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The evolution and future of research on Nature-based Solutions to address societal challenges

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Nature-based Solutions are recognised for their potential to address the biodiversity and climate crises, and less extensively, other societal challenges. However, this nature-society relationship is becoming more important as available food and water resources, income, and human health, are increasingly impacted by environmental changes. Here, we utilise the seven major societal challenges addressed by Nature-based Solutions according to the International Union for Conservation of Nature, to identify the primary themes of the Nature-based Solutions research landscape from 1990-2021. We evaluate how these themes, with respect to the societal challenges, evolved over time, and where. Our findings highlight the under-representation of four societal challenges across the research landscape: economic and social development, human health, food security, and water security. We propose six research pathways to advance the evidence for Nature-based Solutions in these societal challenges, and present opportunities for future research programs to prioritise the needs of society, the environment, and the economy.

Nature-based Solutions (NbS) are defined as *actions to protect, sustainably manage, and restore natural and modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits*[1] (the basis for the UNEA-5 definition[2]). Historically, concepts within the NbS umbrella have focused on managing natural resources and enhancing ecosystem function to reduce habitat loss and increase the provision of ecosystem services[3]. More recently, NbS have been regarded for their role in responding to the climate emergency by mitigating carbon emissions[4], reducing the risk of disasters associated with climate-induced hazards[5,6] and reversing biodiversity loss[7]. However, NbS are now formally considered for their potential to address a range of societal challenges[8,9] beyond climate change mitigation and adaptation[10–12] and the reversal of biodiversity loss[13]. The seven societal challenges that NbS can address according to the International Union for Conservation of Nature (IUCN)[8] are:

1. *Climate change mitigation and adaptation*
2. *Disaster risk reduction*
3. *Economic and social development*
4. *Human health*
5. *Food security*
6. *Water security*
7. *Reversing environmental degradation and biodiversity loss*

These societal challenges highlight the diverse potential of NbS, which includes supporting economic livelihoods via sustainable fisheries[14], creating decent work[15] for local communities with eco-tourism while also providing additional agricultural yields[16], facilitating social wellbeing and human health[17] and building resilience to food and water insecurity[18,19]. This interconnected relationship between nature and society has been identified as critical in addressing global crises[20], where a single NbS intervention can contribute to addressing multiple developmental goals at a time when the confluence of global crises is threatening the existence of society[21].

Scientific evidence of NbS co-benefits can provide technical assurance to investors[22], while leveraging the support of the public[23] and wider

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industries[24] amidst the emerging climate and biodiversity crises. Existing evidence has led to an increase in NbS research funding across a range of societal contexts since 2011[25]. Although NbS is still largely under-funded with respect to the crises affecting species extinction and land degradation[26], NbS research and innovation projects have seen considerable investment since 2015[25,27]. This coincides with the release of the United Nations Sustainable Development Goals (UN SDGs)[28] and the negotiation of the Paris Agreement[29], with many countries now specifying NbS in updated climate pledges[30] and Nationally Determined Contributions (NDCs)[31]. This funding increase has led to a substantial body of academic scholarship over the last three decades[1], which may benefit from systematic and large-scale mapping to identify research trends[32]. To date, previous NbS studies have used a combination of automated machine learning algorithms and desktop reviews to examine the NbS research landscape for specific global issues, including hydrometeorological risk[33,34], social justice[35] and human wellbeing[36,37] across different contexts[38–41] and landscapes[42]. However, few reviews have focused on the entire NbS research landscape, particularly the societal challenges that NbS can address[35,39].

In this study, a systematic analysis was undertaken to identify the primary themes of the NbS research landscape and evaluate how these themes with respect to the societal challenges, have evolved over time and location. Our analysis focuses on seven societal challenges addressed by NbS interventions. These now well-established categories have been identified and adopted by the IUCN[8] community as the major challenges that NbS can address to benefit the environment and society. We assigned these challenges to individual research clusters to understand how NbS research has, to date, targeted global issues. We related the geographical distribution of NbS research to global vulnerability indices to identify regions where research efforts on NbS and societal challenges should be prioritised. Finally, we propose six research pathways to advance NbS research that can address the ongoing societal challenges and thereby help to prioritise and highlight the needs of society, the environment and the economy.

Results

Nature-based solutions research landscape

A systematic analysis of existing NbS research indicates that 14 of the 17 identified research clusters presented in Fig. 1a, have been related to research focused on climate change impacts and biodiversity loss. In contrast, academic publications pertaining to the societal challenges of (i) economic and social development, (ii) human health, (iii) food security and (iv) water security, have been intermixed within existing research clusters. Indeed, up to the end of 2021 these research areas only formed the primary subject of enquiry in one identified research cluster (see cluster 17 on air quality in Fig. 1a). As such, these four societal challenges are deemed understudied compared to the broader research clusters.

The focus on different societal challenges across the NbS research landscape is closely aligned with societal perspectives throughout the decades (see the coloured panels in Fig. 1a). Between 1990 and 2000, research publications primarily focused on forest restoration and ecological engineering, early predecessors of the NbS terminology[1]. This is consistent with the period from the 1970s through to the late 1990s, when negative anthropogenic impacts on nature were identified and initial mitigation measures proposed[3]. From 2000 onwards, the conservation focus shifted towards a more explicit link between nature and human wellbeing (e.g., with the development of the ecosystem services approach and eventually, the NbS concept), as a means to identify and measure nature's benefit to people[3]. This change aligned with the emergence of the first NbS research cluster focused on societal challenges outside climate change adaptation and mitigation and environmental degradation and biodiversity loss (see food security in cluster 7 of Fig. 1a).

In 2010, the establishment of funding sources, such as the Green Climate Fund[43], altered thinking towards values associated with the coexistence of people and nature[3] and several research clusters focusing on environmental degradation and biodiversity loss began to plateau or decelerate. From 2015, the growth in NbS research facilitated more holistic thinking, which led to substantial increases in NbS research funding across Europe[25], particularly through the Horizon 2020[44] and Horizon Europe[9,45] programs. Horizon 2020, the European Union's research and innovation program for 2014–2020, provided substantial funding for projects related to NbS, enabling researchers, innovators and stakeholders across Europe to explore, develop and implement nature-based approaches. This increase in financial support aligned with the emergence of several new research clusters and further NbS research conducted in Western Europe (see Fig. 2).

As a result of the increased NbS research funding mechanisms and coincident with the increase in compound stressors and events associated with the effects of climate change[46], NbS research focusing on disaster risk reduction (clusters 5, 6 and 8 in Fig. 1a) became more prominent. During this time, NbS research addressing human health (clusters 6 and 17) and water security (cluster 8) emerged, aligning with the release of the UN SDGs[28]. However, except for cluster 17, these two societal challenges together with food security and economic and social development, had yet to emerge as primary subjects of enquiry and remained peripheral to the observed research clusters. This is evident in Fig. 1b, which highlights the proportion of societal challenges that have been considered across the NbS research landscape in 4-year periods from 1990 to 2021 and is based on the assignment of societal challenges to each of the 17 research clusters in Fig. 1a.

