studies in the amount of evidence available among types of nature-based interventions, ecosystem types, and climate impacts (Figure S3). Although scenario modeling studies comprised just under half (49%) of all studies, more than half of the studies reporting evidence from restoration and management interventions were scenario modeling (55% and 58%, respectively). Scenario modeling also contributed the bulk of studies across nine ecosystem types, whereas empirical studies provided most of the evidence for 11 ecosystem types. Most evidence for montane ecosystems (59%), temperate forests (63%), streams, rivers, and riparian ecosystems (62%), freshwater wetlands (70%), tropical and subtropical forests (60%), created wetlands (62%), boreal forests and taiga (64%), and mangroves (57%) stemmed from scenario modeling studies. Additionally, all but one of the studies reporting evidence from peatland and tropical ocean ecosystems (six and three, respectively) were scenario modeling. Across climate impacts,

TABLE 2 Examples of nature-based interventions studied in articles identified through our systematic mapping exercise, organized with respect to each of the six broad intervention types. We consider interventions which may not meet guidelines for nature-based solutions (NbS) in practice, because this evidence is needed to build an understanding of what makes for effective NbS (see Section 2). Full details of the references cited in this table are available online (www.naturebasedsolutionsevidence.info)

Broad type of intervention	Example	Select references
Protection	Community-based conservancies operating payments for ecosystem services schemes funded by tourism, to incentivize wildlife conservation	Osano et al. (2013)
	Conservation of old-growth forests, maintaining their ecosystem complexity and function, to mitigate the impact of extreme temperatures, and enhancing vital services including climate regulation, primary production, and water retention	Choi et al. (2016), Norris et al. (2012)
	Riparian habitat conservation to maintain a buffer zone of permanent vegetation cover surrounding a river to stabilize streambanks and reduce sedimentation and flooding	Arthun et al. (2013), Garbrecht et al. (2014)
	Forest protection (from deforestation and human-induced fire hazards) through Indigenous knowledge practices to maintain forest-dependent livelihoods	Lunga et al. (2017)
	No-take marine-protected areas to increase ecosystem resilience (e.g., of coral reefs, kelp beds) and the fisheries these ecosystems support	Cinner et al. (2013), Graham et al. (2007), Ling et al. (2009)
Restoration	Allowing for passive natural revegetation of degraded lands to reduce erosion and restore soil quality and hydrology	Cao et al. (2009), Ford et al. (2011), Jiao et al. (2012)
	Forest landscape restoration to recover hydrological services or to diversify livelihoods by providing non-timber forest products	Hani et al. (2017), Harden et al. (2000)
	Grassland restoration, facilitated by tree planting, to reduce desertification in arid lands	Yuan et al. (2012)
	Restoring degraded mangroves by promoting natural recruitment or active planting to keep pace with sea-level rise, store belowground carbon, and provide coastal protection	Duncan et al. (2016), Krauss et al. (2012)
	Restoration of riparian ecosystems and stream or river structure to provide ecosystem services such as flood reduction, carbon sequestration, sediment retention to improve downstream water quality, and water temperature regulation to support inland fisheries	Elosegi et al. (2017), Filoso et al. (2015), Vermaat et al. (2016), Williams et al. (2015)
	Returning farmlands and degraded floodplains to natural wetlands to improve water quality and reduce flooding	Ardon et al. (2017), Filoso et al. (2017), Peh et al. (2014)
	Restoring coastal ecosystems for coastal protection. E.g., facilitating natural oyster recruitment to rebuild oyster reefs, transplanting vegetation and returning natural hydrology to restore saltmarshes, and replanting vegetation on sand dunes	Calvo-Cubero et al. (2013), Martinez et al. (2016), Scyphers et al. (2011), Silliman et al. (2015)
Management	Forest management (e.g., thinning) in natural forest stands to maintain forest health and optimize timber harvests threatened by droughts and other disturbances	Cabon et al. (2018), Gyenge et al. (2011), Simon et al. (2017)
	Converting intensive forestry to "close to nature" practices, such as increasing stand diversity, allowing natural regeneration, and applying selective logging to increase resilience of timber production to climate change threats	Barsoum et al. (2016), de-Dios-García et al. (2015), Jactel et al. (2012)
	Fire management in forests and grasslands through the use of traditional ecological knowledge	Bilbao et al. (2010), Seijo et al. (2015)
Combining restoration with protection	Landscape-scale initiatives that combine actions to protect remaining intact forest patches and restore degraded forest fragments of watersheds	Pattanayak et al. (2001), Pires et al. (2017)
	Use of enclosures or exclosures to restrict human access and livestock grazing, allowing for passive natural revegetation of degraded rangelands and sustaining provisioning and regulating ecosystem services	Amghar et al. (2012), Descheemaeker et al. (2010), Seymour et al. (2010), Wairore et al. (2016)
	Creating protected areas around recently restored ecosystems or restoring ecosystems that have become degraded in already established protected areas to simultaneously safeguard biodiversity and ecosystem services. E.g., returning and maintaining natural vegetation in watersheds to preserve water supply or along sand dunes to protect from coastal storms and erosion	Biel et al. (2017), Brambilla et al. (2017), Carvalho-Santos et al. (2016), Mander et al. (2017)

(Continues)

TABLE 2 (Continued)

