Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

The Evolution and Future of Research on Nature-based Solutions to Address Societal Challenges

Thomas Dunlop
t.dunlop@unsw.edu.au
UNSW Sydney https://orcid.org/0000-0002-0563-8893
Danial Khojasteh
UNSW Sydney
Emmanuelle Cohen-Shacham
International Union for the Conservation of Nature
William Glamore
UNSW Sydney
Milad Haghani
UNSW Sydney
Matilda van den Bosch
ISGlobal
Daniela Rizzi
ICLEI European Secretariat
Peter Greve
Hereon https://orcid.org/0000-0002-9454-0125
Stefan Felder
UNSW Sydney https://orcid.org/0000-0003-1079-6658

Analysis

Keywords:

Posted Date: October 5th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3312024/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: There is **NO** Competing Interest.

Version of Record: A version of this preprint was published at Communications Earth & Environment on March 15th, 2024. See the published version at https://doi.org/10.1038/s43247-024-01308-8.

Abstract

Nature-based Solutions (NbS) are widely recognised for their potential to prevent the ongoing biodiversity and climate crises, and to a lesser extent, address a broader range of societal issues. However, this relationship between nature and society is becoming more important as available food and water resources, income, and health, are increasingly impacted by changes to the environment. In this study, a systematic analysis, utilising the seven major societal challenges addressed by NbS according to IUCN, was undertaken to identify the primary themes of the NbS research landscape from 1990–2021 and evaluate how these themes and the societal challenges that they target, evolved over time, and where. Our findings highlight the under-representation of four societal challenges across the NbS research landscape, namely economic and social development, human health, food security, and water security. We propose six research pathways to advance the scientific basis of NbS in these four societal challenges, and present opportunities for future NbS research programs to prioritise the needs of society, the environment, and the economy.

Introduction

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 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 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[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 and the societal challenges that they target, have evolved over time and location. Seven IUCN[8] societal challenges were assigned to individual research clusters to understand how global issues have targeted NbS research and potential future trajectories. A comparison of the geographical distribution of NbS research and global vulnerability indices is provided to identify regions where societal challenges could be

prioritised. Six research pathways are proposed that help to advance NbS research and address the ongoing societal challenges. These NbS research pathways may 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 inquiry 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 co-existence 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 significant increases in NbS research funding across Europe[25], particularly through the Horizon 2020[44] and Horizon Europe[45, 9] 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 stresses 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 inquiry 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 understudied societal challenges are better represented. Figure 1c 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). 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. 1c). 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, target areas for future research can be identified (Fig. 2b). Figure 2a highlights the high proportion of NbS research, independent of societal challenge, 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[47], and in the case of Europe where significant funding sources for NbS research were established[25].

A history of ecological restoration in response to rapid development in China[48], and to conserve native vegetation in Australia[49], is likely to have contributed to the high proportion of NbS research in these regions. The 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[50]. 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 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 inquiry 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. This indicates that the high overall NbS research production across Europe could be better aligned with economic and social development. Similarly, Africa and South America, regions also prioritised for biodiversity funding[51], present opportunities for future NbS research programs, due to a combination of low index values and existing overall NbS research.

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, suggesting that NbS research in the less vulnerable nations of these regions could be expanded to address issues in neighbouring nations that are more vulnerable. Contrastingly, Africa maintains the lowest index average across these societal challenges combined with a low NbS research production, demonstrating an urgent need for the development of targeted NbS research.

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, provided funding is granted. 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. The derivation of index values (which includes factors for resilience to disasters and climate change) has not been possible for most Pacific Island nations, which may be vulnerable to the effects of sea level rise impacting health, water quality, and food availability[52].

Discussion

Results from the systematic analysis highlight that NbS research (Fig. 1) has primarily focused on climate change and biodiversity loss. However, 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 these 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 provides an opportunity for prioritising and funding future research in select regions where it is needed most.

To establish these understudied societal challenges as primary subjects of inquiry 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, the importance of building on the current NbS foundations and expanding the research focus into the four understudied societal challenges is discussed. Strategies needed to advance NbS research are presented in Fig. 3, including key research pathways for supporting the scientific basis of NbS, namely:

1. Maintain research on the foundations of the NbS research landscape (NbS addressing climate change, biodiversity loss, and disaster risk);
2. Expand existing studies to consider the impacts of NbS on all societal challenges, and across different contexts;
3. Pilot and experiment with applied new projects to complement theoretical research on understudied societal challenges;
4. Innovate with alternative ideas and solutions to obtain causal evidence for using NbS across sectors;
5. Re-assign research foci to target regions with greatest vulnerability to societal challenges; and
6. Connect scientific evidence from past literature in understudied societal challenges (e.g., agroforestry) to support NbS research.

Economic and social development

The relationship between human activities and the environment can be established by adopting a nature-positive economy (NPE) pathway. An NPE encompasses a holistic approach that goes beyond minimising negative impacts and instead focuses on generating positive outcomes for biodiversity, ecosystems, and people[53]. This is achieved by integrating ecological considerations into socioeconomic development, leading

to a more sustainable and resilient future. It acknowledges the interdependence between healthy ecosystems, thriving economies, and the well-being of communities, fostering a balanced and inclusive approach to progress. When implemented effectively through NbS, it can stimulate job creation, and inclusive and equitable economic development. This pathway has the potential for NbS to support income resilience and social justice in vulnerable regions and future-proof less vulnerable regions from potential unforeseen impacts (see pathway 5 in Fig. 3). However, more research is needed to address the lack of consensus on the definition and conceptual framework of NPE. To advance knowledge on the NPE concept and its market potential, research is needed in sectors such as agri-food, blue economy, forestry, built-environment, and tourism.

To deliver NbS for an NPE, capacity building for the private sector has been identified as crucial[53]. This includes skill building to boost the activities provided by nature-based enterprises (NBEs)[54]. These activities deliver NbS as services and projects, creating new jobs, developing new areas of knowledge and expertise, and fostering innovation, leading to broader socio-economic impacts. While the potential of NBEs in contributing to a just transition and generating economic benefits is recognised, further research is needed[25]. Studies should explore the unique characteristics of NBEs compared to other organisations, across sectors, regions, and scales. Understanding success factors, barriers, and the fit between innovation ecosystems and the needs of NBEs, requires additional theoretical and empirical research, especially in terms of financing and scaling mechanisms.

Applied research is recommended through pilot projects (see pathway 3 in Fig. 3) 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. Local and Indigenous communities and knowledge, cultural considerations, socio-economic dynamics, and environmental characteristics need to be carefully assessed and integrated into the implementation of nature-positive approaches to ensure their effectiveness and suitability for the specific region. In such pilots, collaboration amongst a diverse range of stakeholders across industry value chains that consider the restoration of nature, is key to validate the NPE concept, explore its market potential, and pilot solutions that align with market drivers. By implementing and researching pilots, it becomes possible to demonstrate the practical application of the nature-positive dimension of NbS and perform assessments of feasibility and effectiveness.

Human health

Health research funding agencies should prioritise the field of NbS given its impact and opportunities for evidence that may contribute to win-win-win situations between health, the economy, and the environment. This inherently implies that transdisciplinary research with involvement of stakeholders from the start of the process must be supported and include interdisciplinary institutes across the globe, representing populations across income spectra and in different geographical and climate contexts. Studies on urbanising areas in regions with 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[55], should be prioritised for maximum health impact (see pathway 5 in Fig. 3). The range of Prosperity Index values present in Asia and North America means that existing datasets and research from countries with more favourable indices within these regions could be utilised to expand research to directly address challenges in countries with less favourable indices (see pathway 2 in Fig. 3).