By only considering the NbS research that emerged during the 'People and nature' conservation period[3], the contemporary understudied societal challenges are better represented. This period refers to the current era, defined by the dynamic relationship between human societies and the natural environment[3]. The circled section in Fig. 1b illustrates the proportion of societal challenges prevalent during this period, demonstrating a more balanced research landscape, albeit still with a strong focus on addressing climate change and reversing biodiversity loss. Among the understudied societal challenges, human health has advanced the most during this period, with the emergence of dedicated research on the connection between human wellbeing and nature in an urban context (e.g., the impacts of urban cooling and air quality on health) (clusters 6 and 17). New research clusters dedicated to food security did not emerge during this period, with ongoing food security research tied to fisheries management and biological conservation, which first emerged during the 'Nature despite people' conservation period. NbS research into participatory planning and governance, a new challenge area as defined by the European Commission[9], has also attracted interest at a faster rate than research targeting a specific societal challenge (see clusters 1 and 13 in Fig. 1a) and represents a greater proportion of the research landscape during this period (Fig. 1b). This demonstrates the desire within the research community to include NbS in policy and regulatory frameworks, hence indicating a positive shift towards broader NbS research.

Alignment with global vulnerability

By comparing the geographical distribution of the NbS author affiliations (Fig. 2a) with regions of high vulnerability (Fig. 2b), target areas for future NbS research can be identified. These target areas can be further refined by understanding how the societal challenges have been prioritised in NbS research within each region (Fig. 2c). The development of the research production map in Fig. 2a is based on the assignment of author affiliations from bibliographic data. While this may not always accurately represent the countries that are targeted in NbS research[47], this geographical distribution provides insight into where most research arises and from where researcher input is acknowledged in author affiliations (see Supplementary Note 1). Figure 2a highlights the high proportion of NbS research, independent of societal challenge, conducted in Europe, North America, China, Australia and Brazil. The amount of NbS research in Europe and North America is consistent with regions where most academic research is produced and cited[48] and in the case of Europe where substantial funding sources for NbS research were established[25].

A history of ecological restoration in response to rapid development in China[49] and to conserve native vegetation in Australia[50], is likely to have contributed to the high proportion of NbS research in these regions. The

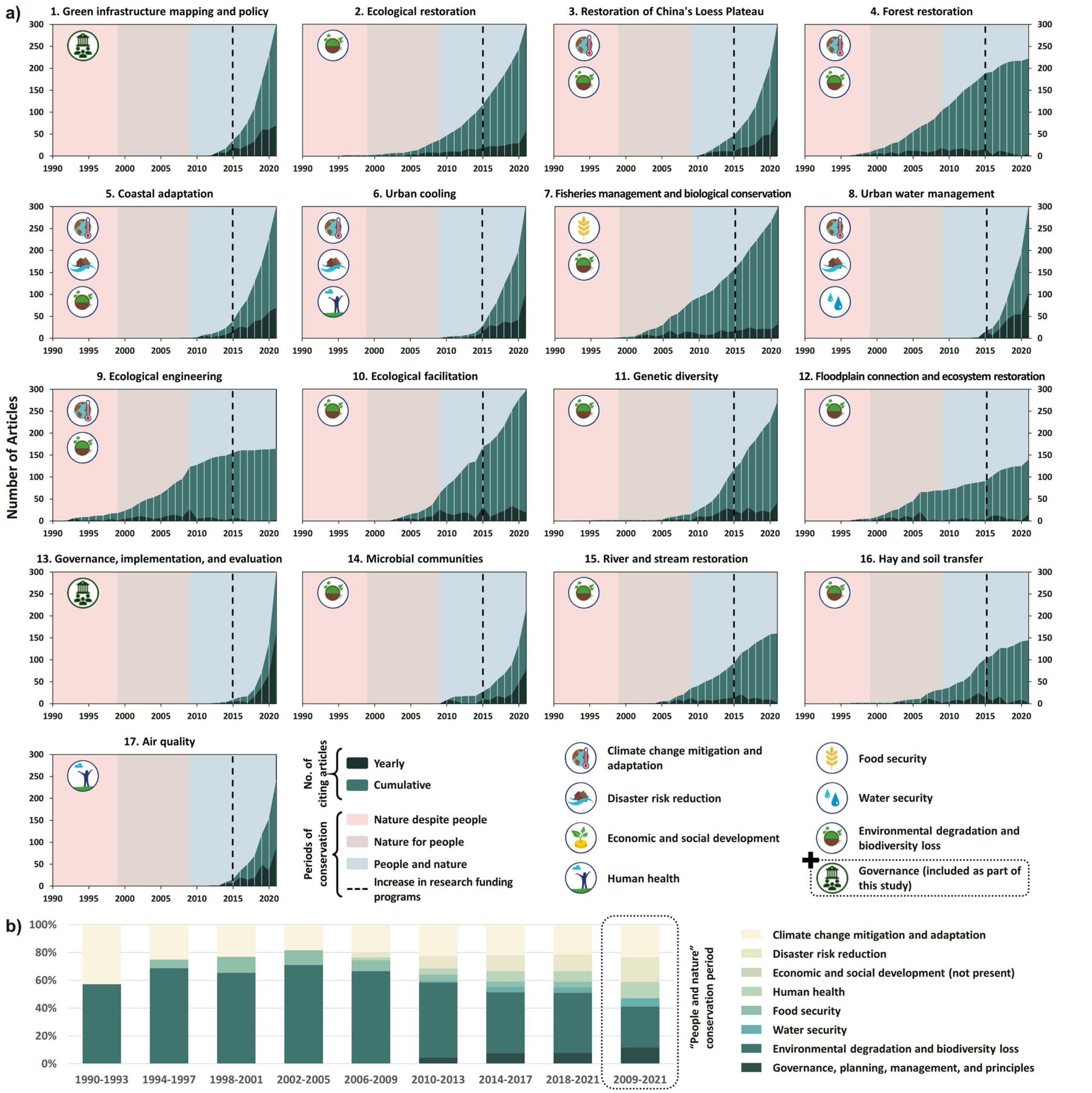

Fig. 1 | Trends in the NbS research landscape. a 17 research clusters with yearly and cumulative citation trends (green bars) and assigned societal challenges (IUCN icons[8]). The clusters are aligned with periods of conservation[3] (pink, brown and blue panels) and an increase in large-scale European research funding programs in 2015[25] (dashed black line); **b** The proportion of societal challenges that are prevalent across all 17 clusters in 4-year periods from 1990 to 2021 and that emerged during the 'People and nature' conservation period[3] (circled with the dashed black line).

large number of NbS studies in Brazil may be attributed to the relatively high proportion of urban NbS interventions for climate change adaptation[39] and the establishment of the EU-Brazil Sector Dialogue on NbS for Resilient Cities[51]. Further, of the twenty countries with the greatest NbS research production, the term 'Nature-based Solutions' is only found in the top five keywords for research undertaken in Western Europe (see Supplementary Note 2 and Supplementary Fig. 1).