Broad type of intervention	Example	Select references
Combining protection with management	Wildlife management in and around protected areas to support wildlife-based tourism, complementing pastoralist livelihoods in Kenya	Osano et al. (2013)
	Multi-functional forest management combining protected no-use areas and areas designated for sustainable harvesting; used for objectives such as promoting slope hazard reduction or sustaining forest-based livelihoods	Getzner et al. (2017), Strauch et al. (2016)
Combining restoration and management	Restoration followed by management for ecosystem service provisioning. E.g., reforestation and forest management to increase timber provisioning in the face of climate change or replanting mangroves followed by community management to restore mangrove-based livelihoods	Bogaart et al. (2016), Brown et al. (2011), Walton et al. (2006)
	Landscape-scale initiatives that designate land for natural habitat restoration and conservation alongside land for sustainable harvesting to achieve multiple objectives, such as biodiversity conservation, supporting livelihoods, and providing regulating ecosystem services	Andersson et al. (2015), Orsi et al. (2011), Robles et al. (2014)
Created ecosystems for regulating services	Large-scale land rehabilitation policies involving afforestation or planting exotic shrubs and grasses to reduce soil erosion or desertification	Ausseil et al. (2013), Jia et al. (2017) Lei et al. (2016), Salinas et al. (2013)
	Planting grass strips and other vegetation near waterways or on slopes to control erosion	Fox et al. (2011), Frank et al. (2014), García-Palacios et al. (2010), Krautzer et al. (2011)
	Afforestation to address natural disasters, such as flooding, wind, and dust storms	Kelly et al. (2016), Missall et al. (2018), Suzuki et al. (2016)
	Constructed wetlands as a method of water purification and flood control; wetlands may be designed for these single purposes or integrated into a multi-functional space such as a nature-recreation park	Li et al. (2013), Liqueste et al., Moustafa et al.
	Establishing a network of created wetlands such as within agricultural landscapes to secure water supplies and reduce flooding by acting as natural water reservoirs or enhancing groundwater recharge	Gujja et al. (2009), Yu et al. (2006)
Created ecosystems for production services	Establishment of exotic and/or monoculture tree plantations for timber production and other ecosystem services, such as carbon storage and erosion prevention	Balthazar et al. (2015), Carvalho-Santos et al. (2016), Yamada et al. (2017)
	Management (including thinning, coppicing, and clearcutting) of exotic and/or monoculture tree plantations to optimize timber production exposed to climate hazards	García-Gonzalo et al. (2014), Jactel et al. (2012), Petuccio and Andrés-Domenech et al. (2018)
Interventions combining created and natural ecosystems	Community-led programs combining tree plantations with management of natural forests to support forest-based livelihoods, including income from carbon credits	Pandey et al. (2016), Wood et al. (2017)
	Landscape-scale initiatives involving afforestation combined with restoration and protection of natural vegetation to address land degradation	Jiang et al. (2016), Zhang et al. (2015)

scenario modeling studies contributed the bulk of studies across eight climate impact categories, compared to nine categories for empirical studies. Most studies reporting effects on freshwater flooding (64%), loss of timber production (76%), wildfire risk (67%), and storm surge (59%) were scenario modeling. Furthermore, all but one of the studies reporting evidence on pests and coastal salt-water intrusion impacts (six and three, respectively), and all four studies on avalanche impacts were scenario modeling.

3.3 | Climate impacts addressed by different types of nature-based interventions

Interventions reported in empirical cases were linked to a range of different climate impacts among the 29 categories defined a-priori

as well as a number of other impacts (see Section 2; Figure 2). We did not code scenario modeling studies at the case level, and therefore do not report linkages between interventions and climate impacts for these (see Section 2). Across empirical studies, effects of each intervention type were reported on for 11–16 different types of climate impacts.

In natural or semi-natural ecosystems, we found the highest occurrence of evidence at the intersection of management and effects on timber production (29 cases, 51% of all management cases) and of restoration and soil erosion (19, 28% of all restoration cases; Figure 2). We found a notable amount of evidence at the intersection of management and water availability (11, 19%) and freshwater flooding (9, 16%); restoration and freshwater flooding (11, 16%), and biomass cover (11, 16%); as well as at the intersection of combination interventions and food production (15, 44%). Less evidence was

found at the intersection of ecosystem protection and almost all climate impacts, though a handful of studies reported an effect on freshwater flooding (5, 22%), food production (5, 22%), water availability (4, 17%), and soil erosion (3, 13%).

For created ecosystems (mostly forests), most evidence concerned water availability (37, 36% of interventions in created ecosystems) and soil erosion (33, 32%), followed by effects on biomass cover (14, 14%). Interventions involving a mix of created and non-created ecosystems were under-represented in the evidence base and, where reported, studies assessed effects on biomass cover (6, 60%), soil erosion (5, 50%), and water availability (3, 30%).

3.4 | Reported effectiveness of nature-based interventions in addressing climate impacts

3.4.1 | Effectiveness of nature-based interventions on climate impacts

Most outcome assessments (59%) across the 293 cases reported a positive effect of the intervention (i.e., the adverse climate impact was reduced), while 12% reported a negative effect (i.e., the climate impact increased), 6% reported mixed effects, and 6% reported no effect (Figure 3). Overall, the proportion of positive outcomes stemming from interventions in natural or semi-natural ecosystems was higher than for interventions involving ecosystem creation (66% vs. 49%, respectively), whereas the converse was true for negative outcomes (7% vs. 19%). In 17% of cases, an unclear effect was reported; however, most of these cases derive from a single study on timber production that provided multiple case study assessments coded as unclear. Most (70%) reports of negative effects were associated with impacts on water availability (see Figure 3), mainly stemming from interventions involving ecosystem creation (primarily created forests and grasslands in China). Other negative effects (e.g., on freshwater flooding or reduced water quality) were mainly associated with either afforestation, reforestation, and other forms of forest management such as thinning, salvage logging, or fire management.

