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Review Article

Nature-based solutions for climate and health: mapping synergies and trade-offs

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Abstract

Nature-based solutions (NbS) are considered a promising approach to addressing the climate-health nexus by mitigating and adapting to climate change impacts. They also serve as a bridging concept that delivers multiple benefits for climate, biodiversity and human well-being, including health. However, evidence on how NbS affect people's health and well-being remains scattered and has not been systematically reviewed. In this study, we explore synergies and trade-offs associated with NbS in the context of climate change and public health, based on a literature review. To explore the specific mechanisms through which NbS influence different public health dimensions, we utilise the UN climate change vulnerability framework. Our results show strong evidence that NbS can effectively mitigate climate change impacts, promote ecosystem resilience and improve human well-being by providing multiple benefits, such as enhanced biodiversity, improved air and water quality, increased food security and reduced urban heat island effects. However, trade-offs also exist, such as disruptions to local biodiversity and increased resource demands, which can lead to unintended negative consequences, like water scarcity and competition for land. We emphasise the importance of integrating NbS into policy frameworks with careful planning and considering their benefits and trade-offs to maximise gains for all communities. In conclusion, research on NbS provides strong

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evidence that they can be essential for addressing climate and health challenges, but implementation must consider local context and potential trade-offs to ensure long-term sustainability. Future research should examine long-term impacts and strengthen monitoring to better manage these trade-offs.

Keywords

Nature-based solutions, climate change, public health, climate vulnerability, resilience, climate-health nexus, ecosystem services

Introduction

Proactive sustainable management, conservation and restoration of diverse ecosystems are essential strategies to mitigate climate change (Cohen-Shacham et al. 2019, Woroniecki et al. 2023). Nature-based Solutions (NbS) refer to using natural processes and ecosystem services to address climate change challenges, including societal challenges and impacts on human well-being (Cohen-Shacham et al. 2016, Bush and Doyon 2019). The IUCN's definition of NbS is "*Actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits*" (Cohen-Shacham et al. 2016, Seddon et al. 2020a, Pörtner et al. 2021)

Globally, interest has been growing in the last decade in the potential of NbS to achieve global goals for reducing greenhouse gas (GHG) emissions (Seddon et al. 2020a). Reports such as the Global Commission on Adaptation and the IPCC Reports have recognised the role of NbS in mitigating climate change as well as international scientific bodies and governments (Global Commission on Adaptation 2019, IPCC 2022, Timboe et al. 2022). The European Green Deal has, for example, integrated NbS into the European Union's policy framework to guide public and private investments towards ecosystem restoration and sustainable land use to achieve climate neutrality by 2050 (European Commission 2019). NbS offer low-cost, effective alternatives to grey infrastructure solutions by utilising natural processes to deliver benefits for both nature and people, including promoting water and food security, enhancing human well-being and supporting ecosystem health (Seddon 2022, Rajput et al. 2023).

Health risks associated with extreme events, including extreme heat, the spread of vector-borne diseases and deteriorating water and air quality, are escalating globally (Chiabai et al. 2018). The health impacts of climate change can be direct, arising from immediate environmental changes or indirect, from the gradual long-term effects of climate change influencing social and economic aspects of human well-being. Mental health impacts are also significant, where climate change can contribute to higher rates of depression, anxiety and stress (Clayton 2021, Romanello et al. 2022, Kumar et al. 2023). The Climate-Health Nexus approach allows for a more comprehensive understanding of how climate change impacts public health and supports decision-

making by identifying health impacts and vulnerable communities (Seddon 2022, Rajput et al. 2023).

The relationship between climate change and human health is increasing public concern (Schnitter and Berry 2019). Furthermore, comprehensive reviews of how NbS affect climate-related health impacts are lacking despite the often-suggested positive effects NbS might have. Understanding this relationship from the perspective of the climate-health nexus will allow for a comprehensive overview of how climate change impacts different aspects of public health (Seddon 2022, Rajput et al. 2023). This systematic analysis will, therefore, support decision-making considering the potential of NbS to contribute to climate adaptation and mitigation, while offering multiple benefits for both nature and people (Seddon 2022, Rajput et al. 2023).