In Fig. 2b, the distribution of authors across NbS research from 1990–2021 for each of the four understudied societal challenges, is compared to global indices that represent the vulnerability of each region to the given societal challenge. Economic and social development was not identified as a primary subject of enquiry in the NbS research landscape (Fig. 1) and no research production has been attributed to this societal challenge in Fig. 2b. However, the 2021 Gini Index results reveal an average index value for Europe that is lower than all other regions except for Africa. Both Africa and South America comprise nations with the lowest Gini Index values.

For human health, food security and water security, NbS research production is greatest in Europe, followed by North America. This contrasts with the low vulnerability of these regions, as presented by the selected indices for these challenges. The moderate level of research across Asia and North America for human health coincides with a high variability in index values for these regions. For food security, North America and Asia possess a large range of index values, while Africa maintains the lowest index average across these societal challenges, combined with low NbS research production.

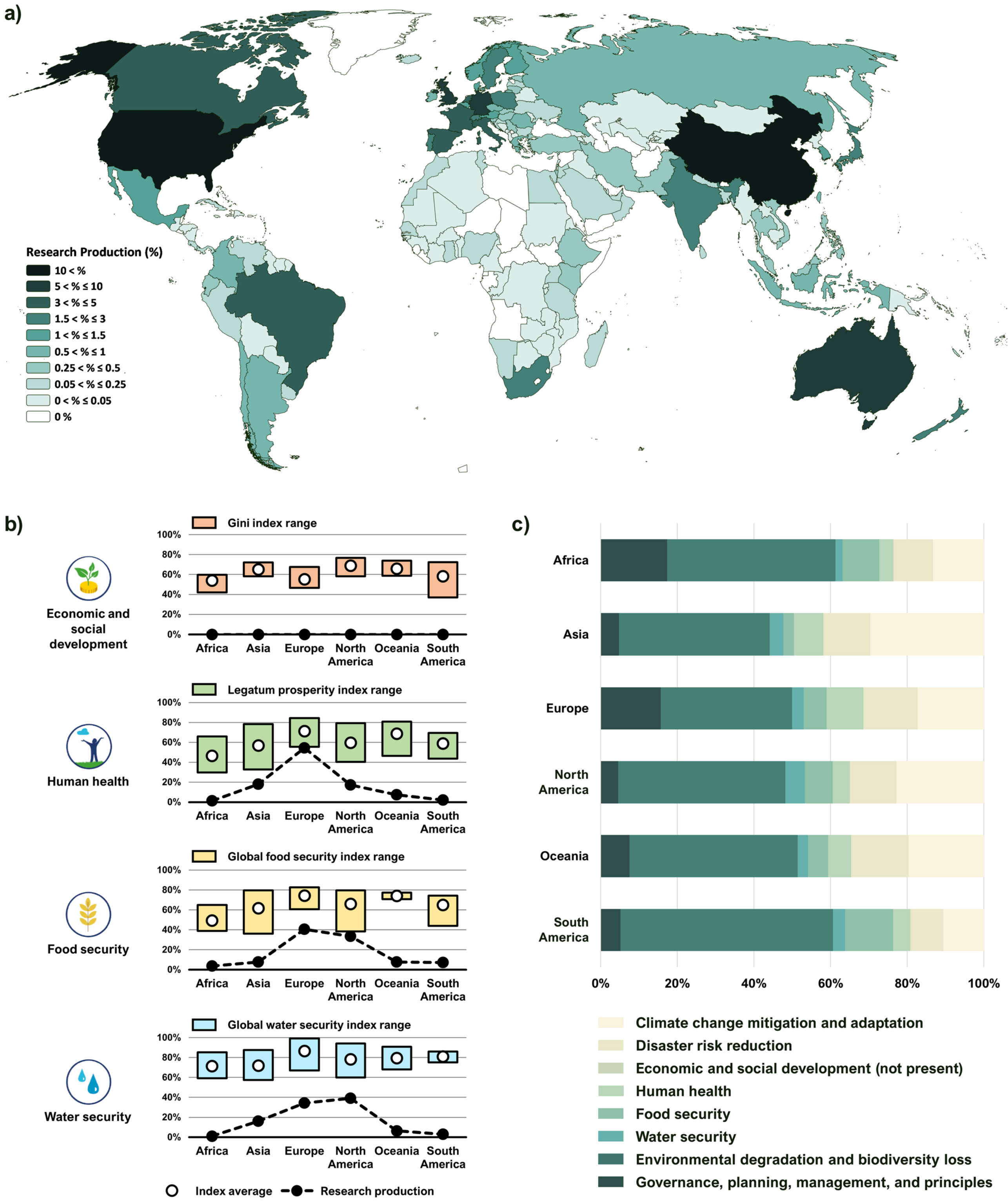

Fig. 2 | Contrast between NbS research production and global vulnerability. **a** Research production, represented by the geographical distribution of author affiliations for NbS research independent of the research focus; **b** Regional vulnerability, evaluated by comparing the proportion of research production (line graph) with vulnerability indices (columns) for each continent in each of the four understudied societal challenges (IUCN icons[8]); and (**c**) The proportion of NbS research dedicated to each societal challenge for each continent.

Vulnerability in the understudied societal challenges is complemented with an understanding of the societal challenges that have been prioritised in NbS research across each continent (Fig. 2c). Figure 2c highlights how Africa has dedicated a higher proportion of its NbS research to governance and planning than any other continent. Similarly, food security has been prioritised highest by Africa and South America. Contrastingly, Africa maintained the lowest percentage of NbS research assigned to water security and human health. NbS research production in Asia has focused on climate change mitigation and adaptation more than any other continent, while food security has been prioritised the least, despite Asia comprising nations with the lowest Global Food Security indices. Oceania has prioritised disaster risk reduction to a higher degree than other continents, with research targeting the reversal of environmental degradation and biodiversity loss comprising over half the NbS research in South America. Research in each of the understudied societal challenges represents less than 10% of the NbS research production for each continent.

Discussion

Results from our systematic analysis highlight that NbS research (Fig. 1) has primarily focused on climate change and biodiversity loss, aligning with the outcomes of earlier reviews into subsets of the NbS research landscape[40,41]. Since the growth of large-scale research funding programs in 2015, NbS research has begun to focus on other societal challenges. For instance, research targeting disaster risk reduction has become prominent in recent years. Nonetheless, four of the adopted IUCN societal challenges tend to remain peripheral to the overall NbS research landscape: (i) economic and social development, (ii) human health, (iii) food security and (iv) water security. Research outputs in these disciplines have been disproportionately skewed towards Europe and North America, despite the greatest vulnerabilities lying outside these regions. This mismatch highlights the need for researchers in vulnerable regions to be included in NbS research stewardship and authorship and for future research to be prioritised and funded in regions where it is needed most.