For most interventions (70% of all cases), only one climate impact was reported. Of the 89 cases (30% of all cases) for which multiple impacts were reported, only 21 reported trade-offs between climate impact outcomes (i.e., the intervention effect on one impact was negative, or mixed, and a positive effect was reported on another). Notably, 11 of these cases reported trade-offs between effects on water availability and effects on soil erosion, freshwater flooding, or biomass cover; addressing the latter impacts came at the cost of exacerbating reduced water availability. Of these cases, eight (73%) were associated with the establishment of created forests and grasslands in mainland China (Box 3). In contrast, 15 interventions reported positive effects on water availability and other climate impact outcomes, and the majority (13) of these synergies were associated with interventions in natural or semi-natural ecosystems, with just two cases in created ecosystems. The remaining 10 cases reporting trade-offs were either between food

production and other impacts (drought, water availability), or between freshwater flooding and soil erosion or water availability.

3.4.2 | Effectiveness of nature-based interventions compared to alternative approaches

Few cases (19, 6%) across 14 studies compared the effectiveness of the nature-based intervention with alternative approaches. Of these, just under half (nine) showed the nature-based intervention to be more effective and three showed it to be the same. A few cases showed the effectiveness of the nature-based intervention compared to the alternative approach to be mixed (three), less effective (three), or unclear (two), but in these cases the nature-based intervention was still reported to be effective at reducing the climate impacts assessed. Of the 19 cases, 12 compared the nature-based intervention to engineered approaches, with eight cases showing the nature-based intervention to be more effective. For example, slope revegetation and wetland protection or creation were reported to be more effective at addressing freshwater flooding than engineered approaches such as check dams, artificial water storage alternatives, and buffer tanks (Amini, Ghazvinei, Javan, & Saghaian, 2014; Grygoruk, Mirosław-Świątek, Chrzanowska, & Ignar, 2013). The remaining seven cases compared nature-based interventions with hybrid interventions (the nature-based intervention was as effective in two cases, and less effective in one), rangeland management interventions (the effectiveness comparisons were mixed in all cases), and a fire suppression policy (the nature-based intervention was more effective).

3.5 | GHG mitigation, socio-economic, and ecological outcomes of nature-based interventions

While most studies reported at least one broader outcome (social, ecological, economic costs/benefits, or GHG mitigation) in addition to the effect on climate impacts, 149 (40%) did not report any. Of those that did, few provided in-depth assessments of these dimensions, and only eight studies (2%) reported on all four dimensions. The reporting of social outcomes and economic costs/benefits was more prevalent across studies from lower-income nations than those in higher-income nations (Table S6). In contrast, reporting on GHG mitigation or ecological outcomes was comparable between higher- and lower-income nation groups. However, this variation depended on intervention and ecosystem type (see Supplementary Results, Appendix C). A greater proportion of scenario modeling studies reported economic costs/benefits and GHG outcomes, whereas a greater proportion of the empirical studies reported social outcomes (Table S7).

3.5.1 | Outcomes for GHG mitigation

Only 19% of studies we identified reported on GHG mitigation outcomes (Figure 4a; either avoided emissions, amount of sequestered

BOX 3 Do nature-based interventions cause trade-offs for water availability when reducing other climate impacts?

Most cases reporting effects on multiple climate impacts reported synergies (i.e., positive effects on all climate impacts assessed). However, some did report trade-offs and most of these were associated with water availability. Negative effects on water availability were reported alongside positive effects on other climate impacts including erosion, biomass cover loss, and freshwater flooding. Almost all of these cases involved created forests, suggesting this trade-off may be a characteristic of this type of intervention.

Most of this evidence was reported from China and was restricted to large-scale afforestation and land rehabilitation policies such as the Grain for Green Program (also known as the Sloping Land Conversion Program or Returning Farmland to Forest Program). These government policies provided farmers with financial incentives to convert their degraded croplands into tree plantations, shrub, or grasslands. The aim was to restore vegetation cover to halt severe soil erosion from lands that were degraded by agriculture (Jia, Shao, Zhu, & Luo, 2017; Trac, Schmidt, Harrell, & Hinckley, 2013). Most studies used remote sensing data to correlate changes in vegetation cover with changes in soil loss and water yield over large areas where these policies were implemented. These analyses show that such interventions were effective at promoting vegetation biomass recovery leading to decreased soil erosion (but see Cao, 2008; Fu et al., 2017), but at a cost to soil moisture and water flows (see also Rodríguez et al., 2016; Shao, Wang, Xia, & Jia, 2018; Yu, Liu, & Liu, 2020). These trade-offs are attributed to the selection of exotic species unsuitable to these arid and semi-arid regions; evapotranspiration rates exceeded precipitation replenishment rates, especially where plantations were established on xeric grasslands that did not have suitable hydrology to support trees (Cao, 2008). These findings highlight potential dangers of such plantation schemes in water stressed areas.

We found little relevant empirical evidence on created ecosystem effects on climate impacts in other parts of the world. However, in many regions not necessarily experiencing climate hazards, afforestation has been shown to induce water yield losses (e.g., global analyses by Farley, Jobbágy, & Jackson, 2005; Filoso et al., 2017) and cause trade-offs between water supply and other ecosystem services (e.g., Bonnesoeur et al., 2019 on effects of afforestation in the Andes). Moreover, while evidence of water trade-offs from our map was largely limited to China, we found studies from other nations focusing only on water supply impacts that found similar effects from created ecosystems. For example, in Chile, the greater the area of watersheds converted from native deciduous forests to exotic conifer timber plantations, the lower the streamflow during the dry summer months (Lara et al., 2009; Little, Lara, McPhee, & Urrutia, 2009). All of this suggests that water-related trade-offs from created ecosystems could be a concern in other locations as well.

