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Author for correspondence:
Nathalie Seddon
e-mail: nathalie.seddon@zoo.ox.ac.uk

Understanding the value and limits of nature-based solutions to climate change and other global challenges

Nathalie Seddon[1], Alexandre Chausson[1], Pam Berry[2], Cécile A. J. Girardin[2], Alison Smith[2] and Beth Turner[1]

[1]Nature-based Solutions Initiative, Department of Zoology, and [2]Environmental Change Institute, School of Geography and Environment, University of Oxford, Oxford, UK

NS, 0000-0002-1880-6104; AS, 0000-0003-2649-2202

There is growing awareness that 'nature-based solutions' (NbS) can help to protect us from climate change impacts while slowing further warming, supporting biodiversity and securing ecosystem services. However, the potential of NbS to provide the intended benefits has not been rigorously assessed. There are concerns over their reliability and cost-effectiveness compared to engineered alternatives, and their resilience to climate change. Trade-offs can arise if climate mitigation policy encourages NbS with low biodiversity value, such as afforestation with non-native monocultures. This can result in maladaptation, especially in a rapidly changing world where biodiversity-based resilience and multi-functional landscapes are key. Here, we highlight the rise of NbS in climate policy—focusing on their potential for climate change adaptation as well as mitigation—and discuss barriers to their evidence-based implementation. We outline the major financial and governance challenges to implementing NbS at scale, highlighting avenues for further research. As climate policy turns increasingly towards greenhouse gas removal approaches such as afforestation, we stress the urgent need for natural and social scientists to engage with policy makers. They must ensure that NbS can achieve their potential to tackle both the climate and biodiversity crisis while also contributing to sustainable development. This will require systemic change in the way we conduct research and run our institutions.

This article is part of the theme issue 'Climate change and ecosystems: threats, opportunities and solutions'.

1. The rise of nature-based solutions

How do we meet three central challenges of the Anthropocene: mitigating and adapting to climate change, protecting biodiversity and ensuring human well-being? A major part of the answer lies in addressing these interdependent challenges together; to do otherwise invites negative consequences and unintended feedbacks. Indeed, the ethos of the United Nations (UN) Sustainable Development Agenda is one of connectivity, inclusivity and partnership; it acknowledges interdependencies of the 17 social, environmental and economic goals and encourages actions that promote synergies among them [1]. Yet, despite the importance of taking account of synergies and trade-offs between these goals [2–4], there is little evidence that this is happening in practice. As a direct result, many goals are unlikely to be met by 2030. In particular, the failure to stabilize and adapt to climate change (SDG 13) [5] or protect biodiversity (SDGs 14 and 15) [6,7] has been exacerbated by the fact that these issues are being treated separately when in fact they are deeply interwoven and share many of the same drivers.

It is against this backdrop that nature-based solutions (NbS)—solutions to societal challenges that involve working with nature (box 1)—are emerging as an integrated approach that can reduce trade-offs and promote synergies

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Box 1. Defining nature-based solutions.

NbS involve working with and enhancing nature to help address societal challenges [8,9]. They encompass a wide range of actions, such as the protection and management of natural and semi-natural ecosystems, the incorporation of green and blue infrastructure in urban areas, and the application of ecosystem-based principles to agricultural systems. The concept is grounded in the knowledge that healthy natural and managed ecosystems produce a diverse range of services on which human wellbeing depends, from storing carbon, controlling floods and stabilizing shorelines and slopes to providing clean air and water, food, fuel, medicines and genetic resources [10]. NbS is an 'umbrella concept' for other established 'nature-based' approaches such as ecosystem-based adaptation (EbA) and ecosystem-based mitigation, eco-disaster risk reduction and green infrastructure [11]. More recently, the term 'natural climate solutions (NCS)' entered the lexicon [12]. NCS also falls under the umbrella of NbS, but refers explicitly to conservation and management actions that reduce greenhouse gas (GHG) emissions from ecosystems and harness their potential to store carbon [12–14].

NbS vary in three important ways, which influence the range of benefits that they provide for people.

(i) They *cover a spectrum of interventions* from protecting or restoring diverse natural ecosystems to creating new managed or hybrid 'grey-green' approaches [15]. While healthy natural forests, grasslands and wetlands may store more carbon than their managed equivalents (e.g. owing to greater soil depth, age and structural diversity [16]), managed and hybrid systems such as city parks or green roofs contribute to urban cooling, storm-water management, and bring mental and physical health benefits [17].

(ii) NbS *vary in the extent to which they support biodiversity,* which in turn affects their resilience, i.e. their capacity to resist and recover from perturbation and maintain the flow of ecosystem services. NbS that protect and restore natural ecosystems and/or make use of diverse native species can play a key role in securing climate change mitigation and adaptation services, while also contributing to cultural ecosystem services such as inspiration and learning from nature. By contrast, NbS that do not harness ecological principles and support biodiversity (such as those involving non-native monocultures) are more vulnerable to environmental change in the long term and may also produce trade-offs among ecosystem services (e.g. carbon storage, erosion control and water supply, as demonstrated in the Loess Plateau, table 1).

(iii) NbS *differ in how much they are designed and implemented by local communities* [18]. EbA places particular emphasis on this; it is a participatory community-based climate adaptation strategy which may include sustainable management, conservation and restoration of ecosystems, as part of an overall adaptation strategy that takes into account the multiple social, economic and cultural benefits for local communities [19].