To establish the understudied societal challenges as primary subjects of enquiry for future NbS research, it is critical to understand their role within the wider NbS context (see Supplementary Discussion) and to develop appropriate pathways that prioritise research in these disciplines. In this section, approaches for building on current NbS research mainly addressing climate change, biodiversity loss and disaster risk (hereafter referred to as foundations of the NbS research landscape) and expanding the focus into the four understudied societal challenges are discussed. Strategies needed to advance NbS research are presented in Fig. 3, including key research pathways for supporting the scientific basis of NbS. Subsequent boxes (Boxes 1–6) provide key details and examples for each pathway.

Research pathway 1. Maintain

Maintaining research in the foundations of NbS research landscape can serve to inform the use of NbS in national policies[33] and underpin the effectiveness of NbS research in the understudied societal challenges. For example, the pledge to utilise NbS within NDCs may be attributed to the growing evidence base of NbS to increase resilience to climate change, but could present an opportunity for nations to develop actions and metrics, such as those defined by the European Commission[9], to complement qualitative indicators[8] for NbS to support the vulnerable sectors of food security, water security and human health[52]. By continuing to draw links between climate change mitigation and the understudied societal challenges through NbS research, the focus can shift towards adopting NbS within policy to provide positive outcomes for people and the economy[25].

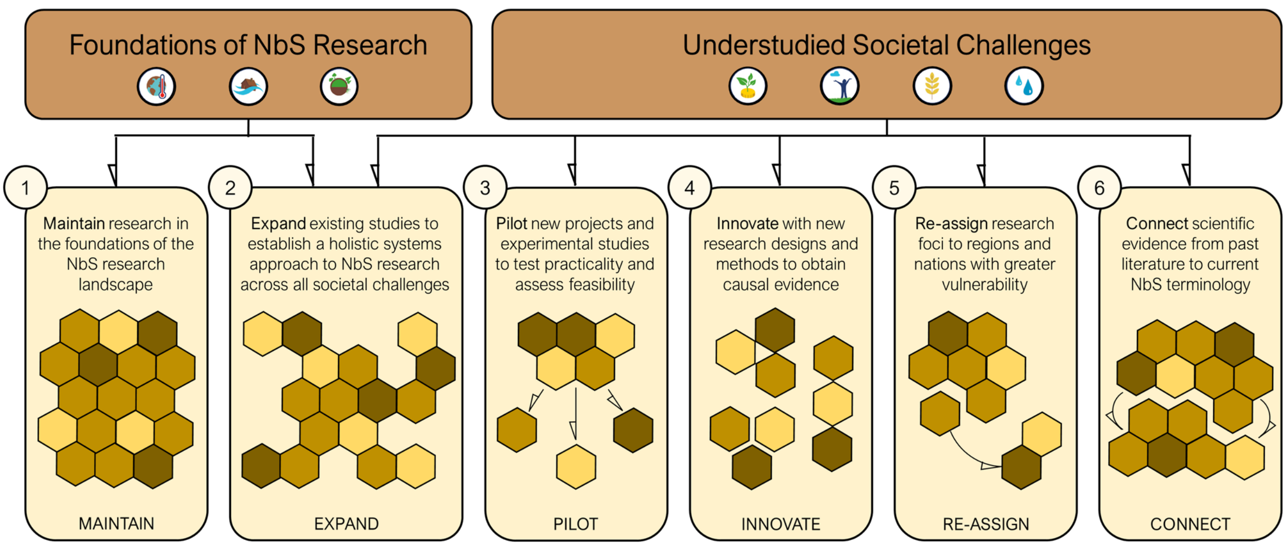

Fig. 3 | NbS research pathways. Six research pathways proposed to build on the foundations of NbS research and advance the scientific basis for NbS to address the societal challenges (IUCN icons[8]) that are currently understudied within the NbS research landscape.

Box 1 | Research pathway 1. Maintain

- Continue to target the foundational aspects of NbS research with an aim to provide high quality evidence to further promote the inclusion of NbS in policy and governing protocols across environmental, societal, and health sectors.
- Draw connections between maintained NbS research in the primary subjects of enquiry across the NbS research landscape and the understudied societal challenges, to enable governing protocols to acknowledge the range of NbS co-benefits.
- Transition the focus of current NbS research to the follow-on effects of climate change mitigation and adaptation, and the reversal of biodiversity loss, on society and the economy.

Example: In South America, the highest proportion of NbS research has been dedicated to reversing environmental degradation and biodiversity loss (Fig. 2c). This research can form the basis for promoting NbS in policy, in a region where NbS governance has not been prioritised over the study period. In contrast, Africa has the highest proportion of NbS research dedicated to governance. This supports the recent inclusion of NbS for adaptation and mitigation in NDCs across Africa[52], demonstrating how research in the foundational aspects of NbS can lead to the inclusion of NbS within policy.

Box 2 | Research pathway 2. Expand

- Expand NbS research to capture the interdependencies between societal challenges and understand how individual societal challenges can be addressed in an integrated way with other societal challenges.
- Optimise solutions for addressing multiple project objectives, expanding on current knowledge that primarily focuses on one societal challenge.
- Apply successful studies across contexts and borders.

Example: The blue carbon model of the Mikoko Pamoja project in Kenya has expanded to neighbouring countries of East Africa[116], linking the societal challenges of economic and social development, climate change mitigation and adaptation, and food security, and overcoming transboundary challenges surrounding governance to enable similar structures to be established within the region. Regions such as Asia and North America that contain a wide range of Prosperity Index values (Fig. 2b), could also profit from this approach, where NbS research from countries with more favourable indices can be expanded and applied to countries with less favourable indices, thereby enhancing knowledge sharing and capacity building to minimise inequalities in economic development.

Box 3 | Research pathway 3. Pilot

- Pilot NbS projects to test the practicality of theoretical research in the understudied challenges.
- Implement field trials to establish long-term monitoring campaigns and datasets that can be used to derive boundary conditions for future NbS projects, and to inform the success of NbS to address the understudied societal challenges.
- Pilot NbS across contexts to understand the variability of impacts to different landscapes, societies and economic structures.

Example: With flood and drought durations increasing amidst rapid climate change[117,118], long-term field trials are needed to establish the boundary conditions for NbS to increase the resilience of vulnerable regions to issues of food and water insecurity (see Africa and Asia in Fig. 2b), and understand how outcomes will differ with ongoing global change. Evaluating the co-benefits or adverse effects on other sectors can help upscale lessons learned from pilot studies to regions experiencing similar, but also different combinations of challenges. Environmental boundary conditions can be derived by monitoring the seasonal changes in temperature, soil moisture content and ecosystem growth and comparing these to indicators of NbS success for the targeted societal challenge[8,9]. This data can then be used to develop relationships between parameters that can provide quantitative guidance to the future resilience of NbS.