Overall, of the cases reporting on both water supply and another impact, there were more synergies reported than trade-offs. Moreover, most synergies resulted from cases in natural or semi-natural ecosystems across a range of geographic regions, involving several climate impacts, including soil erosion, biomass cover loss, and freshwater flooding, and soil or water quality. Therefore, a larger and less geographically biased evidence base exists reporting how nature-based interventions involving protection, restoration or sustainable management of natural or semi-natural ecosystems can promote water availability while addressing a range of other climate impacts. Indeed, Cao, Chen, and Yu (2009); Cao, Zhang, Chen, and Zhao (2016); Jiao, Zhang, Bai, Jia, and Wang (2012) demonstrate how natural vegetation restoration can minimize or eliminate trade-offs with water availability stemming from plantation forests. Similarly, a systematic global review by Smith et al. (2017) noted that water supply trade-offs were apparent mainly for plantations of fast-growing non-native species, such as pine and eucalyptus, in water-scarce regions, while native broadleaved forests in temperate regions tended to have benefits for water supply by improving infiltration. *This supports the notion that nature-based interventions can promote multi-functional landscapes, reducing the risk of trade-offs, when designed in tune with the ecological context.*

carbon, or both). For example, Russell-Smith et al. (2015) assessed the effect of fire management on GHG emissions abatement and carbon sequestration in Australian savannas, Krauss et al. (2017) reported the carbon sequestration benefits of mangrove restoration, and Pandey, Cockfield, and Maraseni (2016) reported how community forest management increased forest carbon stocks. Of the few empirical cases (13%) that reported effects on GHG mitigation outcomes, most (76%) were positive, none reported exclusively negative effects, and 22% reported mixed or unclear effects (Figure 4b).

3.5.2 | Social outcomes and economic costs/benefits

We found that 18% of studies reported social outcomes (i.e., any outcome that was explicitly linked to a specific group of people), and 29% reported economic costs or benefits (Figure 4a). A variety of social outcomes were reported, derived from qualitative or quantitative social assessments, or anecdotal reports. These included effects on food and water security, beyond the climate impact addressed by the intervention, livelihood diversification (e.g., provisioning of

non-timber forest products such as medicinal plants and building materials), recreation opportunities, capacity building and empowerment, social cohesion, or issues of equity and conflict. Quantitative measures included assessments of different aspects of social vulnerability including adaptive capacity or social sensitivity, employment, equity, or the number of site visits as an indicator of recreational health benefits. Most social outcomes were positive (63%), no cases reported exclusively negative effects, and 33% reported mixed or unclear effects (Figure 4b). Mixed results were often found when the intervention had positive social outcomes for some social groups, and negative social outcomes for others. For example, in Kenya, establishing conservancies on grazing lands diversified income sources for landowners from wildlife tourism, but non-conservancy members and the landless, particularly women, were not eligible to receive tourism payments and were negatively impacted by live-stock grazing restrictions imposed by the conservancies (Bedelian & Ogutu, 2017). While we did not capture the direction of economic outcomes, only 30% of cases reporting economic costs/benefits also reported economic appraisals. Of these, only three of were characterized as cost-benefit or cost-effectiveness analyses.

3.5.3 | Ecological outcomes

Overall, 34% of studies reported on the ecological outcomes of interventions (Figure 4a). Ecological outcomes included effects on plant or animal species populations, diversity of species or habitats, community composition, or habitat quality. These were assessed directly with quantitative measures of ecological parameters, or indirectly with environmental proxy measures (e.g., effect of fire frequencies and inferred impact on native species; Russell-Smith et al., 2015), or social methodologies (e.g., local community perceptions of changes in biodiversity; Sjögersten et al., 2013). Quantitative assessments measured changes in ecological parameters from species to ecosystem scales, including measures of diversity, richness, function, cover, structure, abundance, and indices of ecological resilience. Most cases (66%) reported ecological outcomes that were positive, <1% reported exclusively negative effects, and 24% reported mixed or unclear effects (Figure 4b). Mixed ecological outcomes occurred when intervention impacts differed across space (e.g., due to the displacement of drivers of degradation or habitat loss, exacerbating the pressure to surrounding locations; Mekuria et al., 2015), or when the intervention had a positive effect on some ecological attributes but not others (e.g., the intervention increased native species richness as well as increasing abundance of exotic species; Lennox et al., 2011).

3.5.4 | Evidence of multiple benefits

Of the 147 cases that reported an intervention as being effective in reducing one or more climate impact (i.e., only cases showing positive effects), 54% reported on one or more broader outcomes. Of these,

22% reported GHG mitigation outcomes, 70% ecological outcomes, and 47% social outcomes (Table S8). Of those that reported GHG mitigation, ecological, or social outcomes, most were positive (77%, 86%, and 76% respectively; Table S8). In other words, they reported positive effects on one or more climate impacts, and positive GHG mitigation and/or ecological and/or social outcomes. None of the cases reporting positive effects on climate impact(s) reported negative social or ecological outcomes, although 10% reported mixed or unclear ecological outcomes, and 24% reported mixed or unclear effects on the social dimension. From the set of studies reporting positive effects on climate impacts, a small number (28) reported on at least two broader outcomes (GHG, ecological, or social). Of these 21 (75%) showed benefits in terms of climate impacts and at least two broader outcomes.

4 | DISCUSSION

This is the first global, systematic map of studies reporting the effectiveness of nature-based interventions to address the adverse impacts of climate change on people. The mapping exercise revealed a high volume of potentially relevant studies, with an upsurge in research effort since 2012. The dispersion of this knowledge across multiple disciplines and journals, representing a range of timeframes and research objectives, presents a significant challenge to policy-makers and practitioners in need of clear evidence to inform target setting and action on the ground. Responding to calls for more innovative ways to visualize evidence bases (James et al., 2016), we present the results of our systematic map as an open-source, user-friendly online platform that will be updated over time (www.naturebasedsolutionsevidence.info). This provides a tool to support evidence-based decision-making, allowing users to efficiently explore 376 peer-reviewed studies, and to rapidly identify articles that report effects of nature-based interventions on climate impacts across a range of ecosystem types and geographies. Interactive heatmaps reveal the extent and distribution of existing evidence, highlight well-studied linkages between interventions and social and ecological outcomes, and pinpoint major knowledge gaps (for a snapshot of this heatmap, see Figure 2a).