To support the use of NbS in the health sector, causal evidence is needed and can be achieved through new research using new data, with the implementation of longitudinal studies. While NbS have the potential to provide significant benefits over time, quick fixes with immediate measurable effects are unlikely. This is why support must be provided for long-term follow-up studies. To identify mechanisms for the use of NbS in the health sector, innovative research designs and methods are required (see pathway 4 in Fig. 3). These could include collaborations with urban planners or engineers to conduct randomised, controlled NbS trials to significantly reduce the risk of bias and thereby provide stronger proof for the efficiency and impact of NbS.

When implementing NbS, experimental studies (see pathway 3 in Fig. 3) are recommended to understand the biological mechanisms between various NbS and health outcomes. Such trials could, for example, analyse specific components of nature, including biodiversity, to assess impact on the human microbiome and subsequent health effects[56]. 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, 57]. This would likely result in increased awareness in policy and decision-making, leading to better acceptance of NbS for several health challenges.

Food security

The reciprocal nature of food systems to both impact and be impacted by climate-induced hazards, water insecurity, and economic downturns, means that research targeting multiple societal challenges is critical to NbS supporting food security. For instance, considering how degraded farmlands can be reverted to biodiverse ecosystems to restore the protective benefits from floods and drought, without compromising the

available land for agriculture. The complex dynamics between land use and agriculture have been identified as NbS research hotspots[58], with ecosystems continually requiring conversion to agriculture to sustain the growing global population[59, 60]. 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[61] (see pathway 4 in Fig. 3). Further, NbS research that partners with Indigenous communities has the potential to utilise traditional, local knowledge to develop climate and disease resilient crops for enhancing sustainable food systems[62].

By considering food systems through a resilience lens, transformative pathways have been 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[63]. 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 (see pathway 5 in Fig. 3) and re-establishing those in regions that have suffered the most from the effects of climate change and violent conflicts[64]. However, with a global economy that relies on trade between regions, undertaking NbS research in a range of climatic zones can help support the global food industry and the consumers during periods of transitory food insecurity[65].

Water security

To ensure a sufficient water supply under conditions of high demand, further research on the effectiveness of NbS is needed, such as research that addresses the transition from existing grey infrastructure (e.g., concrete channels) to the use of sustainable measures through natural ecosystems. This includes understanding how NbS can replace planned or existing grey infrastructure while enabling a safe, reliable, and just water supply, and how NbS and/or hybrid solutions (combining green and grey elements) can mitigate the environmental impacts of and complement existing large-scale grey infrastructure. Such studies could focus on the aspects of NbS that restore river and habitat connectivity, improve flood and drought resilience, and reduce groundwater and streamflow depletion. Raising awareness and effectively communicating the advantages and disadvantages of NbS is crucial for decision-making, particularly among water engineers and managers who have traditionally prioritised technological solutions to achieve water security.

Evaluating how NbS can achieve these benefits for more sustainable water management in the long-term is crucial to community health and economic livelihoods. Research considering the long-term benefits, costs, and potential drawbacks of water-specific NbS is needed. With flood and drought durations increasing amidst rapid climate change[66, 67], long-term field trials (see pathway 3 in Fig. 3) are needed to establish the boundary conditions for NbS to increase the resilience of certain regions to the impacts of both floods and drought, and how this effectiveness will differ with ongoing global change. Regions with high water-policy challenges[68], 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 (see pathway 5 in Fig. 3). Further, local solutions must be evaluated and upscaled to assess their feasibility across different landscapes and socioeconomic systems. At the same time, any implementation of NbS requires adequate monitoring across different spatial and temporal scales.

The long-term influence of NbS to address water scarcity has direct benefits to agricultural production and irrigation water availability. 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. For example, 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, energy production, and economic development (see pathway 2 in Fig. 3).

Further considerations

Global affiliations and vulnerability indices

The development of the research production map in Fig. 2a is based on the assignment of author affiliations from bibliographic data. However, this may not always accurately represent the countries that are targeted in the research. For example, a study undertaken by researchers in one country will be assigned to the relevant region, although it may take place in a case study elsewhere. To evaluate more precisely how NbS research targets nations with greater vulnerability to the societal challenges, future studies could complement the distribution of research production with manual reviews of case studies and fieldwork locations for each paper, as well as with the research agencies funding the research.

In addition, the vulnerability indices used in this study present a starting point for recommending where future NbS research should be focused, but do not include all nations equally. For example, many nations in the Pacific Islands do not have available data for inclusion in the development of the indices, and thus the vulnerability for Oceania is often skewed towards that of larger nations, such as Australia, New

Zealand, and Papua New Guinea. Therefore, obtaining vulnerability data at a regional scale would help identify the nations that would gain the most benefit from NbS research in each societal challenge.

Alternative terminology

For each of the societal challenges considered in this study, a considerable amount of academic literature exists using alternative terminology that may not be directly linked to the NbS concept. Developing connections between existing literature and the NbS concept is needed to ensure that existing knowledge is captured and used to expand the current state of NbS research (see pathway 6 in Fig. 3). 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[69].

Methods

Data Analysis

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[70].

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.

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

Search Term*	Reference for Definition	Associated Societal Challenges based on Definition of Term	Approximate Percentage of Total Dataset
Nature-based solutions	Cohen-Shacham et al., 2016[1]	All	10%
Ecological restoration	Society for Ecological Restoration, 2004[71]	All	40%
Green infrastructure	European Commission, 2013[72]	All	20%
Ecosystem restoration / Ecosystem-based restoration	UNEP, 2021[73]	All	10%
Ecological engineering / Eco-engineering	Mitsch, 2012[74]	All	8%
Urban greening	Dorst et al., 2019[75]	All	4%
Ecosystem-based approach	HELCOM & OSPAR, 2003[76] (related to ecosystem approach)	All, with a focus on climate change mitigation and adaptation	4%
Engineering with nature	USACE, 2012[77]	All	4%
Building with nature	de Vriend and van Koningsveld, 2012[78]	All	
Ecosystem-based adaptation#	CBD, 2009[79]	All, with a focus on climate change mitigation and adaptation	
Natural infrastructure#	Benedict and McMahon, 2006[80]	All, with a focus on climate change mitigation and adaptation	
Working with nature	PIANC, 2011[81]	All	
Working with natural processes#	Environment Agency, 2017[82]	All, with a focus on disaster risk reduction	
Soft engineering#	Hartig et al., 2011[83]	All, with a focus on disaster risk reduction	

*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.

#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.

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 significant 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.

Table 2
Impact that other terms targeting individual societal challenges would have on the original dataset if included in the search query.