By specifically aiming to address broad societal goals such as human wellbeing, including poverty alleviation and socio-economic development, NbS differ from traditional biodiversity conservation and management approaches. However, to be resilient (and hence sustainable), NbS must be implemented in such a way as to support biodiversity and people [20–22].

among the SDGs [20,23,24]. In contrast with many engineered solutions, NbS have the potential to tackle both climate mitigation and adaptation challenges at relatively low-cost while delivering multiple additional benefits for people and nature. For example, restoring natural forests in upper catchments can help to protect communities downstream from flooding, at the same time as increasing carbon sequestration and protecting biodiversity. Planting trees and increasing green space in cities can help with urban cooling and flood abatement, while storing carbon, mitigating against air pollution, and providing recreation and health benefits (see table 1 for examples). Consequently, NbS were endorsed in the IPBES Global Assessment [6], the Climate Change and Land Report of the Intergovernmental Panel on Climate Change (IPCC) [45] and the Global Adaptation Commission Report [46], and were highlighted as one of nine key action tracks at the 2019 UN Climate Action Summit (https://www.un.org/en/climatechange/climate-action-areas.shtml). Meanwhile, the World Economic Forum's (WEF) Global Risks Report 2019 specifically recognized the economic risks posed by biodiversity loss and ecosystem collapse [47] and the need for nature-positive business solutions. NbS are increasingly being viewed not only as a way to reconcile economic development with the stewardship of ecosystems, but also as a means to diversify and transform business and enable sustainable development [48].

Here, we take a critical look at the potential for NbS to deliver both climate change mitigation and adaptation while also supporting other ecosystem services. As the role of NbS for climate change mitigation rises up the policy agenda, we stress their vital role for climate change adaptation, and the importance of using evidence-based design to maximize synergies and minimize trade-offs. We focus on three key barriers: measuring the effectiveness of NbS; mobilizing investment; and overcoming governance challenges. Finally, we identify the need for systemic institutional change to overcome these barriers, including a more holistic design and evaluation approach that fully incorporates the multiple benefits of NbS.

2. Nature-based solutions for climate change mitigation

Over the past 10 years, there has been growing interest in the potential of NbS to help meet global goals for greenhouse gas (GHG) emissions reductions to mitigate climate change, reflecting the importance of natural ecosystems as sources and sinks for GHGs. The IPCC Climate Change and Land Report states that all scenarios that limit climate change to 1.5°C rely heavily on landuse change mitigation methods, as well as decarbonizing the economy [45]. Agriculture, forestry and other landuse activities accounted for around 23% of total net anthropogenic emissions of GHGs during 2007–2016 (12.0 ± 3.0 Gt CO_{2e} yr^{-1}, includes CO_2, CH_4 and N_2O, [45]). Of this, net emissions of 5.2 ± 2.6 Gt CO_{2e} yr^{-1} were mostly because of deforestation, partly offset by afforestation/reforestation, and emissions and removals by other landuse activities [45].

Table 1. Examples of nature-based solutions relevant for climate change adaptation organized with respect to dimension of socioeconomic vulnerability and type of climate change impact mitigated.

Dimension 1: reducing exposure
Protection from erosion
—*China*: a combination of afforestation, reforestation and conservation of existing natural forests over 25 years in the Poyang Lake basin halved heavy soil erosion while increasing net carbon sequestration fivefold and net income for local farmers sixfold [25]. Meanwhile, restoration of natural herbaceous and shrub-land vegetation on the Loess Plateau reduced soil erosion to a comparably or significantly greater extent than tree plantations, across a range of anti-soil erosion indices. Compared to afforested slopes, these naturally re-vegetated slopes also had 1.3–2 times higher soil water content [26].
Protection from inland flooding
—*Canada*: reforestation in the headwaters of a river basin significantly reduced peak stream flows compared to an adjacent deforested basin, offering greater protection against flooding during spring snow melt [27].
—*USA*: natural regeneration of mixed species hardwood watersheds following forest clearcutting reduced flood risk in lowland areas, reducing stream flows during periods of high precipitation by greater than 104 l ha^{-1} d^{-1} [28].
—*Europe*: restoration of all but one of six rivers reduced flood damage to crops and forests, and was associated with increased agricultural production, carbon sequestration and recreation, with a net societal economic benefit over unrestored rivers of €1400 ± 600 ha^{-1} yr^{-1} [29].
Protection from coastal hazards and sea-level rise
—*Global*: natural coastal habitats significantly reduce wave heights, with coral reefs and saltmarshes being most effective, causing a reduction of 70%, followed by seagrass and kelp beds (36%), and mangroves (31%). Across 52 sites harnessing these habitats in coastal defence projects, NbS were two to five times more cost-effective at lower wave heights and at increased water depths compared to engineered structures [30].
—*Gulf of Mexico*: construction of 'living shorelines' by aiding natural recruitment of oyster reefs can reduce vegetation retreat by 40% compared to unprotected sites, stabilizing the shoreline from the effects of waves and erosion, and increasing abundance and diversity of economically important species [31].
Moderating urban heat waves and heat island effects
—*USA*: daytime air temperature is substantially reduced with greater canopy cover (greater than or equal to 40%) at the scale of a typical city block (60–90 m), especially on the hottest days [32].
—*Global*: green spaces are on average 0.94°C cooler in the day than urban spaces, with stronger effects the larger the green space, according to a meta-analysis of 47 studies comparing the cooling effects of green spaces in cities (parks, areas with trees) with those of purely urban areas [33].
Managing storm-water and flooding in urban areas
—*Italy*: establishment of wetlands and green recreational space has been effective in reducing flood risks, with a 10% higher reduction in downstream flooding and 7.5% higher reduction in peak flow compared to potential grey infrastructure alternatives. NbS also outperform grey infrastructure in terms of water purification and provide greater social and ecological benefits, such as recreation and habitat for biodiversity [34].
Sustaining natural resources in drier and more variable climates
—*Panama*: agroforestry systems yield up to 21% higher economic return than farm mosaic approaches (i.e. where trees and crops are on separate parcels), including under a climate change scenario of more frequent droughts, in models that account for market and climate uncertainty [35].
—*Europe*: agroforestry has reduced erosion and increased soil fertility, with greatest effects in hotter, drier regions such as the Mediterranean basin (which is suffering from soil damage through increasing aridity under climate change) [36].
Dimension 2: reducing sensitivity
Buffering communities from climate shocks by enhancing and diversifying ecosystem services
—*Kenya*: allowing rangelands in the Kenyan drylands to regenerate, through restoration within rangeland enclosures, diversifies income sources, which can cushion against climatic shocks [37,38]. Meanwhile, agroforestry in semi-arid regions provides alternative income sources including fuelwood, fruit, and timber as well as reducing exposure to heat, drought, floods and erosion [39].
—*Zimbabwe*: protection of forested/wooded areas ensures honey production during droughts, thereby providing a degree of food security when other crops fail [40].
Dimension 3: supporting adaptive capacity
Governance reform, empowerment and improving access to resources
—*Sri Lanka*: EbA empowered marginalized groups to respond to climate change impacts by supporting common-pool resource management institutions, and by supporting local adaptive strategies such as home gardening [41].
—*Ethiopia*: community-based natural resource management in pastoral communities has improved institutional governance by transforming it towards a more flexible, inclusive, bottom-up approach, whereby community members become informed members of the decision-making process. This inclusivity in particular empowered women and the most vulnerable households. Altogether this has increased the capacity of these communities to deal with climate change [42].