NbS address three interconnected challenges: climate change adaptation and mitigation, biodiversity conservation and human well-being (Seddon et al. 2020b, Thaler et al. 2023). These challenges are interdependent and must be addressed collectively to avoid negative consequences and trade-offs between them. When integrated effectively, NbS can reduce trade-offs and promote synergies, leading to more holistic and sustainable outcomes (Kabisch et al. 2017, Rajput et al. 2023). However, it is crucial to understand their potential and limitations, as overestimating their contributions could mislead climate policy and create landuse conflicts (Cohen-Shacham et al. 2016, Raymond et al. 2017).

For example, a case study from Uganda showed that poorly-designed NbS can have negative consequences for communities (Edstedt and Carton 2018, Woroniecki et al. 2023). The project primarily focused on afforestation for carbon sequestration without fully considering the broader socio-ecological implications. As a result, NbS implementation led to a reduction of the available cultivation area for local farmers, which forced them to intensify agricultural practices on the remaining land. This led to soil degradation, loss of soil fertility and reduced productivity. Additionally, the project contributed to the depletion of local water resources, as the newly-planted forests increased water consumption, resulting in water scarcity (Woroniecki et al. 2023). However, when NbS are properly designed and implemented, they can provide several benefits for climate adaptation and mitigation, as well as other ecosystem services (Seddon et al. 2020a).

Some studies have explored the relationship between NbS and human health, while others have focused on the potential of NbS to address climate-related health impacts. This study offers a comprehensive synthesis to explore the complex relationship between climate, health and NbS. It provides decision-makers with critical baseline information for planning NbS initiatives that serve climate action or enhance community health outcomes. By highlighting both synergies and trade-offs, the paper reveals how these interactions influence human vulnerability, offering insights to better align NbS strategies with broader climate and health objectives. The Lancet Countdown highlights health co-benefits of climate actions, including those related to working with nature (Romanello et al. 2023). Seddon et al. (2020a) demonstrate how NbS can reduce exposure and sensitivity to climate change impacts and enhance adaptive capacity in response to these

impacts. The approach taken by Seddon et al. (2020a) highlights the ability of NbS to identify and reduce trade-offs, while maximising synergies, making them effective strategies for climate adaptation and health improvement (Tzoulas et al. 2021, Wellmann et al. 2023).

In this study, we will focus on finding how NbS could support climate solutions and healthy people simultaneously. While previous studies have examined either the climate or health benefits of NbS in isolation, this study systematically bridges climate change and public health outcomes through the lens of a vulnerability framework. We focus on how NbS simultaneously address climate hazards and associated health risks, mapping both synergies and trade-offs. The primary objective of this study is to explore the nexus between climate change and health and to showcase how climate impacts directly and indirectly affect health outcomes. We apply the well-established climate change vulnerability framework (exposure, sensitivity, adaptive capacity) to illustrate how NbS can create synergies for climate change and health, while acknowledging potential trade-offs.

Materials and Methods

Stepwise Literature Review

The research design of this study follows a stepwise literature review approach to gain specific insights about the role of NbS in affecting the climate-health nexus (Fig. 1). After screening and selecting relevant studies on NbS, climate and health, we performed a two-stage search. First, we identified studies on climate and health; second, we conducted a targeted search for NbS literature by linking previously identified climate–health connections to NbS interventions.

Criteria for selecting climate hazards and evaluating their impact on health were based on reports from the World Health Organisation (WHO), the International Union for Conservation of Nature (IUCN) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Miles et al. 2021, Miralles-Wilhelm 2021, Romanello et al. 2023). We used the WebOfScience database as our search engine, applying keywords for climate change, health and human health (Table 1). The second stage involved a more targeted search to examine the role of different NbS in mitigating climate impact on human health. This included a reverse selection process: after identifying the specific links between climate and health, we analysed the literature to determine if NbS were cited as having a positive or negative effect on those connections.