Search Term	Reference for Definition	Associated Societal Challenges Based on Definition	Approximate Percentage Increase to Dataset When Term is Added to Initial Search Query
Natural climate solution	Griscom et al., 2017[84]	Climate change mitigation and adaptation	< 1%
Ecosystem-based mitigation	CBD, 2010[85]	Climate change mitigation and adaptation	< 1%
Ecosystem-based disaster risk reduction	PEDRR, 2010[86]	Disaster risk reduction	< 1%
Ecosystem approach to disaster risk reduction	Gupta and Nair, 2012[87]	Disaster risk reduction	< 1%
Ecosystem-based coastal protection / defence	Temmerman et al., 2013[88]	Disaster risk reduction	< 1%
Natural flood management	Forbes et al., 2015[89]	Disaster risk reduction	< 1%
Green economy	UNEP, 2011[90]	Economic and social development	12%
Green finance / Green financial products	Lindenberg, 2014[91]	Economic and social development	< 1%
Green growth	IISD, 2005[92]	Economic and social development	7%
Natural capital	Costanza et al., 1997[93]	Economic and social development	15%
Nature positive economy	WWF, 2022[94]	Economic and social development	< 1%
Ecological economics	Costanza, 1989[95]	Economic and social development	24%
Nature-based health interventions	Shanahan et al., 2019[96]	Human health	< 1%
Agroforestry	Sinclair, 2004[97]	Food security	53%
Agroecology	Gliessman, 2018[98]	Food security	16%
Permaculture	Mollison et al., 1991[99]	Food security	2%
Regenerative agriculture	Regenerative Agriculture Initiative and The Carbon Underground, 2017[100]	Food security	< 1%
Agronomy	Encyclopedia Britannica, 2021[101]	Food security	20%
Organic agriculture	IFOAM, 2008[102]	Food security	19%
Conservation agriculture	FAO, 2022[103]	Food security	12%
Natural regeneration	Brown, 2004[104]	Food security	24%
Evergreen agriculture	Garrity et al., 2010[105]	Food security	< 1%
Climate-smart agriculture	FAO, 2013[106]	Food security	4%

Search Term	Reference for Definition	Associated Societal Challenges Based on Definition	Approximate Percentage Increase to Dataset When Term is Added to Initial Search Query
Forest landscape restoration	Mansourian et al., 2005[107] Maginnis et al., 2014[108]	Environmental degradation and biodiversity loss	1%

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, 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 do not have significant 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[109]. This analysis uses exported text files of bibliographic data, from a database such as the Web of Science, in conjunction with the CiteSpace software[110] 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 belong to other clusters[111]. 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 largest number of references, and cluster 17. "Air quality" contained the smallest). Each research cluster was initially labelled in CiteSpace using an algorithm based on burst terms extracted from the bibliographic data of the cited references[110]. 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.

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 1,200 and 1,300 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 significantly 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 significantly 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 in NbS Research

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.

Global Vulnerability

Distribution of Author Affiliations

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.

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[112] for economic and social development
- Legatum Prosperity Index[113] for human health
- Global Food Security Index[114] for food security
- Global Water Security Index[115] 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 was 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 one 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[116] 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.

Declarations

Author Contribution Statement

TD and DK conceived the study. TD conceptualised the approaches taken for analysing the research landscape and developing research pathways. DK and MH designed and conducted the analysis. TD post-processed the results. ECS reviewed the methodology and assignment of IUCN societal challenges. TD and DK designed the figures. DK, ECS, WG, and SF supervised the development of the paper. TD wrote the original paper. TD, DK, ECS, WG, MH, MvdB, DR, PG, LL, and SF reviewed the methodology, and edited and revised the paper.

Acknowledgements

The authors thank Animesh Gain for providing Global Water Security Index data for the global vulnerability assessment. We thank IUCN for permitting the inclusion of the NbS societal challenge icons in our study. We also thank Abbas Shamsipour for assistance with figure conceptualisation. MvdB acknowledges support from the grant CEX2018-000806-S funded by MCIN/AEI/10.13039/501100011033, and support from the Generalitat de Catalunya through the CERCA Program.

References

1. COHEN-SHACHAM, E., WALTERS, G., JANZEN, C., MAGINNIS, S. (EDS) 2016. Nature-based Solutions to address global societal challenges. 978-2-8317-1812-5. Gland, Switzerland: IUCN. http://dx.doi.org/10.2305/IUCN.CH.2016.13.en.
2. UNEP 2022. Resolution adopted by the United Nations Environment Assembly on 2 March 2022. 5/5. Nature-based solutions for supporting sustainable development. United Nations Environment Assembly of the United Nations Environment Programme. Nairobi: UNEP.
3. MACE, G. M. 2014. Whose conservation? Science, 345, 1558-1560.
4. PAN, H., PAGE, J., SHI, R., CONG, C., CAI, Z., BARTHEL, S., THOLLANDER, P., COLDING, J. & KALANTARI, Z. 2023. Contribution of prioritized urban nature-based solutions allocation to carbon neutrality. Nature Climate Change, 13, 862-870.
5. DEPIETRI, Y. & MCPHEARSON, T. 2017. Integrating the Grey, Green, and Blue in Cities: Nature-Based Solutions for Climate Change Adaptation and Risk Reduction. In: KABISCH, N., KORN, H., STADLER, J. & BONN, A. (eds.) Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice. Cham: Springer International Publishing.
6. ZHU, Z., VUIK, V., VISSER, P. J., SOENS, T., VAN WESENBEECK, B., VAN DE KOPPEL, J., JONKMAN, S. N., TEMMERMAN, S. & BOUMA, T. J. 2020. Historic storms and the hidden value of coastal wetlands for nature-based flood defence. Nature Sustainability, 3, 853-862.
7. XIE, L. & BULKELEY, H. 2020. Nature-based solutions for urban biodiversity governance. Environmental Science & Policy, 110, 77-87.
8. IUCN 2020. Global Standard for Nature-based Solutions. A user-friendly framework for the verification, design and scaling up of NbS. 978-2-8317-2058-6. Gland, Switzerland. https://doi.org/10.2305/IUCN.CH.2020.08.en.
9. EUROPEAN COMMISSION 2021. Evaluating the impact of nature-based solutions: A summary for policy makers, Publications Office. doi/10.2777/521937.
10. MIJATOVIĆ, D., VAN OUDENHOVEN, F., EYZAGUIRRE, P. & HODGKIN, T. 2013. The role of agricultural biodiversity in strengthening resilience to climate change: towards an analytical framework. International Journal of Agricultural Sustainability, 11, 95-107.
11. MCGREEVY, S. R., RUPPRECHT, C. D. D., NILES, D., WIEK, A., CAROLAN, M., KALLIS, G., KANTAMATURAPOJ, K., MANGNUS, A., JEHLIČKA, P., TAHERZADEH, O., SAHAKIAN, M., CHABAY, I., COLBY, A., VIVERO-POL, J.-L., CHAUDHURI, R., SPIEGELBERG, M., KOBAYASHI, M., BALÁZS, B., TSUCHIYA, K., NICHOLLS, C., TANAKA, K., VERVOORT, J., AKITSU, M., MALLEE, H., OTA, K., SHINKAI, R., KHADSE, A., TAMURA, N., ABE, K.-I., ALTIERI, M., SATO, Y.-I. & TACHIKAWA, M. 2022. Sustainable agrifood systems for a post-growth world. Nature Sustainability.
12. RAO, N. D. & WILSON, C. 2022. Advancing energy and well-being research. Nature Sustainability, 5, 98-103.
13. SEDDON, N., CHAUSSON, A., BERRY, P., GIRARDIN, C. A. J., SMITH, A. & TURNER, B. 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philosophical Transactions of the Royal Society B: Biological Sciences, 375, 20190120.
14. DEBROT, A. O., PLAS, A., BOESONO, H., PRIHANTOKO, K., BAPTIST, M. J., MURK, A. J. & TONNEIJCK, F. H. 2022. Early increases in artisanal shore-based fisheries in a Nature-based Solutions mangrove rehabilitation project on the north coast of Java. Estuarine, Coastal and Shelf Science, 267, 107761.
15. ILO-UNEP-IUCN 2022. Decent Work in Nature-based Solutions 2022. Geneva. https://www.ilo.org/wcmsp5/groups/public/---ed_emp/documents/publication/wcms_863035.pdf
16. BOYLE, A. & KUHL, L. 2021. Nature-based Solutions are Job and Livelihood Solutions. Nature-based Solutions Policy Briefs.
17. SUN, Q., JORGENSEN, ANNA, CORCORAN, AMY 2022. An investigation into the value of design in nature-based solutions for health and wellbeing in a post-COVID world. AMPS Proceedings Journal Series.
18. BOMMARCO, R., KLEIJN, D. & POTTS, S. G. 2013. Ecological intensification: harnessing ecosystem services for food security. Trends in Ecology & Evolution, 28, 230-238.
19. OPPERMAN, J., OYARE, E., BALETA, H., FAHRBACH, S., CAMARGO, R. 2021. Waterways to Resilience: Nature-based Solutions for Adaptation in Africa. Gland, Switzerland: WWF-International. https://wwfint.awsassets.panda.org/downloads/waterways_to_resilience_naturebased_solutions_wwfabinbev.pdf
20. LIEUW-KIE-SONG, M. & PEREZ-CIRERA, V. 2020. Nature hires: how nature-based solutions can power a green jobs recovery. Geneva: ILO and World Wide Fund for Nature.
21. UNITED NATIONS 2022. The Sustainable Development Goals Report 2022. United Nations,. https://unstats.un.org/sdgs/report/2022/The-Sustainable-Development-Goals-Report-2022.pdf
22. WWF 2022. Nature Based Solutions - a review of current financing barriers and how to overcome these. https://www.wwf.org.uk/sites/default/files/2022-06/WWF-NBS-Public-Report-Final-270622.pdf
23. SARI, R., SOYTAS, U., KANOGLU-OZKAN, D. G. & SIVRIKAYA, A. 2023. Improving the climate resilience of European cities via socially acceptable nature-based solutions. npj Urban Sustainability, 3, 9.