Box 4 | Research pathway 4. Innovate

- Innovate with new research designs, strategies and materials to obtain causal evidence for the use of NbS in the understudied societal challenges.
- Collaborate with experts from outside the field of the primary research objectives to establish multi-faceted approaches to global issues.
- Innovate with materials to transition current artificial practices to NbS.

Example: A modular, reusable structure that protects ecosystems during the early establishment and growth stages, like wooden fences for protecting mangrove aquaculture farms[119], can offer a sustainable solution for overcoming challenges with restoring ecosystems, enhancing food security and maintaining economic livelihoods. Such a solution offers flexibility to adapt to unexpected changes, particularly in regions where future projections are uncertain[120]. This could be developed with NbS for the local context of nations within Asia and Africa that are identified as having high vulnerability and low comparative research production in these fields (Fig. 2).

Research pathway 2. Expand

Due to the complex interdependencies between societal challenges, long-term research projects measuring the success of NbS in one sector, can be expanded to consider how NbS may impact other sectors[53]. As identified in earlier systematic analyses of urban NbS[39], this research expansion across all forms of NbS can help overcome the gaps between NbS and socio-economic issues, which are critical for achieving transformative change and socially just futures. Prime case studies for expansion include those where secondary benefits are already measured but are not yet the primary focus of the implemented NbS. For example, the long-term influence of NbS to address water scarcity has direct benefits to agricultural production and irrigation water availability, thus also improving food security. New research that considers the potential for NbS to benefit multiple sectors will have direct applications to the transition and/or transformation of livelihoods and landscapes towards a more sustainable use of available water resources. Like Action 1a of the NetworkNature European Roadmap to 2030[25], research that targets the impact of NbS concerning the many interconnections within the water-energy-food nexus, can establish the scientific evidence base for NbS as a multifaceted mitigation measure and highlight the trade-offs and synergies to requirements concerning food security, water security and economic development.

Research pathway 3. Pilot

Applied research is recommended through pilot projects that serve as real-world testing grounds. These projects may be considered in regions that can draw on the success of neighbouring nations with stable economies and lower inequality (see Fig. 2b). However, it is important to note that the particularities of each context should always be carefully considered and there is no one-size-fits-all or copy-paste solution[54,55]. In such pilots, collaboration amongst a diverse range of stakeholders across industry value chains that consider the restoration of nature, is key to validate holistic approaches such as the Nature-Positive Economy

Box 5 | Research pathway 5. Re-assign

- Re-assign regional NbS research priorities to address the societal challenges that countries within the specific region are most vulnerable to.
- Re-assign global NbS research projects to support regions with the greatest vulnerability to the understudied societal challenges.
- Ensure local researchers are engaged and appropriately included in NbS research authorship when re-assigning research priorities regionally and internationally.

Example: Studies on urbanising areas in regions with increasing population growth[38] and low Prosperity Index values, such as Africa and Asia (Fig. 2b), and where exposure to climate change impacts heightens the vulnerability to ill-health related to, for example, heat exposure, malnutrition and vector-borne diseases[121], should be prioritised for maximum health impact. Similarly, regions with high water-policy challenges[120] and low Global Water Security Index values (Fig. 2b), present opportunities to introduce knowledge from regions with extensive research and low vulnerability to water insecurity. However, local solutions must be evaluated and upscaled to assess their feasibility across different landscapes and socioeconomic systems.

Box 6 | Research pathway 6. Connect

- Connect scientific evidence from past academic literature to the NbS terminology and associated concepts.
- Understand how past research can support and promote the use of NbS within the understudied societal challenges.
- Consider the nuances in the definitions between old and new terms, to understand whether the broader co-benefits associated with NbS have been adequately integrated into past research.

Example: Early research that is directly related to the understudied societal challenges can be linked to the NbS concept to demonstrate the breadth of research in the field. An example of this is with food security, where extensive research into concepts such as 'fisheries management' (see cluster 7 in Fig. 1) and 'agroforestry'[104] has been undertaken over several decades, but often without targeting the broader impacts to other societal challenges. By comparing the objectives of past research to current NbS studies, relevant case studies and research outcomes can be linked to the modern terminology and used to enhance the scientific evidence base of NbS.

(NPE) concept[56], explore its market potential and pilot solutions that align with market drivers.

Experimental studies are also recommended to understand the biological mechanisms between various NbS and health outcomes. Such trials could analyse specific components of nature, including biodiversity, to assess impact on the human microbiome and subsequent health effects[57]. In a highly urbanised world with a disrupted relation to nature, this kind of evidence could be groundbreaking and motivate broad implementation of NbS across regions. Proof of a cause-effect relationship could also serve to reduce scepticism within the medical establishment and support the use of NbS in health care[36,58]. This would likely result in increased awareness in policy and decision-making, leading to better acceptance of NbS for several health challenges.

Research pathway 4. Innovate

To support the use of NbS in the understudied societal challenges, causal evidence is needed and can be achieved through new research using new data, with the implementation of longitudinal studies. To identify mechanisms for the use of NbS in the health sector, innovative research strategies could include collaborations between health specialists, urban planners and engineers, to conduct randomised, controlled NbS trials to considerably reduce the risk of bias and thereby provide stronger proof for the efficiency and impact of NbS[37].

Aligning NbS research with both environmental and social needs can similarly provide support for the use of NbS to address the complex dynamics between land use and agriculture. These sectors have been identified as NbS research hotspots[59], with ecosystems continually requiring conversion to agriculture to sustain the growing global population[60,61]. Where it is unfeasible to revert agriculture to ecosystems, utilising more sustainable types of agriculture with NbS to enhance biodiversity, minimise soil erosion and sequester carbon, without impacting production, should be promoted in place of intensive farming[62]. Further, NbS research partnering with Indigenous communities, has the potential to utilise traditional, local knowledge to both develop climate and disease resilient crops for enhancing sustainable food systems[63] and to identify key project drivers and support community transformation via co-production[54]. Within this context, the spiritual and restorative qualities of nature and the impact on human health and wellbeing could also be acknowledged.

Research pathway 5. Re-assign

Complementing previous NbS analyses that have advocated for NbS research to close existing global knowledge gaps[39], the comparison of NbS research production with global vulnerability (Fig. 2) indicates that the high overall NbS research production in Europe could be better aligned with economic and social development. Similarly, Africa and South America, regions also prioritised for biodiversity funding[64], present opportunities for future NbS research programs, due to a combination of low index values and existing overall NbS research. When implemented effectively through NbS, an NPE pathway can stimulate job creation and enable inclusive and equitable economic development. This pathway has the potential for NbS to support income resilience and social justice in vulnerable nations with low Gini Index values in Africa, Europe and South America (Fig. 2b), and future-proof less vulnerable regions like North America from potential unforeseen impacts.