The scope of this review encompassed diverse categories of NbS in various settings, from urban green infrastructure and blue-green spaces, to agroforestry and forest restoration in rural landscapes and wetland conservation in coastal or inland areas. This approach ensured that we captured evidence on NbS benefits and trade-offs relevant to both urban planning and more rural or ecosystem-based management contexts.

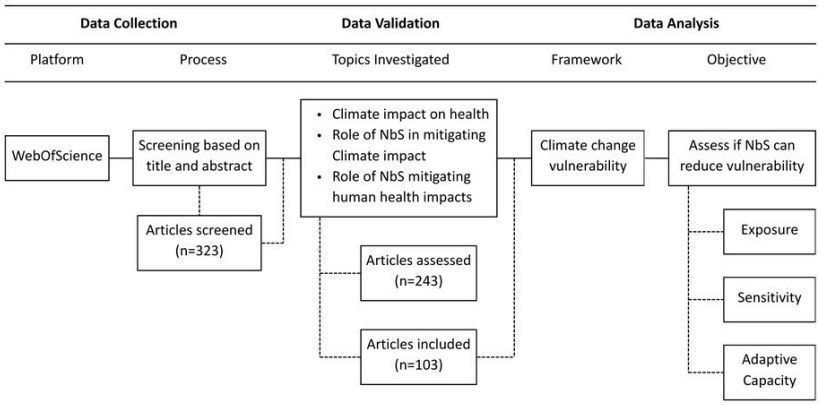

Figure 1.

Overview of the methodology process.

Table 1.

Search string used for targeted literature review in WebOfScience.

Category	Search String
Nature-based solutions	"Nature-based Solutions" OR "Agroforestry" OR "Forestation" OR "Wetlands" OR "Green built environment" OR "Urban green spaces" OR "Blue-Green space" OR "Organic farming"
Climate	"Climate change" OR "Air pollution" OR "Floods" OR "Droughts" OR "Heat" OR "Desertification" OR "Wildfires" OR "Dust storms" OR "Heavy rainfall"
Health	"Health" OR "Mental health" OR "Physical health" OR "food-borne" OR "water-borne" OR "vector-borne" OR "Heat-related illness" OR "injury" OR "morbidity" OR "mortality" OR "Cardiopulmonary" OR "non-communicable diseases"

Employment of the Climate Change Vulnerability Framework

We used the climate change vulnerability framework to analyse the studies selected from the literature review on three domains: exposure, sensitivity and adaptive capacity, to assess the role of NbS within the climate-health nexus (Woroniecki et al. 2023). Exposure refers to the extent to which people are subject to climate change impacts and associated health risks (Woroniecki et al. 2023). Exposure was assessed, based on concepts, such as climate change risk mitigation, hazard exposure reduction and enhancing relevant ecosystem services (e.g. flood regulation, air quality improvement) to reduce hazards. Conversely, mismanagement of ecosystems and natural resources can exacerbate exposure to climate hazards, a trade-off scenario since it undermines the protective benefits ecosystems provide (Cohen-Shacham et al. 2019, Ruangpan et al. 2020).

Sensitivity measures the degree to which people are impacted by such exposure (Turner et al. 2022). We explore how NbS can reduce sensitivity through diversifying livelihood opportunities, resource security and ecosystem stability (Cohen-Shacham et al. 2019, Selvan et al. 2023). However, trade-offs may occur if NbS fail to distribute benefits equitably, resulting in resource competition, inequities or instabilities (Woroniecki et al. 2023). Adaptive Capacity is the ability of individuals or communities to respond to the hazard's impacts (Turner et al. 2022) and can be assessed by evaluating the ability of ecosystems and communities to adapt to climate-related risks for health. NbS enhance ecosystem resilience, enabling natural systems to recover and maintain critical functions even after disturbances, which support long-term adaptation (Chrysoulakis et al. 2021). Still, reliance on a single ecosystem service can decrease adaptive capacity over time, reducing the ability of people to face future climate and health risks (Castelo et al. 2023, Torkfar and Russo 2023).