Here, we discuss the main findings of the evidence map and its limitations, including important evidence gaps and related opportunities for future synthesis and research.

4.1 | Synopsis of key findings

Our map revealed a broad evidence base, covering a wide range of nature-based interventions and outcomes, but with significant evidence gaps. We found 376 studies which met our criteria of providing evidence on the effectiveness of nature-based interventions to reduce adverse climate impacts, although few were explicitly identified as NbS. The evidence base is biased toward the establishment of created ecosystems (34%) or restoration of natural and semi-natural

ecosystems (24%), while only 21% of studies involved protection of existing ecosystems either as a standalone intervention (11%) or in combination with other approaches (10%).

Most (66%) empirical outcome assessments reported that interventions in natural or semi-natural systems reduced climate impacts and hence supported people's adaptation to climate change. This finding is consistent with Doswald et al. (2014) who found that 63% of EbA-relevant studies reported positive results for addressing climate impacts. Conversely, in non-natural systems, interventions involving ecosystem creation (often using non-native species) were associated with trade-offs where benefits for soil erosion or biomass cover loss were accompanied by adverse effects on water availability. This evidence, however, was regionally specific (Box 3). Overall, studies reported more synergies than trade-offs between reducing climate impacts and broader social, ecological, and economic benefits, although this may be partly due to a bias in under-reporting of negative effects and trade-offs. Whereas only a few studies compared the effectiveness of nature-based interventions with alternative approaches, most showed the nature-based intervention to be as or more effective across a range of climate impacts.

We found important evidence gaps, including a relative paucity of peer-reviewed studies from low and lower middle-income nations in the Global South, and gaps on key intervention types, ecosystems, and climate impacts. Some of the gaps may reflect our exclusion of the gray literature and studies published in languages other than English, as well as the global inequality in the distribution of funding and capacity for scientific research. Although the gray literature has been found to provide comparatively less evidence on the effectiveness of ecosystem-based approaches (Doswald et al., 2014), including it in future syntheses on this topic may help reduce geographic gaps. The gray literature can also provide more depth on the planning and implementation of nature-based projects on the ground, such as in relation to stakeholder engagement (Doswald et al., 2014). Here, we consider priority areas for further research, to address what we understand to be genuine knowledge gaps and biases in research efforts identified through our mapping exercise.

4.2 | Evidence gaps, research biases, and priorities for future research

4.2.1 | Research across the Global South and SIDS

We found a marked imbalance in the distribution of studies across nations, with 79% comprising interventions in the Global North. Only 15% were from low and lower middle-income nations in the Global South, even though these nations are generally most vulnerable to the impacts of climate change (IPCC, 2018), have the highest levels of direct dependency on biodiversity and ecosystem services (Yang, Dietz, Liu, Luo, & Liu, 2013), and place greatest emphasis on NbS in their NDCs (Seddon, Daniels, et al., 2020). Notably, we only found 10 studies in SIDS. SIDS are particularly exposed to tropical storms

and sea-level rise (Zari, Kiddle, Blaschke, Gawler, & Loubser, 2019), and evidence from other regions suggests that protection and restoration of coastal ecosystems is vital for building resilience in the face of climate change. Although incorporating evidence from the gray literature in the Global South would reduce this disparity (e.g., Kapos et al., 2019; Osti, Woroniecki, Mant, & Munroe, 2015; Raza Rizvi, 2014; Reid et al., 2019) more peer-reviewed research is needed across the Global South on the effects of interventions over large scales and of their economic costs and benefits compared to alternatives. This would enhance our understanding of how NbS can reduce vulnerability of Global South communities to climate change and inform evidence-based policy and practice.

4.2.2 | Ecological outcomes of nature-based interventions

What is the evidence that NbS can address climate change adaptation while supporting biodiversity? Our map revealed 91 cases that reported ecological outcomes of nature-based interventions in addition to effectiveness in reducing a climate impact. Of these, most had positive outcomes, such as an increased number of species, functional diversity, or higher plant or animal productivity (e.g., Barsoum et al., 2016; Biel, Hacker, Ruggiero, Cohn, & Seabloom, 2017; Liqueste, Udias, Conte, Grizzetti, & Masi, 2016). Moreover, 47 of these positive cases also reported benefits to address one or more climate impacts. Indeed, there were no interventions which reduced a climate impact alongside exclusively negative ecological effects, and only four had mixed ecological effects. Our study therefore supports the contention that investments in NbS for climate change adaptation can also be beneficial for ecosystems.

Further synthesis of this subset of studies is now needed to test the strength of this evidence and determine the impact of nature-based interventions on robust metrics of biodiversity and ecosystem health. This will improve our understanding of the capacity of NbS to support biodiversity conservation goals. At the same time, such a synthesis on ecological outcomes is essential to understand the long-term effectiveness and sustainability of NbS. NbS must be designed in line with ecological principles to deliver solutions which are resilient to future changes in climate (Calliari, Staccione, & Mysiak, 2019). Reduced ecological resilience can reduce the potential of NbS to support adaptive capacity in the long run (Lavorel et al., 2015). For example, while using fast-growing, exotic vegetation can rapidly reduce soil erosion and increase fodder for livestock, this can come at the cost of compromising ecological functions sustaining water flows, in turn reducing ecosystem stability and resilience (Amghar et al., 2012; García-Palacios et al., 2010; Hanke, Wesuls, Münchberger, & Schmiedel, 2015). A synthesis of the ecological outcomes of NbS will therefore support the development of guidelines for climate-resilient NbS that support and enhance biodiversity, while harmonizing policy objectives across the United Nations Convention on Biological Diversity and the UNFCCC. However, for the improved understanding of the

relationship between NbS and biodiversity to support NbS on the ground, it must be integrated with knowledge of other elements of NbS (see Section 4.2.5 on the need for integrated assessments including social outcomes).