24. SONNEVELD, B. G. J. S., MERBIS, M.D., ALFARRA, A., ÜNVER, O., ARNAL, M.A 2018. Nature-Based Solutions for Agricultural Water Management and Food Security. FAO Land and Water Discussion Paper. Rome, Italy.
25. EL HARRAK, M., LEMAITRE, F. 2023. Draft European Roadmap for Research and Innovation on Nature-based Solutions. NetworkNature. https://networknature.eu/sites/default/files/images/NetworkNature_Draft_EU_RI_Roadmap_on_NBS.pdf
26. UNEP AND ELD 2022. State of Finance for Nature. Time to act: Doubling investment by 2025 and eliminating nature-negative finance flows. Nairobi. https://wedocs.unep.org/20.500.11822/41333
27. WHITE HOUSE COUNCIL ON ENVIRONMENTAL QUALITY, W. H. O. O. S. A. T. P., WHITE HOUSE DOMESTIC CLIMATE POLICY OFFICE 2022. Opportunities for Accelerating Nature-Based Solutions: A Roadmap for Climate Progress, Thriving Nature, Equity, and Prosperity. Report to the National Climate Task Force. Washington, D.C. https://www.whitehouse.gov/wp-content/uploads/2022/11/Nature-Based-Solutions-Roadmap.pdf
28. UNITED NATIONS 2015. Transforming our World: The 2030 Agenda for Sustainable Development. https://sdgs.un.org/sites/default/files/publications/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf
29. UNITED NATIONS 2015. Paris Agreement. United Nations. https://unfccc.int/sites/default/files/english_paris_agreement.pdf
30. BAKHTARY, H., HAUPT, F., ELBRECHT, J. 2021. NDCs - A Force for Nature? Nature in Enhanced NDCs. United Kingdom: WWF-UK. https://wwfint.awsassets.panda.org/downloads/wwf_ndcs_for_nature_4th_edition.pdf
31. SEDDON, N., SENGUPTA, S., GARCÍA-ESPINOSA, M., HAULER, I., HERR, D. & RIZVI, A. R. 2019. Nature-based solutions in nationally determined contributions. IUCN and University of Oxford. Gland, Switzerland and Oxford.
32. DONTHU, N., KUMAR, S., MUKHERJEE, D., PANDEY, N. & LIM, W. M. 2021. How to conduct a bibliometric analysis: An overview and guidelines. Journal of Business Research, 133, 285-296.
33. CHAUSSON, A., TURNER, B., SEDDON, D., CHABANEIX, N., GIRARDIN, C. A. J., KAPOS, V., KEY, I., ROE, D., SMITH, A., WORONIECKI, S. & SEDDON, N. 2020. Mapping the effectiveness of nature-based solutions for climate change adaptation. Global Change Biology, 26, 6134-6155.
34. RUANGPAN, L., VOJINOVIC, Z., DI SABATINO, S., LEO, L. S., CAPOBIANCO, V., OEN, A. M. P., MCCLAIN, M. E. & LOPEZ-GUNN, E. 2020. Nature-based solutions for hydro-meteorological risk reduction: a state-of-the-art review of the research area. Nat. Hazards Earth Syst. Sci., 20, 243-270.
35. COUSINS, J. J. 2021. Justice in nature-based solutions: Research and pathways. Ecological Economics, 180, 106874.
36. DICK, J., CARRUTHERS-JONES, J., CARVER, S., DOBEL, A. J. & MILLER, J. D. 2020. How are nature-based solutions contributing to priority societal challenges surrounding human well-being in the United Kingdom: a systematic map. Environmental Evidence, 9, 25.
37. VAN DEN BOSCH, M. & ODE SANG, Å. 2017. Urban natural environments as nature-based solutions for improved public health – A systematic review of reviews. Environmental Research, 158, 373-384.
38. ESCOBEDO, F. J., GIANNICO, V., JIM, C. Y., SANESI, G. & LAFORTEZZA, R. 2019. Urban forests, ecosystem services, green infrastructure and nature-based solutions: Nexus or evolving metaphors? Urban Forestry & Urban Greening, 37, 3-12.
39. GOODWIN, S., OLAZABAL, M., CASTRO, A. J. & PASCUAL, U. 2023. Global mapping of urban nature-based solutions for climate change adaptation. Nature Sustainability.
40. KONG, X., ZHANG, X., XU, C. & HAUER, R. J. 2021. Review on Urban Forests and Trees as Nature-Based Solutions over 5 Years. Forests [Online], 12.
41. LI, L., CHESHMEHZANGI, A., CHAN, F. K. & IVES, C. D. 2021. Mapping the Research Landscape of Nature-Based Solutions in Urbanism. Sustainability, 13.
42. NYIKA, J. & DINKA, M. O. 2022. Integrated approaches to nature-based solutions in Africa: Insights from a bibliometric analysis. Nature-Based Solutions, 2, 100031.
43. UNFCCC 2011. The Cancun Agreements: Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention. Report of the Conference of the Parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010. Cancun: United Nations Framework Convention on Climate Change. https://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf
44. MAES, J. & JACOBS, S. 2017. Nature-Based Solutions for Europe's Sustainable Development. Conservation Letters, 10, 121-124.
45. EUROPEAN COMMISSION 2020. Commission welcomes political agreement on Horizon Europe, the next EU research and innovation programme. European Commission.
46. IPCC 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA. 10.1017/9781009157896.
47. COLLYER, F. M. 2016. Global patterns in the publishing of academic knowledge: Global North, global South. Current Sociology, 66, 56-73.