—*Bangladesh*: EbA has increased the adaptive capacity of coastal communities to extreme weather events and climate change by improving their access to institutional services and climate change information, as well as their access to natural resources to support diverse livelihood options [43].

—*Togo*: EbA increased social inclusion and self-sufficiency of women and youth groups, leading to increased crop yields for these savannah communities as a whole, whose food security is threatened by climate change. Community members were involved from the beginning, allowing them to learn how to design and implement such projects to be able to independently adapt to future changes [44].

Decreasing sources and increasing sinks of GHGs through terrestrial ecosystem stewardship and improvements in agriculture are widely cited as having the potential to provide around 30% of the CO_2 mitigation needed through to 2030 to keep warming to less than 2°C [12,49,50]. However, a more recent analysis focusing on tropical nations and involving tighter model constraints (e.g. on where ecosystem regeneration can take place) indicates that this figure is an overestimate, and emphasizes the need to explore this potential on a national level [51]. Low GHG emissions and high forest cover in many tropical nations mean that natural climate solutions can mitigate over 50% of national emissions, mainly through avoided deforestation. Further, Griscom *et al*. [51] highlight a particular set of countries with strong governance and intermediate financing capacity, where the focus on nature-based climate solutions would have the most potential for contributing to emissions mitigation (e.g. India).

Some NbS may eventually reach a saturation point when the ecosystem is at equilibrium and sequestration is balanced by emissions. However, NbS have key advantages over other carbon dioxide removal (CDR) options. For example, direct air capture is expensive, energy-intensive and not yet deployable at scale; bioenergy with carbon capture and storage (BECCS) requires large areas of land for biofuel production; enhanced weathering entails quarrying, pulverizing and transporting rock on a large scale [52]; and all engineered approaches to CDR do not bring the suite of additional ecosystem services offered by well-implemented and managed NbS [53]. It is clear that engineered approaches to CDR must only be deployed once we better understand how to reduce trade-offs with biodiversity and ecosystem services [53].

The IPCC Climate Change and Land Report emphasizes that the mitigation potential from terrestrial ecosystems comes from restoration and management of forests and from curbing deforestation [45], especially in tropical and subtropical regions [54], where forests grow fast and there are no adverse effects from reduced albedo (unlike boreal regions) [12,55–57]. The report [45] states a mitigation potential range of 0.4–5.8 Gt CO_2 yr^{-1} from avoided deforestation and land degradation, as well as a carbon sequestration potential of 0.5–10.1 Gt CO_2 yr^{-1} in vegetation and soils from afforestation/reforestation.

However, reliance on forests for GHG mitigation raises several practical and ethical concerns. First, if policy is not grounded in sound ecosystem and biodiversity science, parties risk investing in monocultures or low diversity plantations. For example, 45% of the 350 Mha currently pledged for reforestation is set to become commercial plantations, usually involving single species (i.e. monocultures) [22]. This is problematic for a number of reasons. Fast-growing monocultures sequester carbon rapidly but they may not maximize carbon storage in the long term as they are vulnerable to disease, pests and climate extremes (e.g. [58–60]). Moreover, when plantations are harvested, typically every 10–20 years in the tropics, much of the stored carbon is returned to the atmosphere [22]. By contrast, forests that regenerate naturally have high carbon sequestration rates [61], and older and more diverse forests store more carbon and are more resilient to climate extremes and disease [62,63]. When rotation times and GHG emissions from fertilizer application are taken into account, Lewis *et al*. [22] calculate that natural forest regeneration could store 40 times more carbon than commercial plantations, and seven times more than agroforestry. They conclude that targets for climate stabilization cannot be achieved under current reforestation plans that comprise mainly plantations, even with the use of BECCS. Another issue is that plantations often involve fast-growing non-native species which may become invasive, introduce new pests and diseases [64], or exacerbate water scarcity in arid or semi-arid regions ([63], table 1). In environments where forests do not naturally thrive, such as savannahs prone to drought and fire risk, afforestation may reduce resilience to climate change and could compromise long-term carbon storage [65]. More diverse ecosystems also tend to deliver a wider range of other regulating and cultural ecosystem services [63], increasing the cost-effectiveness of NbS.