By similarly considering food systems through a resilience lens, transformative pathways can be developed to overcome the dichotomy of local and global perspectives on food insecurity, to achieve commonalities across scales and minimise the dependence on stable food processes at either the global or local level[65]. Achieving resilience in food systems is necessary in regions with the greatest vulnerability, such as in Africa and parts of Asia and North America (Fig. 2). Future NbS research should seek to establish methods for creating resilient food systems in these regions and re-establishing those in regions that have suffered the most from the effects of climate change and violent conflicts[66].

Further research may also be focused in areas of high resilience, to either maintain and document the success of these regions, or to reduce the variability between nations. This is evident for Oceania, where the high resilience of the region to these challenges is based on data obtained from a select few nations, despite the vulnerability of many Pacific Island nations to the effects of sea level rise impacting health, water quality, and food availability[67].

Research pathway 6. Connect

For each of the societal challenges considered in this study, a sizeable academic scholarship exists using alternative terminology that may not be directly linked to the NbS concept. Developing connections between existing literature and the NbS concept is necessary to ensure that existing knowledge is recognised and used to expand the current state of NbS research. For example, 'urban green spaces' and 'urban forests' are terms often used in literature on nature and health. Evidence from these studies can be used to support the use of NbS for sustainable health care and disease prevention.

Future scoping reviews could identify other terminology (including from Traditional Ecological Knowledge) and how it has been used in previous nature and interdisciplinary research in various parts of the world among different populations. For example, while the concept of 'ecosystem services' has been widely recognised within environmental sciences for decades, it has only recently been understood and adopted by human health disciplines to guide research questions and study designs[68].

Conclusions

At a time when humanity is faced with a multitude of crises, understanding the extent to which NbS can support the environment, society and economy, is paramount. The findings from our analysis highlight a transition in the NbS research landscape from studies mostly targeting climate change and biodiversity loss, to those considering the impacts of NbS on society and the economy. NbS research is trending towards promoting NbS in policy, evaluating the interdependencies between societal challenges and integrating understudied challenges within core research themes. However, NbS research prioritising economic and social development, human health, food security, and water security, remains limited.

Our analysis seeks to inform the objectives of future research and the direction taken by NbS researchers, policymakers and practitioners. Targeted responses are needed to facilitate dedicated research on NbS addressing the understudied societal challenges individually, or in an integrated manner that complements the more visible societal challenges. We identified key regions where future NbS research should be prioritised and where local researchers should be included in stewardship and authorship. This presents an opportunity for policymakers and directors of NbS research funding programs to invest in research that stipulates the need for local knowledge and enhances the scientific basis of NbS. Our six proposed pathways have been developed to aid researchers and practitioners in prioritising NbS research that can build knowledge and capacity for the use of NbS to address the four understudied societal challenges and promote NbS across sectors.

Methods

Search strategy

A term-based search strategy was implemented to obtain relevant literature from the Web of Science Core Collection (1900-present) database. This literature comprised research articles from scholarly journals, books and scientific proceedings.

In developing the search strategy, a preliminary search of the Web of Science using only the term 'Nature-based solution*' was carried out to understand the number of publications associated with this term between 1990 and 2021. This preliminary search only yielded between 1,200 and 1,300 results, with no research identified prior to 2009 and only six articles prior to 2016. This dataset was deemed to be too narrow for a bibliometric analysis of the evolution of scientific fields within the NbS research landscape. To expand the search and subsequent dataset, a list of terms was compiled that reflected the varying terminology under the NbS umbrella (see Table 1). These terms were obtained from an available review of global NbS guidelines[1] and existing terminology summaries[69].

To remove any bias towards one or more societal challenges, this list was refined to only include terms that most similarly referred to the NbS concept and addressed several global challenges, rather than those solely pertaining to one societal challenge. For example, terms such as 'ecosystem-based disaster risk reduction' and 'natural flood management' were removed from the list because they are more closely related to mitigating disaster risk. Other terms, such as 'ecological restoration' and 'ecosystem restoration', that may be viewed as more closely related to addressing environmental degradation and biodiversity loss but have greater application to a variety of societal challenges, were included in the search query. The relevance of these terms to the NbS concept is evident in their definitions (see Table 1) and by manually reviewing the foci of the papers that were found using these terms in the Web of Science. It is noted that the initial definitions of several search terms may vary from the definition of 'Nature-based Solutions' and be weighted towards one or more societal challenges, because an understanding of how these concepts could impact a broader range of societal challenges was not established at the time the terms were coined.

Other search terms related to NbS were also considered but were excluded from the final search query due to their inherent connection to one or two societal challenges. Many of these terms would provide very few additional papers to the overall dataset and thus would have a limited impact on the overall analysis. However, some of these additional terms have sizable academic scholarships alone and thus if these terms were included, the overall research landscape may be heavily biased towards a particular theme. The impact that these additional terms would have on the size of the dataset obtained from the original search query, is given by the percentage increase in dataset size as listed in Table 2.

Final search query

Once the list of terms had been refined, the terms were combined using the Boolean operator 'OR' such that the database would retrieve any research article that included any of the search terms in the title (TI), abstract (AB), or author keywords (AK). The search query for the analysis is presented below.

TI = ('Nature based solution' OR 'Working with nature*' OR 'Engineering with nature*' OR 'Building with nature*' OR 'Ecological engineering*' OR 'Eco-engineering*' OR 'Green infrastructure*' OR 'Ecosystem based adaptation*' OR 'Ecosystem based approach*' OR 'Working with natural processes*' OR 'Urban greening*' OR 'Ecological restoration*' OR 'Natural infrastructure*' OR 'Soft engineering*' OR 'Ecosystem restoration*' OR 'Ecosystem based restoration*') OR*

AB = ('Nature based solution' OR 'Working with nature*' OR 'Engineering with nature*' OR 'Building with nature*' OR 'Ecological engineering*' OR 'Eco-engineering*' OR 'Green infrastructure*' OR 'Ecosystem based adaptation*' OR 'Ecosystem based approach*' OR 'Working with natural processes*' OR 'Urban greening*' OR 'Ecological restoration*' OR 'Natural infrastructure*' OR 'Soft engineering*' OR 'Ecosystem restoration*' OR 'Ecosystem based restoration*') OR*

AK = ('Nature based solution' OR 'Working with nature*' OR 'Engineering with nature*' OR 'Building with nature*' OR 'Ecological engineering*' OR 'Eco-engineering*' OR 'Green infrastructure*' OR 'Ecosystem based adaptation*' OR 'Ecosystem based approach*' OR 'Working with natural processes*' OR 'Urban greening*' OR 'Ecological restoration*' OR 'Natural infrastructure*' OR 'Soft engineering*' OR 'Ecosystem restoration*' OR 'Ecosystem based restoration*')*

The above search string was entered into the Web of Science Core Collection database on 25 March 2022 and the date range restricted to 01-01-1990 to 31-12-2021, yielding 16,290 unique publications (herein referred to as 'citing articles') to form the initial dataset. The bibliographic data, including title, journal, abstract, cited references, author list, keywords,