48. OUYANG, Z., ZHENG, H., XIAO, Y., POLASKY, S., LIU, J., XU, W., WANG, Q., ZHANG, L., XIAO, Y., RAO, E., JIANG, L., LU, F., WANG, X., YANG, G., GONG, S., WU, B., ZENG, Y., YANG, W. & DAILY, G. C. 2016. Improvements in ecosystem services from investments in natural capital. Science, 352, 1455-1459.
49. TRIGGER, D., MULCOCK, J., GAYNOR, A. & TOUSSAINT, Y. 2008. Ecological restoration, cultural preferences and the negotiation of 'nativeness' in Australia. Geoforum, 39, 1273-1283.
50. EUROPEAN COMMISSION & DIRECTORATE-GENERAL FOR RESEARCH AND INNOVATION, H., C., ANTUÑA ROZADO, C., FREITAS, T., ENFEDAQUE, J., WIEDMAN, G. 2019. The EU–Brazil sector dialogue on nature-based solutions : contribution to a Brazilian roadmap on nature-based solutions for resilient cities, Publications Office of the European Union. doi/10.2777/569867.
51. CUMING, V., BROMLEY, H. 2023. Biodiversity Finance Factbook. BloombergNEF. https://assets.bbhub.io/professional/sites/24/REPORT_Biodiversity_Finance_Factbook_master_230321.pdf
52. OPPENHEIMER, M., GLAVOVIC, B., HINKEL, J., VAN DE WAL, R., MAGNAN, A. K., ABD-ELGAWAD, A., CAI, R., CIFUENTES-JARA, M., DECONTO, R. M., GHOSH, T., HAY, J., ISLA, F., MARZEION, B., MEYSSIGNAC, B. & SEBESVARI, Z. 2019. Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge: Cambridge University Press.
53. EUROPEAN COMMISSION & DIRECTORATE-GENERAL FOR RESEARCH INNOVATION 2022. The vital role of nature-based solutions in a nature positive economy, Publications Office of the European Union. doi/10.2777/307761.
54. KOOIJMAN, E. D., MCQUAID, S., RHODES, M.-L., COLLIER, M. J. & PILLA, F. 2021. Innovating with Nature: From Nature-Based Solutions to Nature-Based Enterprises. Sustainability [Online], 13.
55. MODA, H. M., FILHO, W. L. & MINHAS, A. 2019. Impacts of Climate Change on Outdoor Workers and Their Safety: Some Research Priorities. International Journal of Environmental Research and Public Health [Online], 16.
56. GRÖNROOS, M., PARAJULI, A., LAITINEN, O. H., ROSLUND, M. I., VARI, H. K., HYÖTY, H., PUHAKKA, R. & SINKKONEN, A. 2019. Short-term direct contact with soil and plant materials leads to an immediate increase in diversity of skin microbiota. MicrobiologyOpen, 8, e00645.
57. TAMBYAH, R., OLCOŃ, K., ALLAN, J., DESTRY, P. & ASTELL-BURT, T. 2022. Mental health clinicians' perceptions of nature-based interventions within community mental health services: evidence from Australia. BMC Health Services Research, 22, 841.
58. BUNCLARK, L. & HERNÁNDEZ, I. M. D. L. V. 2022. Scientific Mapping of Research on Nature-based Solutions for Sustainable Water Management. Water Resources Management.
59. TSCHARNTKE, T., CLOUGH, Y., WANGER, T. C., JACKSON, L., MOTZKE, I., PERFECTO, I., VANDERMEER, J. & WHITBREAD, A. 2012. Global food security, biodiversity conservation and the future of agricultural intensification. Biological Conservation, 151, 53-59.
60. POTAPOV, P., TURUBANOVA, S., HANSEN, M. C., TYUKAVINA, A., ZALLES, V., KHAN, A., SONG, X.-P., PICKENS, A., SHEN, Q. & CORTEZ, J. 2022. Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. Nature Food, 3, 19-28.
61. BLASER, W. J., OPPONG, J., HART, S. P., LANDOLT, J., YEBOAH, E. & SIX, J. 2018. Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. Nature Sustainability, 1, 234-239.
62. ANTONELLI, A. 2023. Indigenous knowledge is key to sustainable food systems. Nature, 613, 239-242.
63. WOOD, A., QUEIROZ, C., DEUTSCH, L., GONZÁLEZ-MON, B., JONELL, M., PEREIRA, L., SINARE, H., SVEDIN, U. & WASSÉNIUS, E. 2023. Reframing the local–global food systems debate through a resilience lens. Nature Food, 4, 22-29.
64. QUEIROZ, C., NORSTRÖM, A. V., DOWNING, A., HARMÁČKOVÁ, Z. V., DE CONING, C., ADAMS, V., BAKARR, M., BAEDEKER, T., CHITATE, A., GAFFNEY, O., GORDON, L., HAINZELIN, É., HOWLETT, D., KRAMPE, F., LOBOGUERRERO, A. M., NEL, D., OKOLLET, C., REBERMARK, M., ROCKSTRÖM, J., SMITH, M., WABBES-CANDOTTI, S. & MATTHEWS, N. 2021. Investment in resilient food systems in the most vulnerable and fragile regions is critical. Nature Food, 2, 546-551.
65. FAO 2008. An Introduction to the Basic Concepts of Food Security. Food Security Information for Action: Practical Guides. FAO. https://www.fao.org/3/al936e/al936e00.pdf
66. ARNELL, N. W. & GOSLING, S. N. 2016. The impacts of climate change on river flood risk at the global scale. Climatic Change, 134, 387-401.
67. CHIANG, F., MAZDIYASNI, O. & AGHAKOUCHAK, A. 2021. Evidence of anthropogenic impacts on global drought frequency, duration, and intensity. Nature Communications, 12, 2754.
68. GREVE, P., KAHIL, T., MOCHIZUKI, J., SCHINKO, T., SATOH, Y., BUREK, P., FISCHER, G., TRAMBEREND, S., BURTSCHER, R., LANGAN, S. & WADA, Y. 2018. Global assessment of water challenges under uncertainty in water scarcity projections. Nature Sustainability, 1, 486-494.
69. LINDGREN, E. & ELMQVIST, T. 2017. Ecosystem Services and Human Health. Oxford Research Encyclopedia of Environmental Science. Oxford University Press.