Second, policies that offer financial incentives to scale up NbS for the purpose of GHG mitigation risk compromising local land rights, leading to land grabs by governments and private investors. Whereas the Warsaw framework for Reduced Emissions from Deforestation and Degradation + specifies conservation of biodiversity and the respect of indigenous people and local communities rights in the Cancun Safeguards [66], the guidance relating to other NbS action is too vague on both accounts.

Third, encroachment of tree plantations onto other ecosystems can have devastating impacts on biodiversity. It is particularly concerning, for example, that 9 Mha of ancient grassland is wrongly classified as degraded land suitable for afforestation [65]. It is clear that NbS needs to be grounded in robust understanding of the geographical distribution of the biomes of the world, the value of their biodiversity and their ecological resilience.

Finally, and perhaps most critically, it is essential that enthusiasm for nature-based climate change mitigation does not curtail or distract from the urgent need to rapidly decarbonize our economy, including through radical systemic change [67].

Despite these caveats, well-designed NbS that incorporate diverse native species, avoid damaging biodiverse ecosystems and respect social safeguards offer good opportunities for mitigation with key benefits for local people [67]. These options should include restoration of natural forests and wetlands (e.g. peatlands and mangroves), especially in tropical biodiversity hotspots [54], as well as agroforestry, and increasing carbon in agricultural soils [45]. It is urgent that we strengthen policy frameworks to ensure that NbS can provide multiple benefits for both climate mitigation and adaptation, and other vital ecosystem services secured by biodiversity [6].

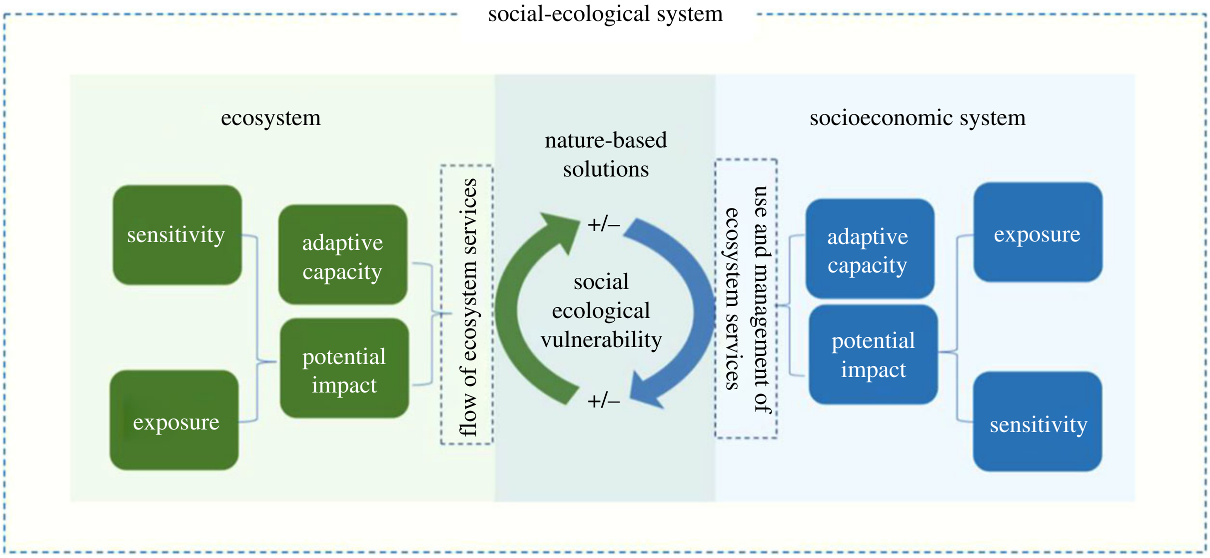

Figure 1. Integrating NbS to climate change impacts into the social–ecological vulnerability framework. *Ecosystem exposure* is the extent to which systems are subject to pressures (floods, droughts, landslides, fires, etc.). It is determined by the intensity, duration and frequency of events, geomorphology and the extent of use and management of natural resources by human societies. *Ecosystem sensitivity* is the degree to which ecosystem structure and function alters as a result of perturbations. Ecosystem exposure combined with ecosystem sensitivity creates a *potential impact*. This is buffered over time by the *adaptive capacity* of the ecosystem. Both ecosystem sensitivity and adaptive capacity are determined by the diversity, heterogeneity and connectedness of the ecosystem and the characteristics and condition of its component species and habitats. Overall *ecosystem vulnerability* is shaped by the combination of potential impact and adaptive capacity. This ultimately affects the delivery of ecosystem goods and services upon which people and economies depend. In this way, ecosystem vulnerability affects *socioeconomic vulnerability*, i.e. the degree to which the social system is adversely affected by change. *Socioeconomic sensitivity* is also influenced by a range of social, political and economic factors. For example, corruption or low levels of health, education or employment, and a lack of economic diversification can increase socio-economic sensitivity. Likewise, *socioeconomic adaptive capacity*, that can moderate the potential impact from social exposure and sensitivity, includes the ability to innovate (e.g. improving health, education and finding alternatives sources of income). NbS bring all these elements together and can, if implemented properly and equitably, decrease social–ecological vulnerability (see main text, and table 1). (Online version in colour.)