Table 1 | Summary of terms used in the final search query

Search Term[a]	Definition Reference	Societal Challenge	Percentage of Total Dataset
Nature-based solutions	Cohen-Shacham et al.[1],	All	10%
Ecological restoration	Society for Ecological Restoration[78],	All	40%
Green infrastructure	European Commission[79],	All	20%
Ecosystem restoration / Ecosystem-based restoration	UNEP[80],	All	10%
Ecological engineering / Eco-engineering	Mitsch, 2[81]	All	8%
Urban greening	Dorst et al.[82],	All	4%
Ecosystem-based approach	HELCOM & OSPAR[83], (related to ecosystem approach)	All, with a focus on climate change mitigation and adaptation	4%
Engineering with nature	USACE[84],	All	4%
Building with nature	de Vriend and van Koningsveld[85],	All	
Ecosystem-based adaptation[b]	CBD[86],	All, with a focus on climate change mitigation and adaptation	
Natural infrastructure[b]	Benedict and McMahon[87],	All, with a focus on climate change mitigation and adaptation	
Working with nature	PIANC[88],	All	
Working with natural processes[b]	Environment Agency[89],	All, with a focus on disaster risk reduction	
Soft engineering[b]	Hartig et al.[90],	All, with a focus on disaster risk reduction	

[a]In the final search query, an asterisk was included at the end of each search term for truncation. Further, the presence or absence of a hyphen within the search term was found not to impact the results.
[b]These terms may be more closely related to a specific societal challenge than the broader concept of Nature-based Solutions but had negligible impact on the overall dataset and subsequent Document Co-citation Analysis.

Table 2 | Impact of additional search terms on the original dataset

Search Term	Definition Reference	Societal Challenge	Dataset Increase
Natural climate solution	Griscom et al.[91],	Climate change mitigation and adaptation	<1%
Ecosystem-based mitigation	CBD[92],	Climate change mitigation and adaptation	<1%
Ecosystem-based disaster risk reduction	PEDRR[93],	Disaster risk reduction	<1%
Ecosystem approach to disaster risk reduction	Gupta and Nair[94],	Disaster risk reduction	<1%
Ecosystem-based coastal protection / defence	Temmerman et al.[95],	Disaster risk reduction	<1%
Natural flood management	Forbes et al.[96],	Disaster risk reduction	<1%
Green economy	UNEP[97],	Economic and social development	12%
Green finance / Green financial products	Lindenberg[98],	Economic and social development	<1%
Green growth	IISD[99],	Economic and social development	7%
Natural capital	Costanza et al.[100],	Economic and social development	15%
Nature positive economy	WWF[101],	Economic and social development	<1%
Ecological economics	Costanza[102],	Economic and social development	24%
Nature-based health interventions	Shanahan et al.[103],	Human health	<1%
Agroforestry	Sinclair[104],	Food security	53%
Agroecology	Gliessman[105],	Food security	16%
Permaculture	Mollison et al.[106],	Food security	2%
Regenerative agriculture	Regenerative Agriculture Initiative and The Carbon Underground[107],	Food security	<1%
Agronomy	Encyclopedia Britannica[108],	Food security	20%
Organic agriculture	IFOAM[109],	Food security	19%
Conservation agriculture	FAO[110],	Food security	12%
Natural regeneration	Brown[111],	Food security	24%
Evergreen agriculture	Garrity et al.[112],	Food security	<1%
Climate-smart agriculture	FAO[113],	Food security	4%
Forest landscape restoration	Mansourian et al.[114], Maginnis et al.[115],	Environmental degradation and biodiversity loss	1%

publication year and author affiliations, for each citing article, were exported from the Web of Science database as text files. These text files served as the basis for the Document Co-citation Analysis. It is noted that due to the robustness of the Document Co-citation Analysis, minor changes in the number of publications have negligible impacts on the final analysis of the state of research and the evolution of the field.

Document co-citation analysis

The analysis of the search results was undertaken in the form of a Document Co-citation Analysis[70]. This analysis uses exported text files of bibliographic data, from a database such as the Web of Science, in conjunction with the CiteSpace software[71] to identify the dominant themes of a research field and present the historical evolution and temporal trends of each theme. The strength of the Document Co-citation Analysis lies in its capacity to identify trends within the NbS research landscape even if several publications are missing from the initial dataset. This analysis detects the fundamental references (herein termed 'cited references') that have been frequently co-cited (cited together) by the citing articles of the NbS research landscape, regardless of whether the publications are themselves included in the initial dataset. These cited references may lie outside the main field of NbS research (e.g., in water legislation) when co-cited by the citing articles. In doing so, this technique enables the underlying cited references of the NbS research landscape to be included in the analysis.

Cited references that are frequently co-cited by NbS articles with a particular theme, can be thematically categorised into research clusters, where their citing articles represent a particular cluster of NbS research and the cited references themselves form the knowledge foundation of the cluster. The cited references with the greatest influence on each cluster were identified using three primary metrics: local citation counts, bursts of citation count, and reference centrality, and can be cited together with references belonging to other clusters[72]. These research clusters represent individual streams of the NbS research landscape.

Following their development, the research clusters were then ordered based on the number of cited references within them (i.e., in Fig. 1, cluster 1. 'Green infrastructure mapping and policy' contained the most references and cluster 17. 'Air quality' contained the fewest). Each research cluster was initially labelled in CiteSpace using an algorithm based on burst terms extracted from the bibliographic data of the cited references[71]. However, because this labelling process has the potential to overlook key phrases that provide greater distinction between clusters, a full-scale review of the titles of all papers within each cluster was undertaken to determine the dominant themes and clarify the labels for the reader. Some of the research cluster labels refer to similar themes, such as ecological restoration (cluster 2) and forest restoration (cluster 4), or ecological facilitation (cluster 10) and genetic diversity (cluster 11), but are derived from citing articles targeting unique fields of research. For example, the citing articles in the research cluster on ecological facilitation (cluster 10) refer to the interactions and facilitations between ecosystem types, water and vegetation and habitats, while the citing articles in the cluster for genetic diversity (cluster 11) consider seed sourcing and the impacts of restoration with genomically diverse species.

In this study, 17 major research clusters were formed containing between 150 and 1200 cited references and more than 200 citing articles, providing sufficient subsets for analysis and inclusion within this study. Other research clusters contained fewer than 150 cited references and fewer than 40 citing articles, presenting datasets that were too small for the identification of consistent themes and were subsequently excluded from the analysis. For each of these research clusters, the number of citing articles per year and cumulative number of citing articles, were graphed in Fig. 1 to examine the change in research production.