70. NESSHÖVER, C., ASSMUTH, T., IRVINE, K. N., RUSCH, G. M., WAYLEN, K. A., DELBAERE, B., HAASE, D., JONES-WALTERS, L., KEUNE, H., KOVACS, E., KRAUZE, K., KÜLVIK, M., REY, F., VAN DIJK, J., VISTAD, O. I., WILKINSON, M. E. & WITTMER, H. 2017. The science, policy and practice of nature-based solutions: An interdisciplinary perspective. Science of The Total Environment, 579, 1215-1227.
71. SOCIETY FOR ECOLOGICAL RESTORATION 2004. The SER International Primer on Ecological Restoration. https://www.ser-rrc.org/resource/the-ser-international-primer-on/
72. EUROPEAN COMMISSION 2013. Green Infrastructure (GI) - Enhancing Europe's Natural Capital. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels, Belgium. https://eur-lex.europa.eu/resource.html?uri=cellar:d41348f2-01d5-4abe-b817-4c73e6f1b2df.0014.03/DOC_1&format=PDF
73. UNEP 2021. Becoming #GenerationRestoration: Ecosystem restoration for people, nature and climate. Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/36251/ERPNC.pdf
74. MITSCH, W. J. 2012. What is ecological engineering? Ecological Engineering, 45, 5-12.
75. DORST, H., VAN DER JAGT, A., RAVEN, R. & RUNHAAR, H. 2019. Urban greening through nature-based solutions – Key characteristics of an emerging concept. Sustainable Cities and Society, 49, 101620.
76. HELCOM & OSPAR 2003. Statement on the Ecosystem Approach to the Management of Human Activities: Towards an Ecosystem Approach to the Management of Human Activities. Bremen. http://archive.iwlearn.net/helcom.fi/stc/files/BremenDocs/JointEcosystemApproach.pdf
77. U.S. ARMY CORPS OF ENGINEERS 2012. Engineering with Nature. https://ewn.erdc.dren.mil/wp-content/uploads/2021/03/EWNFactSheet_Final.pdf
78. DE VRIEND, H. J., VAN KONINGSVELD, M. 2012. Building with Nature: Thinking, acting and interacting differently. 978-94-6190-957-2. Dordrecht, The Netherlands: EcoShape, Building with Nature. https://www.ecoshape.org/app/uploads/sites/2/2016/07/ECOSHAPE_BwN_WEB.pdf
79. CBD 2009. Connecting Biodiversity and Climate Change Mitigation and Adaptation: Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change. Montreal. https://www.cbd.int/doc/publications/cbd-ts-41-en.pdf
80. BENEDICT, M. A., MCMAHON, E. T. & FUND, C. 2006. Green Infrastructure: Linking Landscapes and Communities, Island Press. https://books.google.com.au/books?id=8iZPAAAAMAAJ
81. PIANC 2011. Working with Nature PIANC Position Paper. https://www.pianc.org/wp-content/uploads/2023/06/WwN-Position-Paper-English.pdf
82. ENVIRONMENT AGENCY 2017. Working with Natural Processes to reduce flood risk: The evidence behind Natural Flood Management. United Kingdom. https://assets.publishing.service.gov.uk/media/6036c730d3bf7f0aac939a47/Working_with_natural_processes_one_page_summaries.pdf
83. HARTIG, J. H., ZARULL, M. A. & COOK, A. 2011. Soft shoreline engineering survey of ecological effectiveness. Ecological Engineering, 37, 1231-1238.
84. GRISCOM, B. W., ADAMS, J., ELLIS, P. W., HOUGHTON, R. A., LOMAX, G., MITEVA, D. A., SCHLESINGER, W. H., SHOCH, D., SIIKAMÄKI, J. V., SMITH, P., WOODBURY, P., ZGANJAR, C., BLACKMAN, A., CAMPARI, J., CONANT, R. T., DELGADO, C., ELIAS, P., GOPALAKRISHNA, T., HAMSIK, M. R., HERRERO, M., KIESECKER, J., LANDIS, E., LAESTADIUS, L., LEAVITT, S. M., MINNEMEYER, S., POLASKY, S., POTAPOV, P., PUTZ, F. E., SANDERMAN, J., SILVIUS, M., WOLLENBERG, E. & FARGIONE, J. 2017. Natural climate solutions. Proceedings of the National Academy of Sciences, 114, 11645-11650.
85. CBD 2010. X/33 Biodiversity and climate change, Decision Adopted by the Conference of the Parties to the Convention on Biological Diversity at its Tenth Meeting. Nagoya, Japan: Conference on Biological Diversity. https://www.cbd.int/doc/decisions/cop-10/cop-10-dec-33-en.pdf
86. PARTNERSHIP FOR ENVIRONMENT AND DISASTER RISK REDUCTION (PEDRR) 2010. Demonstrating the Role of Ecosystems-based Management for Disaster Risk Reduction. https://www.preventionweb.net/english/hyogo/gar/2011/en/bgdocs/PEDRR_2010.pdf
87. GUPTA, A. K., NAIR, S.S. 2012. Ecosystem Approach to Disaster Risk Reduction. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=5dab1bb95463e9e91e85739754aa80afaa75add2
88. TEMMERMAN, S., MEIRE, P., BOUMA, T. J., HERMAN, P. M. J., YSEBAERT, T. & DE VRIEND, H. J. 2013. Ecosystem-based coastal defence in the face of global change. Nature, 504, 79-83.
89. FORBES, H., BALL, K., MCLAY, F. 2015. Natural Flood Management Handbook. 978-0-85759-024-4. Stirling, Scotland: Scottish Environment Protection Agency. https://www.sepa.org.uk/media/163560/sepa-natural-flood-management-handbook1.pdf
90. UNEP 2011. Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication - A Synthesis for Policy Makers. www.unep.org/greeneconomy