3. Nature-based solutions for climate change adaptation

The WEF Global Risks Report lists extreme weather events and natural disasters as the top two greatest risks to the global economy and human wellbeing, both in terms of severity of impact and likelihood of occurrence [47]. It also ranks the failure to mitigate and adapt to climate change—which exacerbates both extreme weather and natural disasters (https://www.worldweatherattribution.org/) —as one of the most impactful risks.

To date, the dominant approach to addressing the risks posed by extreme weather, natural disasters and climate change has involved engineered interventions such as sea walls, levees or irrigation infrastructure [68]. For example, in Bangladesh—a country subject to some of the worse extremes of climate change impacts and natural disasters—291 of 329 (88%) adaptation projects approved by the Bangladesh Climate Change Trust between 2009 and 2016 involved engineered (i.e. grey) interventions; only 38 involved nature-based (i.e. 'green') solutions [69]. This bias in investment towards engineered approaches is global (reasons why are discussed below). Yet there is growing evidence that NbS can in certain contexts provide a powerful complement (or alternative) to grey infrastructure [46].

A conceptual model for understanding nature's role in supporting human adaptation to climate change is the vulnerability framework for social–ecological systems, formalized by the IPCC ([70,71]; figure 1). The framework explicitly integrates the vulnerability of ecosystems with the vulnerability of socioeconomic systems. It recognizes that, in each system, vulnerability to climate change has three dimensions. The first is *exposure*; that is, the extent to which a region, ecosystem, resource or community is impacted by climate change (dimension 1). The second is *sensitivity* to these impacts; that is, the degree to which a system is affected by, or responsive to, those effects (dimension 2). The third is the *adaptive capacity* of the system; that is, the ability to adjust or innovate in response to changing conditions (dimension 3). NbS act at the interface of the socioeconomic system and the ecosystem to reduce the vulnerability of the social–ecological system as a whole. In other words, through the protection, restoration and careful management of ecosystems (§4), NbS can positively influence all three dimensions of socioeconomic vulnerability.

(a) Nature-based solutions for reducing socioeconomic exposure (dimension 1)

Most evidence for nature's role in supporting human adaptation pertains to the first dimension of the vulnerability framework, i.e. reducing exposure to the immediate impacts of climate change (see table 1 for examples). In particular, there is growing evidence that: (i) protecting, restoring or managing natural forests and wetlands in catchment areas (for example, in headwaters and along rivers) in many cases can secure and regulate water supplies [26], reduce flood risk [72] and/or reduce exposure to soil erosion and landslides [25]; (ii) restoring coastal ecosystems (i.e. mangroves, coral reefs, oyster beds and saltmarshes) protects communities from coastal flooding [73], reduces damages caused by storm surges [74] and limits coastal erosion

[31,75,76]; (iii) nature-based agricultural practices such as agroforestry (planting trees among crops or crops among trees) can maintain and in some cases enhance yields in drier, more variable climates [36,77]; and (iv) creating green roofs and walls, and/or planting trees and increasing green space in and around urban areas can moderate the impacts of heat waves [32,33,78] and regulate water flow ([79]; reviewed in [80]).

(b) Nature-based solutions for reducing socioeconomic sensitivity (dimension 2)

Properly implemented and supported by biodiversity, NbS can reduce the sensitivity of individuals, communities and societies to climate change. They can secure or enhance the delivery of ecosystem services that sustain livelihoods and wellbeing, and provide diverse sources of income to help communities adapt to climatic or other environmental shocks (table 1). For example, the rehabilitation of degraded semi-arid rangelands in Kenya cushions agro-pastoral communities against climatic shocks such as drought [37,38]. Communities using enclosures also reported having healthier, more productive livestock, more diverse sources of income (e.g. wood and grass cuttings, grass seeds, poultry products, fruits and honey) and an improved standard of living. Similarly, protecting forests in Zimbabwe ensures honey production during droughts, thereby providing a degree of food security when other crops fail [40]. Agroforestry can also provide alternative income sources (fuelwood, fruit, timber) as well as reducing exposure to heat, drought, floods and erosion [39].

(c) Nature-based solutions for supporting socioeconomic adaptive capacity (dimension 3)

NbS can contribute to adaptive capacity in two main ways. First, NbS that are designed to support genetic or species diversity will help to maintain a reservoir of wild species that can help us adapt to change, e.g. for breeding food and timber crop varieties that are resilient to climate change, pests and diseases, and as a source of knowledge for technical innovations based on biomimicry. Second, NbS can be implemented in a way that brings communities together to learn and experiment, for example, through the process of EbA focusing on sustaining the supply of ecosystem services, including those that reduce exposure and sensitivity of vulnerable groups. For example, the implementation of community-based natural resource management in pastoral communities in Ethiopia is reported to have empowered local communities to develop systems for managing natural resources in the face of change, improved institutional governance and thereby potentially increased capacity to deal with future climate change [42]. Similar benefits of ecosystem-based approaches to adaptation have been reported across the globe, including in Togo [44] and Sri Lanka [41] (table 1). However, NbS will only deliver these benefits if they are specifically designed to do so. Many other factors influence adaptive capacity, including financial and human resources, as well as education and governance [81] and these factors also influence opportunities to implement NbS. The extent to which NbS contribute to adaptive capacity, however, is poorly understood and further monitoring and evaluation is needed [41].