Sensitivity analysis

Due to the subjectivity of the selection of several terms in the initial search query, a preliminary co-citation analysis was undertaken using the narrow dataset that was obtained from the term 'Nature-based solution*'. Although this dataset was too small (between 1200 and 1300 citing articles) to undertake the full Document Co-citation Analysis with the same accuracy as the initial broad dataset, the preliminary findings were observed to understand whether the themes of the research landscape would be considerably different without the inclusion of other terms under the NbS umbrella. This preliminary co-citation analysis revealed that the themes of the observed research clusters from 2009–2021 (the period of the new dataset) were consistent with the clusters formed during this period from the original dataset. This finding demonstrates that the inclusion of additional terms under the NbS umbrella did not considerably change the outcomes of this study over the last decade, but instead has been useful for understanding the evolution of the field prior to the introduction of the term 'Nature-based solutions'.

Assignment of societal challenges

The seven societal challenges developed by IUCN[8] were manually assigned to the research clusters that were formed through the Document Co-citation Analysis to understand how the documented potential of NbS is being considered across the NbS research landscape. This assignment of societal challenges complements the labelling of the research clusters to highlight the core objectives behind the research. To assign the societal challenges to each research cluster, a thorough review of abstracts, introductions and conclusions of select papers was conducted to confirm the core objectives. Due to the volume of research articles obtained in this study, a full review of each paper was not undertaken.

Where more than one core objective was identified in a research cluster, multiple societal challenges were assigned. A sensitivity analysis was carried out to determine the impact that assigning additional societal challenges to research clusters with multiple foci would have on the understudied societal challenges. For example, in research clusters 3 (Restoration of China's Loess Plateau) and 17 (Air quality), water security and climate change mitigation and adaptation, respectively, could have been included in the main analysis because each cluster's research papers have multiple foci. By incorporating these additional challenges, water security would emerge earlier in the NbS landscape, in 2010 instead of 2013, but with negligible other impacts due to the prevalence of climate change mitigation and adaptation throughout the field. Minor changes in the selection of societal challenges for each research cluster have the potential to influence when societal challenges were targeted in NbS research, but with limited impacts on the overall results. Further scoping reviews are recommended once the NbS research landscape has evolved further to understand the change in focus of these research clusters.

All except two of the identified research clusters were assigned one or more of the IUCN societal challenges. These two research clusters focused more broadly on the policy, governance and management of NbS, without directly addressing specific societal challenges. These research clusters were assigned a separate identifier relating to the governance of NbS. As a result, an eighth icon was created for the purposes of this research (see Fig. 1a), independent of the seven IUCN societal challenge icons.

Comparison of societal challenges

For each 4-year period from 1990 to 2021, the research clusters that contained citing articles in each of these periods were identified and the number of clusters associated with each societal challenge was recorded. These tallies were compared to one another as percentages of the total number of assigned societal challenges for each 4-year period to understand which societal challenges were being considered and to what extent, during the evolution of the NbS research landscape.

A similar exercise was also undertaken for research clusters that emerged during the latest period of conservation (2009 to present)[3], where the term 'Nature-based Solutions' became prevalent. This comparison was conducted to highlight the shift in perspective on the importance of NbS for addressing global environmental and societal crises.

Distribution of author affiliations and societal challenges

Combining research trends with the geographical distribution of author affiliations provides an insight into the issues that researchers prioritise in different regions. The number of author affiliations per country and region was exported from the dataset retrieved from the Web of Science Core Collection using the search query described above. For each publication in the dataset, the affiliations of all authors were considered. However, each country is restricted to being counted only once per publication, regardless of the number of author affiliations from the same country.

The proportion of author affiliations per continent and societal challenge was also determined for a visual comparison with global vulnerabilities in the understudied societal challenges (Fig. 2b). Each country was assigned to a continent and the total number of author affiliations per continent was recorded as a percentage of the total number of author affiliations globally. This process was repeated for each research cluster to disaggregate the total number of author affiliations per societal challenge, based on the societal challenges that were assigned to each research cluster in the preceding section.

A similar exercise was undertaken to complement the global distribution of author affiliations in NbS research with an understanding of how NbS research has been prioritised in each region, with respect to the IUCN societal challenges (Fig. 2c). For each research cluster, the total number of author affiliations per continent was recorded. These tallies were attributed to the societal challenge assigned to the research cluster (Fig. 1a). For each continent, the proportion of author affiliations assigned to each societal challenge was recorded as a percentage of the total number of author affiliations for that continent. These proportions were then plotted in Fig. 2c to illustrate the breakdown of NbS research by societal challenge for each continent.

Vulnerability indices

To align the NbS research production in the four understudied societal challenges with regions of high vulnerability to these challenges, the following four indices were selected as proxies for vulnerability:

- Gini Index[73] for economic and social development
- Legatum Prosperity Index[74] for human health
- Global Food Security Index[75] for food security
- Global Water Security Index[76] for water security

The Legatum Prosperity Index and Global Food Security Index data were obtained for the year 2021 to align with the end of the 1990–2021 period used for the analysis. However, for the Gini Index and Global Water Security Index, data were not always available for each country in 2021 and thus the most recent indices were used. The average index data for each continent were calculated and the range of indices graphed and compared to the distribution of author affiliations (Fig. 2b). Of these indices, the Gini Index is the only index where a higher value is less favourable. Therefore, for consistency, the Gini Index values were subtracted from 100% when plotted in Fig. 2b such that all indices used the same scale, where low values are less favourable.

Keyword analysis

To complement the geographical distribution of author affiliations, the most popular author keywords in the NbS research landscape were determined for the 20 countries with the highest proportion of author affiliations. The Web of Science Core Collection search results using the query presented above were filtered for each country independently and the subsequent bibliographic data exported as text files. The VOSviewer software[77] was then used to determine the total number of times each keyword appeared in research from each country. The top 5 keywords per country were recorded and compared in Supplementary Fig. 1. Author keywords that referred to the country of the research, or an ecosystem type/location particular to the research, were excluded from the analysis.

Data availability

The bibliographic text files, Global Water Security Index data and data used to generate the figures in this paper can be accessed at https://doi.org/10.5281/zenodo.10426552. The source data for the other vulnerability indices can be obtained from the following pages: Gini Index: https://data.worldbank.org/indicator/SI.POV.GINI Legatum Prosperity Index: https://www.prosperity.com/about-prosperity/prosperity-index Global Food Security Index: https://impact.economist.com/sustainability/project/food-security-index/download-the-index.

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Author contributions
T.D. and D.K. conceived the study. T.D. conceptualised the approaches taken for analysing the research landscape and developing research pathways. D.K. and M.H. designed and conducted the analysis. T.D. post-processed the results. E.C.S. reviewed the methodology and assignment of IUCN societal challenges. T.D. and D.K. designed the figures. D.K., E.C.S., W.G. and S.F. supervised the development of the paper. T.D. wrote the original paper. T.D., D.K., E.C.S., W.G., M.H., M.v.d.B., D.R., P.G. and S.F. reviewed the methodology and edited and revised the paper.

Competing interests
The authors declare no competing interests.

Additional information

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