91. LINDENBERG, N. 2014. Definition of Green Finance. Deutsches Institut fur Entwicklungspolitik. https://www.cbd.int/financial/gcf/definition-greenfinance.pdf
92. INTERNATIONAL INSTITUTE FOR SUSTAINABLE DEVELOPMENT (IISD) 2005. MCED 2005 Bulletin: A summary report of the Fifth Ministerial Conference on Environment and Development in Asia and the Pacific. Seoul, Republic of Korea. https://enb.iisd.org/events/5th-ministerial-conference-environment-and-development-asia-and-pacific-mced-2005/summary
93. COSTANZA, R., D'ARGE, R., DE GROOT, R., FARBER, S., GRASSO, M., HANNON, B., LIMBURG, K., NAEEM, S., O'NEILL, R. V., PARUELO, J., RASKIN, R. G., SUTTON, P. & VAN DEN BELT, M. 1997. The value of the world's ecosystem services and natural capital. Nature, 387, 253-260.
94. WORLD WIDE FUND FOR NATURE (WWF) 2022. Proposal to establish a Roadmap to a Nature Positive Economy. https://wwfint.awsassets.panda.org/downloads/proposal_for_a_roadmap_to_nature_positive_economy_20220603.pdf
95. COSTANZA, R. 1989. What is ecological economics? Ecological Economics, 1, 1-7.
96. SHANAHAN, D. F., ASTELL-BURT, T., BARBER, E. A., BRYMER, E., COX, D. T. C., DEAN, J., DEPLEDGE, M., FULLER, R. A., HARTIG, T., IRVINE, K. N., JONES, A., KIKILLUS, H., LOVELL, R., MITCHELL, R., NIEMELÄ, J., NIEUWENHUIJSEN, M., PRETTY, J., TOWNSEND, M., VAN HEEZIK, Y., WARBER, S. & GASTON, K. J. 2019. Nature-Based Interventions for Improving Health and Wellbeing: The Purpose, the People and the Outcomes. Sports (Basel), 7.
97. SINCLAIR, F. L. 2004. AGROFORESTRY. In: BURLEY, J. (ed.) Encyclopedia of Forest Sciences. Oxford: Elsevier.
98. GLIESSMAN, S. 2018. Defining Agroecology. Agroecology and Sustainable Food Systems, 42, 599-600.
99. MOLLISON, B. C., SLAY, R. M. & JEEVES, A. 1991. Introduction to permaculture, Tyalgum, Australia, Tagari Publications Tyalgum, Australia.
100. REGENERATIVE AGRICULTURE INITIATIVE, T. C. U. 2017. What is Regenerative Agriculture? Chico, California: California State University, Chico. https://02fe55.p3cdn1.secureserver.net/wp-content/uploads/2017/02/Regen-Ag-Definition-7.27.17-1.pdf
101. BRITANNICA, T. E. O. E. 2021. agronomy [Online]. Encyclopedia Britannica. Available: https://www.britannica.com/science/agronomy [Accessed].
102. INTERNATIONAL FEDERATION OF ORGANIC AGRICULTURE MOVEMENTS (IFOAM) 2008. Agenda IFOAM General Assembly 2008. Vignola, Italy. https://archive.ifoam.bio/sites/default/files/ia_97_2008_ga.pdf
103. FAO 2022. Conservation Agriculture. Rome, Italy. https://www.fao.org/3/cb8350en/cb8350en.pdf
104. BROWN, N. 2004. SILVICULTURE | Natural Regeneration of Tropical Rain Forests. In: BURLEY, J. (ed.) Encyclopedia of Forest Sciences. Oxford: Elsevier.
105. GARRITY, D. P., AKINNIFESI, F. K., AJAYI, O. C., WELDESEMAYAT, S. G., MOWO, J. G., KALINGANIRE, A., LARWANOU, M. & BAYALA, J. 2010. Evergreen Agriculture: a robust approach to sustainable food security in Africa. Food Security, 2, 197-214.
106. FAO 2013. Introducing Climate-Smart Agriculture. Climate Smart Agriculture Sourcebook. Food and Agriculture Organization of the United Nations.
107. MANSOURIAN, S., VALLAURI, D., DUDLEY, N. 2005. Forest Restoration in Landscapes: Beyond Planting Trees, Springer New York, NY. https://doi.org/10.1007/0-387-29112-1.
108. MAGINNIS, S., LAESTADIUS, L., VERDONE, M., DEWITT, S., SAINT-LAURENT, C., RIETBERGEN-MCCRACKEN, J., SHAW, D.M.P. 2014. Assessing forest landscape restoration opportunities at the national level: A guide to the Restoration Opportunities Assessment Methodology (ROAM). Gland, Switzerland: International Union for the Conservation of Nature. https://portals.iucn.org/library/sites/library/files/documents/2014-030.pdf
109. CHEN, C. 2004. Searching for intellectual turning points: Progressive knowledge domain visualization. Proceedings of the National Academy of Sciences, 101, 5303-5310.
110. CHEN, C. 2006. CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. Journal of the American Society for Information Science and Technology, 57, 359-377.
111. KHOJASTEH, D., HAGHANI, M., NICHOLLS, R. J., MOFTAKHARI, H., SADAT-NOORI, M., MACH, K. J., FAGHERAZZI, S., VAFEIDIS, A. T., BARBIER, E., SHAMSIPOUR, A. & GLAMORE, W. 2023. The evolving landscape of sea-level rise science from 1990 to 2021. Communications Earth & Environment, 4, 257.
112. CERIANI, L. & VERME, P. 2012. The origins of the Gini index: extracts from Variabilità e Mutabilità (1912) by Corrado Gini. The Journal of Economic Inequality, 10, 421-443.
113. LEGATUM INSTITUTE FOR GLOBAL DEVELOPMENT 2007. The 2007 Legatum Prosperity Index: A Global Assessment of Wealth and Wellbeing. https://www.prosperity.com/download_file/view_inline/2855
114. ECONOMIST, T. 2012. Global Food Security Index 2012: An assessment of food affordability, availability and quality. The Economist Intelligence Unit Limited. https://impact.economist.com/sustainability/project/food-security-index/resource-library

115. GAIN, A. K., GIUPPONI, C. & WADA, Y. 2016. Measuring global water security towards sustainable development goals. Environmental Research Letters, 11, 124015.
116. VAN ECK, N. J., WALTMAN, L. 2006. A New Method for Visualizing Similarities between Objects. ERIM Report Series. Rotterdam, The Netherlands: Erasmus Research Institute of Management. https://ssrn.com/abstract=902749

Figures

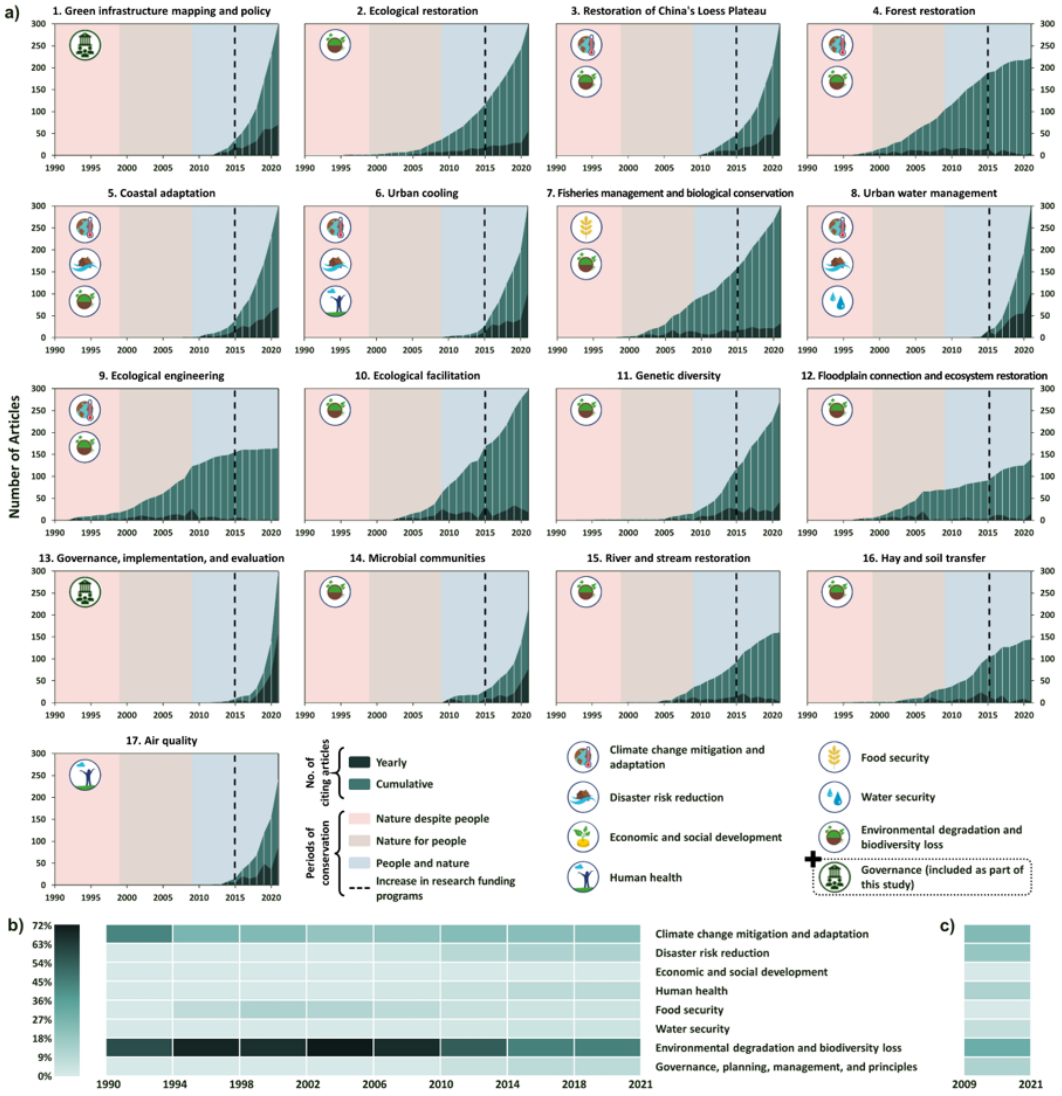


Figure 1

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) proportion of societal challenges that are prevalent across all 17 clusters in 4-year periods from 1990 to 2021; and c) proportion of societal challenges that are prevalent in clusters that emerged during the 'People and nature' conservation period.*