4. Effectiveness of nature-based solutions under climate change

The ability of ecosystems to act as a sink for CO_2 emissions (§2) and reduce socioeconomic vulnerability to climate change (§3) is directly and indirectly affected by the exposure, sensitivity and adaptive capacity of the ecosystems themselves (as illustrated in figure 1). Sensitivity and adaptive capacity vary among ecosystems and can be strongly influenced by management approaches [82,83].

Natural ecosystems are usually well adapted to their natural disturbance regimes such as episodes of drought, flooding, storms or wildfires. Some ecosystems, such as grasslands, are able to recover normal ecosystem function after major droughts and fires [84]; others are more sensitive, as evidenced by dieback in forests across the globe [85]. Problems are arising because the increasing frequency and intensity of these disturbances under climate change, combined with other stressors such as landuse change and pollution, is causing disturbances to recur before the system has a chance to recover. This can result in a dramatic decline in the adaptive capacity of the ecosystem, leading to a transition to a new community of species or an entirely new ecosystem. For example, the increasing frequency and severity of fires in Yellowstone National Park is depleting the seed bank for forest regeneration (e.g. [86]). There is some evidence that mangrove forests can keep pace with moderately high rates of sea-level rise (SLR) [87]. Saltmarshes, however, appear to be more vunerable and may be lost globally to SLR by the end of century without major intervention [88]. Exposure to such impacts can be reduced through active management such as tree thinning (shown to reduce fire frequency in *Eucalyptus* plantations) or by maintaining or creating connectivity between ecosystems (which enables species to track preferred ecological niches across the landscape [21]).

Ecosystem sensitivity can be minimized by reducing the pressures affecting ecosystem function (pollution, invasive species, habitat loss and fragmentation, over-exploitation) and enhancing genetic, species and functional richness, which buffer the impacts of extreme weather [58,89] and pests [90]. Greater diversity also safeguards the evolutionary potential of ecosystems, allowing for ecological adaptation (often in the form of phenological changes), and reduces the likelihood of trade-offs among different ecosystem services. Diversity can be enhanced through active management (for example, in multi-species crop or timber plantations), or through allowing degraded areas to regenerate naturally. Evidence is emerging that the latter can result in ecosystems with higher biodiversity that support a range of climate change adaptation services, with fewer trade-offs [21]. Areas of the Loess Plateau in China, for example, that were allowed to regenerate naturally into herbaceous cover and shrub land provide comparable levels of erosion control to those with afforestation, without compromising water supply or biodiversity ([26,91]; table 1).

With or without active management, many ecosystems have transitioned or are in the process of transitioning to alternative states under climate change [92]. Clearly, some of these new states cannot support human adaptation (e.g. algae-dominated reefs after mass coral mortality [93]). However, sometimes new communities will provide similar adaptation benefits to the pre-disturbance communities and/or provide additional novel adaptation services [94,95]. Further work is now urgently needed to model how the performance of NbS varies under climate change, drawing on knowledge of the eco-evolutionary mechanisms that underpin the ecosystem's capacity to resist and recover or adapt to major perturbations. Many physical models have been developed to forecast the effectiveness of hard infrastructure under different climate change scenarios; the equivalent ecological models now need to be developed for NbS.

5. Moving beyond pitching green solutions against grey

Over the last 10 years, UN institutions (UN Environment, UN Development Programme and Food and Agriculture Organization) as well as international conservation organizations (e.g. International Union for Conservation of Nature, World Wildlife Fund, BirdLife International and Conservation International) have been implementing community-led nature-based approaches to adaptation (i.e. EbA) and/or ecosystem-based disaster risk reduction projects across the globe (e.g. [96,97]). Emerging evidence from these initiatives suggests that NbS, in certain contexts, provide low-cost solutions to many climate change-related impacts and offer key advantages over engineered solutions [18]. In particular, NbS are reported to deliver a wider range of ecosystem services, especially to more vulnerable sectors of society, to protect us against multiple impacts and to be deliverable at lower cost [18]. Many of these observations are increasingly backed up by research (table 1), although there remains a lack of scientific synthesis and there are several knowledge gaps, in particular around how the cost-effectiveness of NbS compares to alternatives (www.naturebasedsolutionsevidence.info). Here, we argue that instead of framing NbS as an alternative to engineered approaches, we should focus on finding synergies among different solutions.

(a) Difficulties in measuring effectiveness

A major difficulty comes in identifying appropriate indicators and metrics for the social–ecological effectiveness of nature-based interventions [98]. Effectiveness in delivering a specific climatic adaptation benefit—for example, reducing the impact of floods arising through increased precipitation—is influenced by many interacting, context-specific factors that fluctuate over time. These may be socioeconomic (e.g. institutional capacity to respond to an impact, including human and financial capital to design and implement an intervention), biophysical (e.g. frequency and intensity of natural hazards) and ecological (e.g. variation in the delivery of ecosystem services as a result of seasonal and spatial changes in biomass [99]). Also, what counts as effective depends on the perspectives and needs of those involved. Even if reasonable metrics could be identified, the dynamic and complex nature of social–ecological systems, including unexpected shifts in political support or ecosystem condition, make measuring and comparing the outcomes of interventions across scales extremely challenging [100–102]. As such, simple standardized metrics of NbS effectiveness that work across different scales, or that comprehensively capture the social–ecological dimensions of effectiveness, are unlikely to be found. Instead, we must devise a suite of context-specific metrics (e.g. [105]). Such metrics will help increase our understanding of NbS effectiveness at the local level, and reduce the chance of unintended consequences or maladaptation.