4.2.3 | Effectiveness of nature-based interventions in non-forest ecosystems

The most studied ecosystems were forests (created or semi-natural/natural) in temperate regions, with less on tropical/subtropical and boreal forests. There were comparatively fewer studies on the effectiveness of nature-based interventions across grasslands, coastal ecosystems, and freshwater wetlands. The bias of the evidence base toward forests is reflected in existing NbS policies and pledges, which focus on the use of nature for contributing to GHG reduction objectives primarily through afforestation and reforestation (Lewis et al., 2019; Seddon, Daniels, et al., 2020). While nature-based interventions in forests have the potential to address a range of climate impacts, it is essential not to displace focus from other ecosystems which can be crucial for delivering adaptation and mitigation benefits in many parts of the world (Bossio et al., 2020; Griscom et al., 2017, 2020; Roe et al., 2019).

Grassland ecosystems

Covering approximately 40% of terrestrial land, grassland ecosystems harbor unique, diverse species assemblages (Bond, 2016; Habel et al., 2013), and provide a wide range of ecosystem services, including vital carbon storage benefits (Section 4.2.6) and grazing lands for livestock that supports millions of people, especially poor, marginalized groups (Coppock et al., 2017; Parr, Lehmann, Bond, Hoffmann, & Andersen, 2014). Yet, only 9% of studies in this map reported interventions in natural or semi-natural grassland ecosystems. More research is needed on how interventions may sustain or enhance the delivery of grassland ecosystem services in the face of climate change.

Coastal ecosystems

Evidence from natural coastal ecosystems shows them to be highly effective at reducing wave heights and energy and hence minimizing exposure to hydrometeorological hazards (Ferrario et al., 2014). Each year, these ecosystems protect over 13 million people from coastal flooding (Menéndez, Losada, Torres-Ortega, Narayan, & Beck, 2020; Van Coppenolle & Temmerman, 2020), avoid millions of dollars' worth of damage to property and infrastructure, and can be up to five times cheaper than alternative, engineered approaches (Beck et al., 2018; Narayan et al., 2016). At the same time, more than 775 million people in coastal nations are highly dependent on them for sources of nutrition, jobs, and income (Selig et al., 2019). Nonetheless, such evidence tends to involve spatially explicit hazard-risk modeling at global scales. We found few studies investigating the effect of site-specific interventions in coastal ecosystems or their cost-effectiveness, although there were a few additional studies involving interventions in other ecosystems to promote the

resilience and functioning of coastal ecosystems (e.g., slope revegetation to reduce downstream sedimentation of coral reefs; Shelton III & Richmond, 2016). The lack of context-specific evidence makes it more challenging to design and implement NbS to reduce coastal vulnerability to climate change, in part because the extent of effectiveness is strongly influenced by contextual elements, such as geomorphology (Bouma et al., 2014).

Freshwater wetland ecosystems

Our map indicated that effectiveness of interventions in natural wetlands, peatlands, ponds, and lakes is under-reported in the literature and concentrated in North America and Europe, despite the existence of vast wetlands with high human population densities throughout the Global South. There is a growing understanding of the value of these ecosystems for providing regulating services, such as flood risk mitigation (at least at lower intensities; Dadson et al., 2017). However, the lack of research into the effectiveness of site-specific interventions, especially compared to engineered alternatives, will hinder investment and implementation. Meanwhile, while created wetlands have been demonstrated as cost-effective for improving water quality and reducing flooding from heavy rain in urban areas (Haase, 2017; Stefanakis, 2019) there is very little evidence from rural and peri-urban areas, especially in lower-income nations.

4.2.4 | Under-reported climate impacts: Slope hazards and wildfire risk

Studies in montane ecosystems were well represented in our map, but few of these (6, 8%) reported effects on slope hazards, suggesting an important evidence gap (see also de Jesús Arce-Mojica, Nehren, Sudmeier-Rieux, Miranda, & Anhuf, 2019). However, there is considerable evidence showing the capacity of existing vegetation to reduce slope hazards, outside the context of nature-based interventions (Moos et al., 2018). For example, landslides become more frequent and extensive following deforestation of areas with steep slopes, due to loss of tree roots essential for soil stability (Lehmann, von Ruetten, & Or, 2019). As the damage caused by slope hazards is expected to increase under climate change in certain regions (Gariano & Guzzetti, 2016), we need to better understand how NbS can address these hazards, in particular, how cost-effective they are in comparison to engineered approaches, which can be expensive to implement and maintain (Moos et al., 2018).

Similarly, we found few studies reporting effects of nature-based interventions on wildfire risk, especially empirical assessments. Wildfire is intrinsic to the composition, structure and dynamics of many ecosystems (Russell-Smith et al., 2015). However, changing climate conditions, logging and the spread of non-native species are increasing the frequency and severity of fires, threatening landscapes and human settlements (Barlow, Berenguer, Carmenta, & França, 2020; Dowdy et al., 2019; Fuentes, Duguay, & Nadal-Sala, 2018; Lindenmayer, Kooyman, Taylor, Ward, & Watson, 2020; Paritsis et al., 2018), and releasing large amounts

of carbon into the atmosphere (Dowdy et al., 2019; Van Der Werf et al., 2017). Evidence is emerging that forests managed for resilience, such as by reducing fuel load through thinning, or controlled seasonal fire management, can significantly reduce the severity, incidence, or spatial extent of wildfires (Bilbao, Leal, & Méndez, 2010; Bowman et al., 2020; Fuentes et al., 2018; Paritsis et al., 2018; Seijo et al., 2015; Volkova, Bi, Hilton, & Weston, 2017), and limit carbon emissions (Bowman et al., 2020; Defossé, Loguercio, Oddi, Molina, & Kraus, 2011; Russell-Smith et al., 2015). Some studies report that carefully prescribed seasonal burning can preserve or even increase biodiversity (Fuentes et al., 2018; Russell-Smith et al., 2015; Volkova et al., 2017). To reduce fire hazards and promote the resilience of carbon stores, more evidence is needed on how forest and grassland ecosystems can be managed to mitigate fire risk while supporting biodiversity.