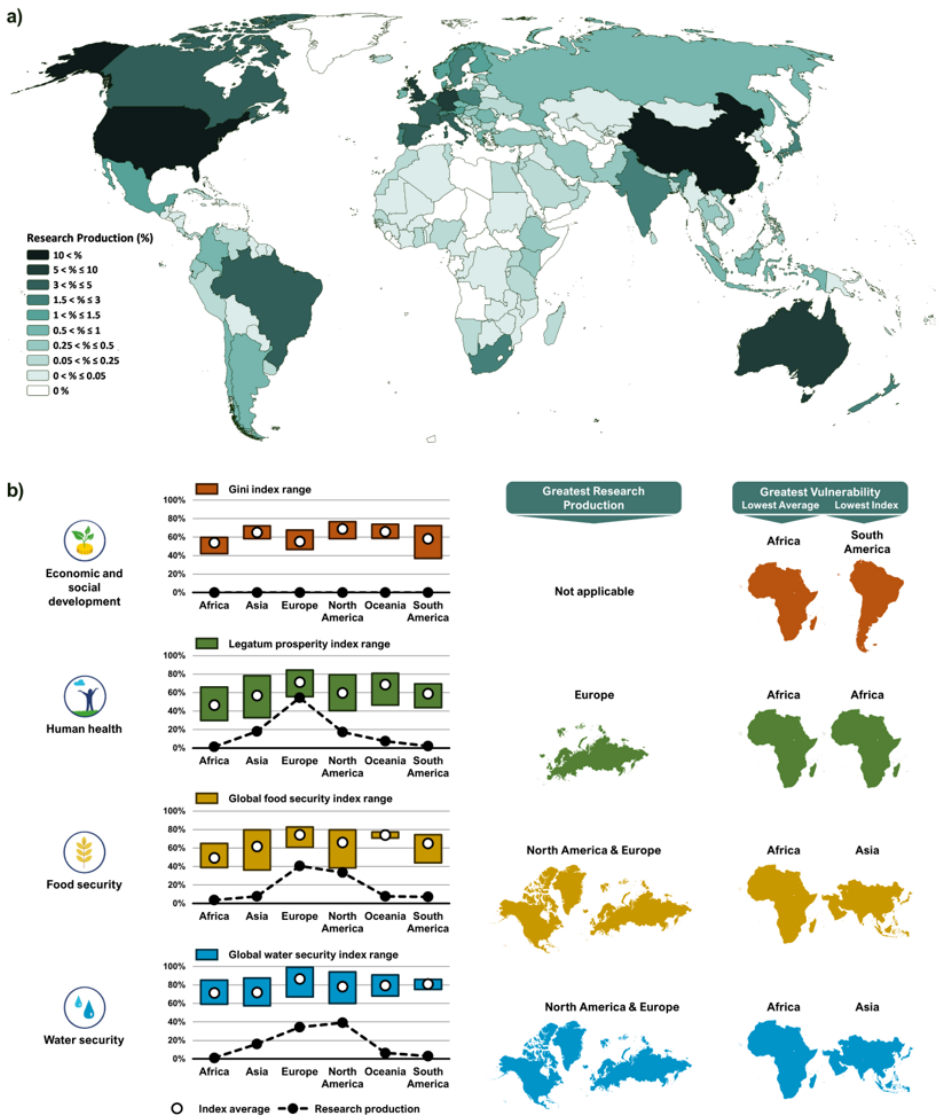


Figure 2

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; and (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]). The regions with the greatest research production and vulnerability are presented visually by their outlines.*

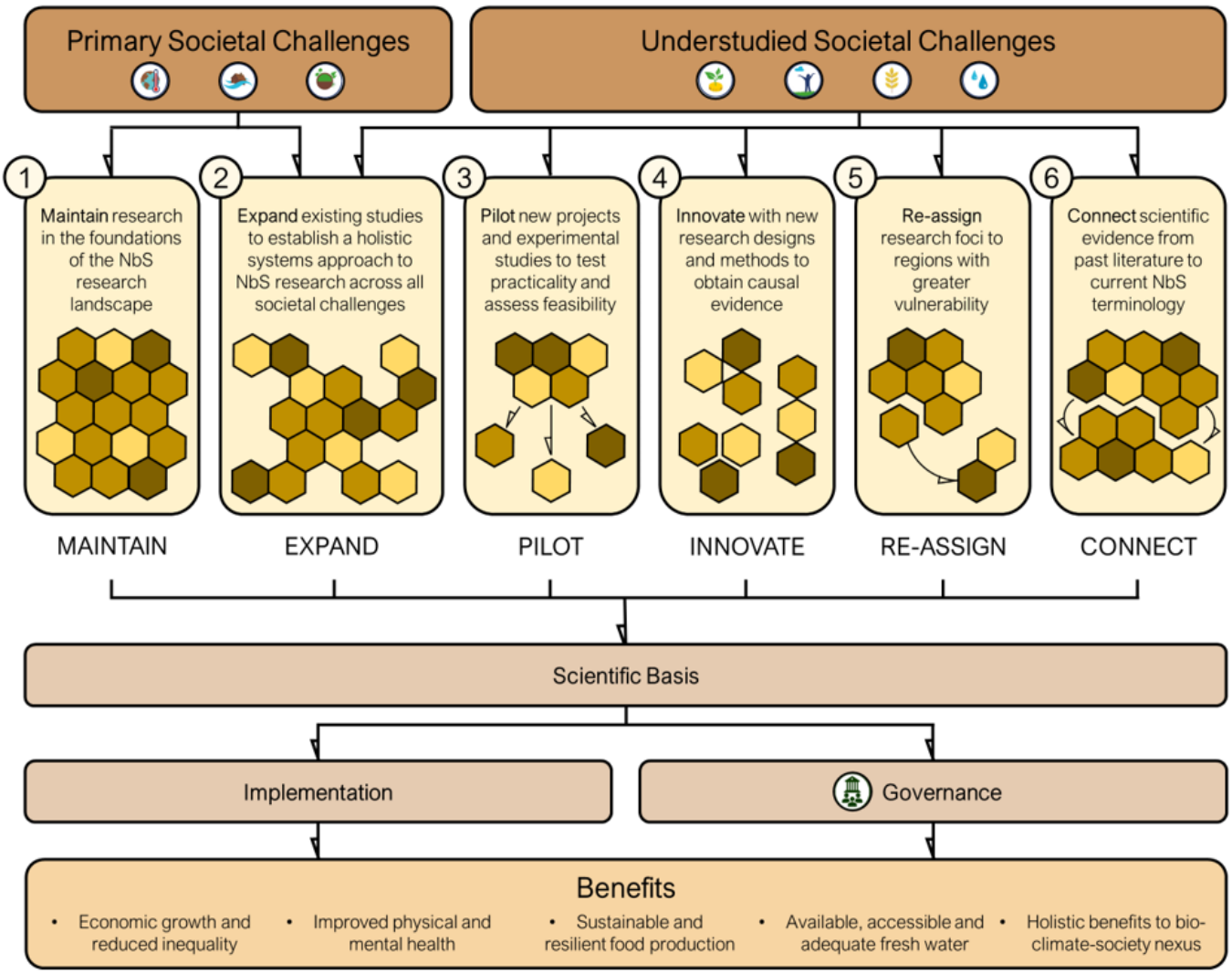


Figure 3

***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.*

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryInformationDunlopetal..pdf