(b) How cost-effective are nature-based solutions?

The benefits of NbS have been found to outweigh the costs of implementation and maintenance in a range of contexts, including disaster (mainly flood) risk reduction along coasts [82,104,105] and in river catchments [106]. There is also growing evidence that NbS can be more cost-effective than engineered alternatives, at least when it comes to less extreme hazard scenarios [107]. For example, across 52 coastal defence projects in the USA, NbS were estimated to be two to five times more cost-effective at lower wave heights and at increased water depths compared to engineered structures [30]. Natural flood management approaches in the UK (such as leaky dams and catchment woodland) significantly reduce hazards associated with small floods in small catchments, but do not appear to have a major effect on the most extreme events (though data from such events are lacking) [108,109].

The problem with current evidence for the cost-effectiveness of NbS is that appraisals in general do not use an appropriate framework, and as a result underestimate the economic benefits of working with nature, especially over the long term. There are four major issues that need addressing. First, NbS are often highlighted as multi-functional, with the potential to deliver a wide range of benefits to both local and global communities. Yet, benefits such as food and water security, carbon sequestration and space for recreation, whether locally or beyond the immediate area of implementation [110], are rarely accounted for. This may be because they are difficult to monetize, or there is high uncertainty about non-market value [111,112].

Second, appraisals rarely factor in trade-offs among different interventions and ecosystem services, or between stakeholder groups, which may experience the costs and benefits of NbS differently (often reflecting differences in the extent of dependency on natural resources [113]).

Third, changes in the provision of ecosystem services over time, for example, under climate change and other stressors, are rarely considered, and there are major questions about how to balance future benefits with current costs [80,114]. Engineered solutions can usually be implemented with relative certainty about the type and timescale of benefits, whereas NbS generally offer more flexible long-term solutions with benefits that might not be reaped when the costs are felt (or within standard political or electoral cycles).

Finally, perhaps the biggest challenge around estimating the cost-effectiveness of nature-based approaches relates to the variable levels of protection they offer (as discussed above, efficacy can vary with intensity and frequency of threats, the resilience of the ecosystem to withstand climate change impacts and the vulnerabilities of the socioeconomic system). As a result, the response of ecosystems is much harder to predict and cost than engineered/grey infrastructure [115], although recent modelling advances for predicting the efficacy of natural landforms in reducing hazards are helping to reduce this uncertainty [116].

In view of the complementary costs and benefits of NbS versus engineered approaches to dealing with the risks posed by climate change, there is growing consensus among ecologists, engineers and managers that a combination of green and grey may be the best solution in many contexts [105,117].

For example, the effectiveness of saltmarshes for flood risk reduction can be increased by constructing breakwaters or by artificially elevating salt-marsh foreshores [118]. Such a mix of interventions may also help address diverging stakeholder needs [113]. We urge researchers, policy makers and practitioners alike to focus on identifying integrated solutions that address a range of climatic impacts, provide additional ecosystem services and can be feasibly implemented and managed over the long term.

6. Financing and governing nature-based solutions

To translate our understanding of the socioeconomic effectiveness of NbS into action on the ground, we need to consider the political processes that shape which interventions are adopted and why, and understand how to effectively finance, implement and govern those interventions.

(a) Lack of investment in nature-based solutions

Despite broad recognition of the severe threats to the global economy posed by climate change [47], less than 5% of climate finance goes towards dealing with climate impacts, and less than 1% goes to coastal protection, infrastructure and disaster risk management including NbS [119]. This is despite growing evidence that natural habitats provide major economic benefits in the form of avoided losses from climate change-related disasters [30,74], as well as supporting ecosystems services worth an estimated $125 trillion annually [120]. For example, in their recent report, the Global Adaptation Commission highlights that the benefits of mangrove protection and restoration (i.e. fisheries, forestry, recreation and disaster risk reduction) are up to 10 times the costs [46]. However, NbS are ‘deploringly undercapitalized’ [121], and this lack of finance is widely recognized as one of the main barriers to the implementation and monitoring of NbS across the globe [122–125].

Funding for NbS comes from public and private, bilateral and multilateral, national and international funds (e.g. Global Environmental Facility, Green Climate Fund, Adaptation Fund). Climate finance for forestry projects is mainly provided through payments for ecosystem services programmes (PES, including carbon credits) under the UN Framework Convention on Climate Change compliance (Green Climate Fund) or the voluntary market (private funding). However, there remains much uncertainty about the extent to which PES can deliver social and ecological benefits [126].

The availability of funding is often the trigger needed for action [127], especially when there are significant implementation costs [128,129] such as where infrastructure and people need to be relocated for planned retreat to create intertidal habitats for flood protection [128]. However, raising the necessary finance for such interventions is complex. Funding instruments can be difficult to apply for and/or require co-financing [80]. Moreover, the short-term nature of public and private sector decision-making hinders the longer-term planning and maintenance required for the emergence and sustained provisioning of NbS benefits [80].

A large part of the problem is that many of the benefits associated with NbS cannot be capitalized by any one party or organization. They create externalities that impact on many different groups, resulting in a problem of ownership. Financing for NbS requires the provision of appropriate risk-sharing arrangements. In most cases, investments are financed by debt, leaving those undertaking the projects to bear a substantial proportion of the risks. For example, bank lending and microfinance—the most widely used sources of external funding in developing countries—often impose risks on those least suited to bear them. Another problem with conventional finance is that it draws a distinction between providers (i.e. financial institutions and markets) and users of finance (i.e. business and individual borrowers), and traditional providers tend to lack understanding of and, most importantly, participation in the project.