4.2.5 | Integrated assessment of the multiple outcomes of NbS

Few studies reported the effects of nature-based interventions on more than one or two different climate impacts, or reported broader social, economic, or ecological outcomes alongside effects on climate impacts. This highlights the need for more integrated assessments of intervention outcomes to uncover potential synergies and trade-offs. For example, integrated assessments have shown how NbS can deliver jobs from mangrove planting for coastal protection (Ahammad, Nandy, & Husnain, 2013) or income from wildlife tourism (Bedelian & Ogutu, 2017) and how those benefits are fairly distributed (Osano et al., 2013; Peh et al., 2014). NbS can also reduce vulnerability by supporting local adaptive strategies and empowering marginalized groups to respond to climate impacts through common-pool resource management institutions (Woroniecki, 2019).

Evidence on these outcomes is also needed to better elucidate the social-ecological interactions which underpin effectiveness for climate change adaptation. To ensure that NbS can promote systemic resilience under rapid global environmental change, they need to be designed, implemented, and managed in tune with the social-ecological context (Seddon, Chausson, et al., 2020). For example, Lavorel et al. (2020) show how the benefits of EbA in the French Alps are co-produced by harnessing ecological and social capital (e.g., traditional knowledge or social networks) using stakeholder engagement and empowerment to promote resilient ecosystems with high connectivity and functional diversity. Properly implemented, NbS can strengthen social infrastructure and foster a sense of place, supporting virtuous cycles of community engagement to sustain interventions over time (Tidball, Metcalf, Bain, & Elmqvist, 2018). Poorly implemented NbS, meanwhile, can have the opposite effect; for example, local communities in Portugal uprooted eucalyptus plantations because they were concerned about their negative impacts on groundwater resources and fire risk (Rodríguez, 2017). Deeper understanding of the interlinked effects

of NbS on social, economic, and ecological dimensions is needed to avoid such negative outcomes and enable effective, sustainable NbS (Woroniecki, 2019).

Various factors may explain the scarcity of integrated assessments of NbS outcomes. For example, financial constraints or funding priorities can confine the scope of research to a narrow set of outcomes, or research teams may lack the capacity and resources to pursue interdisciplinary approaches (Klenk & Meehan, 2015). Such approaches are inherently challenging as they involve bridging disciplinary divides and divergences in values, interests, and problem framings (Knickel, Knickel, Galli, Maye, & Wiskerke, 2019; Nightingale et al., 2020).

4.2.6 | Trade-offs and synergies with GHG mitigation

Due to the paucity of integrated assessments, few studies reported synergies or trade-offs between climate impact and GHG mitigation outcomes. This was especially the case for non-forest ecosystems such as saltmarsh, created wetlands, and tropical and subtropical grasslands. Yet, wetlands and grasslands represent globally important carbon stores (Burden, Garbutt, & Evans, 2019; Ward et al., 2016). Grasslands store over 10% of terrestrial biomass carbon (Follett & Reed, 2010), and could sequester one billion tons of carbon annually if sustainably managed (Smith et al., 2020). Moreover, they may be more reliable as carbon sinks than forests in regions facing increased drought and wildfire risk (Dass, Houlton, Wang, & Warlind, 2018) and forest dieback because of increasing climate stress (Allen et al., 2010). It is likely, therefore, that unrecognized synergies exist between mitigation and adaptation from interventions in these ecosystems given the evidence captured in this study on their role in reducing climate impacts. For example, Peh et al. (2014) estimated that converting 479 ha of intensively farmed arable land to wetland in Cambridgeshire, UK, could reduce GHG emissions by 65%, while also increasing flood water storage capacity, and freeing up land for livestock grazing, wildlife, and recreation.

Evidence from forests highlights the necessity to simultaneously evaluate adaptation and mitigation outcomes to maximize synergies and minimize trade-offs, as different actions in similar ecosystems can have contrasting effects on these outcomes. For example, mixed-species forest management approaches can promote the resilience of timber production and aboveground carbon stocks under climate change while also benefiting biodiversity (de-Dios-García, Pardos, & Calama, 2015; Jactel et al., 2012; Pukkala, 2018). Species-poor tree plantations, in contrast, have impoverished biodiversity and hold less resilient carbon stocks than natural/semi-natural forests (Osuri et al., 2020). However, GHG effects were reported for only a few of the interventions involving created forests in our map. This limits the opportunity to identify potential trade-offs between their contributions to adaptation and mitigation, and how that may change over time.

4.2.7 | Comparisons with alternative interventions and holistic economic appraisals

Our map shows a paucity of studies reporting effectiveness comparisons between nature-based interventions and engineered/managed alternatives. Of those that did compare effectiveness, results varied with the climate impact addressed, outcome measure, comparator intervention, and biogeographic context (De Keersmaecker et al., 2016; Liqueste et al., 2016; Salinas & Mendieta, 2013; Shelton III & Richmond, 2016). This limits generalizability and emphasizes the place-based character of nature-based interventions. Additionally, while progress is being made to assess the economic benefits of NbS, cost-benefit comparisons with engineered approaches remain inherently more challenging (Seddon, Chausson, et al., 2020). Indeed, we only found two studies that attempted to do this. NbS costs and benefits are often spread across different sectors, stakeholders, and scales, while economic appraisals are generally restricted to a defined area, timeframe, or stakeholder group (Reddy et al., 2015). Additionally, methodologies to determine cost-effectiveness and the selection of costs or benefits to consider vary substantially between studies, in part because these analyses must be tailored to the social-ecological context to be meaningful for local governance. This makes it challenging to capture and synthesize the full economic benefits of NbS in comparison to alternatives, for which cost-effectiveness is easier to capture (Czembrowski, Kronenberg, & Czepkiewicz, 2016; Jacob, Rowan, Brown, & Ellis, 2014; Mukherjee et al., 2014).

Yet, current decision-making processes for adaptation-relevant policies rely heavily on economic appraisal frameworks tailored to conventional, engineered interventions. It is important to develop and harness frameworks combining economic appraisals with more holistic approaches capturing the broader array of material and non-material benefits NbS can bring. For example, Reddy et al. (2015) show that although engineered defenses had a greater net present value for businesses than natural salt marsh defenses, salt marshes generated greater public benefits, supported crucial habitat for wildlife and fisheries, and hence had a higher net value overall. In other words, assessing NbS exclusively through an economic lens can hide the non-economic benefits, resulting in undervaluing NbS (Wild, Henneberry, & Gill, 2017). More research is needed on integrated approaches to valuation, such as multi-criteria analyses, and mechanisms to harness different ways of valuing nature. This will help to promote equitable and inclusive policy and governance of NbS (Pascual et al., 2017).

4.2.8 | Appraising the effectiveness of NbS under future scenarios

Comprising almost half of the articles captured, scenario modeling studies helped fill key evidence gaps found in empirical studies on the effectiveness of nature-based interventions. Notably, scenario modeling studies contributed the bulk of evidence on restoration

and management interventions, and for several ecosystems and climate impacts, including freshwater flooding, loss of timber production, wildfire risk, and storm surge. Most reports of economic costs and benefits also came from scenario modeling studies.

An in-depth synthesis of these studies is now needed to better appraise the effectiveness of nature-based interventions under future scenarios of environmental change. We found that 40% of scenario modeling studies incorporated climate change scenarios. Closer analysis to assess how NbS perform under different scenarios would help with the design and implementation of resilient NbS that deliver benefits to people in a warming world. For example, many studies relevant to the forestry sector investigated the effectiveness of different forest management interventions for increasing the resilience of timber production under changing socio-environmental conditions. Scenario modeling studies can also demonstrate how the effectiveness of alternative management strategies depends on future conditions, such as the extent of warming. For example, Wada et al. (2017) show that in Hawaii, the most cost-effective sites and methods for forest restoration to address wildfire risk and reduced water availability vary between current and future climate change scenarios. Meanwhile, Krauss et al. (2017) show that the extent to which mangroves adapt to sea-level rise through soil accretion and hence protect coastal communities, depends on the rate of sea-level rise. In addition, scenario modeling can assist with the spatial prioritization of NbS; for example, Langridge et al. (2014) identify where and to what extent natural infrastructure can protect engineered coastal defenses, coastal populations, and farmland from coastal flooding and erosion. Synthesizing evidence on future scenarios of nature-based interventions would provide a more comprehensive picture of the effectiveness of NbS for climate change adaptation across landscapes. On this basis, practitioners could make more informed choices between different landscape management options and determine their cost-effectiveness.

5 | CONCLUSIONS

Nature-based solutions currently have considerable political traction, with the greatest emphasis on the role of ecosystems as sinks of GHGs. However, there is a large and growing body of evidence that protected, restored, or well-managed natural or semi-natural ecosystems are essential to help people and economic sectors adjust to and manage the negative impacts of climate change. On this basis, many organizations are advocating for national and subnational policies to raise ambition for the use of NbS as a means of climate change mitigation and adaptation. In 2020, this is highly relevant for the revision of NDCs to the Paris Agreement (Seddon, Daniels, et al., 2020). However, this ambition is unlikely to be met unless the process is informed by robust evidence from science, practice, and local and indigenous knowledges.

To help increase the impact of science on the design and implementation of NbS for climate change adaptation, our systematic map helps guide policymakers to the information they need.

However, the map also reveals that the evidence base has substantial gaps. First, there is a marked imbalance in the geographic distribution of evidence, with most studies concentrated in the Global North. Yet, it is communities in the Global South which overall are more vulnerable to climate impacts and could potentially gain most from the multiple benefits of NbS. Second, there is a lack of robust, site-specific investigations of the effectiveness of interventions compared to alternatives and of more holistic appraisals that take broader social and ecological outcomes into account. To build the resilience of communities globally to our rapidly warming world, it is imperative that we protect and harness the benefits that nature can provide, and for that, a strengthened evidence base is key.

ACKNOWLEDGEMENTS

This study was supported by a Natural Environmental Research Council Knowledge Exchange Fellowship to N. Seddon, with additional funding from the University of Oxford (John Fell Fund and Oxford Martin School). For their invaluable advice as steering committee members in developing the scope and methods used for this systematic map, as well as for comments that helped to improve this manuscript, we extend our deepest thanks to Pam Berry, Francesca Booker, Hannah Reid, and Sylvia Wicander. We also thank Xiaoting Hou-Jones for commenting on a draft of this manuscript and Gillian Petrokofsky for reviewing the protocol for the selection criteria and coding framework.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the Supporting Information and on the Nature-based Solutions Evidence platform, www.naturebasedsolutionsevidence.info.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Chausson A, Turner B, Seddon D, et al. Mapping the effectiveness of Nature-based Solutions for climate change adaptation. *Glob Change Biol*. 2020;26:6134–6155. <https://doi.org/10.1111/gcb.15310>