Instead, what is emerging as critical to the provision of large scale, long-term investments in ecosystems is the creation of multilateral consortia of close partnerships between companies, communities, local governments, national governments, non-governmental organizations, local financial institutions, and national and international financial institutions. The consortia’s willingness to provide various forms of capital reflects an understanding, influence and trust in the programme being undertaken [130,131]. Funding is then best provided in the form of equity to reflect mutual sharing and involving the measurement of less conventional forms of capital. In this way, measurement and accounting are intimately related to the successful provision of finance.

Further work is urgently needed to test the effects of employing equity, risk-sharing arrangements rather than debt finance for NbS, such as by conducting randomized control trials to examine the effects of moving from traditional to more innovative forms of financing. Finally, because the investments relate to human, social and natural capital, not just material and financial capital, there is also a need to greatly improve the measurement of these forms of capital. The failure to recognize expenditures on human, social and natural capital as assets, depreciated accordingly, partly explains the lack of investment in NbS projects.

Ultimately, the demands of growth-based economies, with entrenched policy and market conditions favouring industrialized and extractive land-uses, present a serious barrier to upscaling sustainable landscape interventions [132]. The focus on economic growth and short-term profits can reduce options considered by private or government sector actors which may not see NbS projects as bankable, particularly when faced with severe budget constraints [80].

(b) Challenges to governing nature-based solutions

NbS often involve multiple actions taking place over broad landscapes and seascapes, crossing jurisdictional boundaries. For example, effective management of storm-water drainage across watersheds using nature-based approaches requires joint decision-making across different local, regional or even national governments and among multiple ministries (agriculture, forestry, and environment, finance, development, transport). Therefore, to be successful, governance of NbS requires (and indeed enables) active cooperation and coordinated action between stakeholders whose priorities, interest, or values may not align, or may even conflict [125]. A lack of policy coherence can lead to inaction when one agency sees ‘adaptation’ as the responsibility of another [80]. It can also result in trade-offs, leading to conflicts. For example, landslide control through tree planting to protect infrastructure might come at the cost of agricultural productivity if ground water recharge is compromised, as shown in some NbS projects, including nature-based coastal management [125]. However, these trade-offs can be reduced if watersheds are restored with native trees where positive benefits of water supply materialize over time [133].

Unsupportive or even conflicting incentives and regulations can also hinder the uptake of NbS [91,123,134,135]. For example, a lack of government incentives is a key barrier to scaling up green infrastructure in Hong Kong [91]. Existing regulatory frameworks, such as landuse rights or environmental and building permit schemes, plans, or codes, or sectoral policies, can conflict with environmental management needs and hinder NbS uptake [123,125]. Examples include rural development payment schemes [124], post-disaster recovery policies [105], policies promoting intensive agriculture such as oil palm and subsidies for sheep farming [134].

Other institutional norms also limit the uptake of NbS. Path dependency, whereby decision-makers implement solutions familiar to them, can be a formidable barrier to NbS [135]. Decisions may be driven by power-relations, whereby choice of infrastructure is influenced by interests connected to property and appropriation regimes which do not support NbS [136]. Grey infrastructural approaches are deeply engrained in certain cultural contexts, and shape institutional practices. Such biases are compounded by cognitive factors such as a lack of awareness of ecosystem services provided by NbS, lack of perceived responsibility for action or the discounting of climate risks [123,137,138] and similar issues that constrain innovation [95]. Overcoming these challenges requires strong institutions, and well-established planning structures, processes and instruments to ensure benefits across landscapes and seascapes [127,134].

7. Conclusion

NbS are gaining traction in international policy and business discourse. They offer huge potential to address both causes and consequences of climate change while supporting biodiversity and thereby securing the flow of ecosystem services on which human wellbeing depends. Yet three barriers hinder the evidence-based integration of NbS into international, national and local climate and development policy and practice. First, challenges in measuring or predicting the effectiveness of NbS lead to high uncertainty about their cost-effectiveness compared to alternatives. Second, poor financial models and flawed approaches to economic appraisal lead to under-investment in NbS. And third, inflexible and highly sectoralized forms of governance hinder uptake of NbS, with grey, engineered interventions still being the default approach for many climate adaptation and mitigation barriers [139].

Overcoming these challenges requires major systemic change in how we conduct and communicate interdisciplinary research, and how we organize and run our institutions. More fundamentally, fully integrating NbS as solutions to both the climate and biodiversity crises requires a new approach in economic thinking, shifting from a focus on infinite economic growth to a recognition that the energy and material flows needed for human wellbeing must remain within safe biophysical limits [140,141]. NbS can play a key role in enabling sustainable development within planetary boundaries. However, their benefits will not be realized unless they are implemented within a systems-thinking framework that accounts for multiple ecosystem services and recognises trade-offs among them from the perspectives of different stakeholders. As nations revise their climate policies (Nationally Determined Contributions), and climate policy increasingly turns towards GHG removal approaches to help achieve climate targets [142], further elucidation of this systematic framework should be an urgent priority for future research. The revision of the Convention on Biological Diversity Aichi Biodiversity Targets and widespread calls for a new Global Deal for Nature should prompt scientists of all disciplines to fully engage with these issues, working together to find climate solutions that also address the biodiversity crisis and help to restore planetary health.

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