Coding the Nexus

To systematically analyse and visualise the connections between climate hazards, health outcomes and the contributions of NbS, we employed a structured coding system. Each unique relationship between climate-related hazards and health outcomes was assigned a distinct nexus code (N), ranging from N1 to N8. These codes were used to represent the specific nexus relationships identified in our analysis.

The codes act as a bridge between the climate and health relationships and how different NbS types interact with them. It served as a simple way to track and label the identified climate and health linkages, allowing them to be referenced throughout the tables and the Sankey diagram. This coding helped visualise how each NbS type corresponds to specific climate and health relationships and also guided the interpretation of potential negative health outcomes when examining trade-offs.

This approach allowed us to map how NbS interventions interact with the identified nexus relationships (N1-N8), either creating synergies that reduce climate vulnerabilities or leading to trade-offs that exacerbate them. Conversely, certain NbS might inadvertently increase sensitivity or reduce adaptive capacity in specific contexts, highlighting potential trade-offs. By employing this coding and visualisation framework, we were able to systematically assess how NbS interventions influence the dimensions of vulnerability — exposure, sensitivity and adaptive capacity across the eight identified nexus relationships.

Literature Screening and Synthesis

Publications retrieved from the WebOfScience platform were manually screened for inclusion according to the inclusion and exclusion criteria (Table 2). After publication selection, the articles were thoroughly reviewed and assessed, based on their contribution to the study's objectives. A qualitative synthesis of the selected information was performed and the findings were reported consistently to first illustrate the impact of

climate on health. Secondly, the role of NbS in mitigating climate impacts on health was examined, utilising the climate change vulnerability framework to assess synergies and trade-offs. This framework helped identify how NbS reduce exposure and sensitivity to climate risks, while also building adaptive capacity, to provide a more comprehensive understanding of their role in the climate-health nexus.

Table 2.

Publication screening criteria.

Screening Criteria	
Inclusion Criteria	**Exclusion Criteria**
Peer-reviewed articles, systematic reviews, meta-analyses and case studies.	Non-peer-reviewed articles, grey literature.
Studies examining the direct impact of climate events on physical and/or mental human health.	Studies focusing solely on climate impact on biodiversity or nature health without linking to human health outcomes.
Studies examining the indirect impacts of climate change on human health, influenced due to alterations in biodiversity and natural health.	Studies unrelated to NbS interventions, strategies or their role in mitigating climate and health.
Studies discussing specific NbS interventions to mitigate the impacts of climate change on human health.	Studies focus on ecological or economic aspects while excluding the social aspect.
Studies published in the last decade (2013 – present).	Studies published before 2013.
Search outputs in English were only considered.	Search outputs in languages other than English.

The entire review process was qualitative in nature. All identified linkages amongst climate hazards, health outcomes and NbS were derived through manual assessment of the reviewed studies. The analysis was jointly conducted by two authors who independently screened, coded and cross-checked the findings to maintain consistency and reduce bias. Only linkages agreed upon by both reviewers were included in the synthesis. The resulting relationships are presented in the tables and visually summarised through Sankey diagrams to facilitate interpretation. In cases where multiple studies reported the same relationship, these were grouped, and all supporting references were cited for that single identified linkage. This approach was applied consistently throughout the review to ensure that each reported relationship reflects consolidated evidence.

Results

Climate-Health Nexus

Our literature review indicates that a variety of health outcomes are linked to different climate hazards (Table 3). Air pollution contributes, for example, to non-communicable diseases (NCDs) and respiratory and cardiovascular issues, with pollutants like nitrogen dioxide and fine particulates playing a critical role (Almetwally et al. 2020). Extreme

weather events, such as floods, droughts and heat waves, increase the risks of food-borne, water-borne and vector-borne diseases and heat-related conditions, directly impacting food security, water quality and mental health (Vins et al. 2015, Chapman et al. 2017, Bai et al. 2018). These hazards can, therefore, lead to immediate physical health impacts, such as injuries, mortality and morbidity, as well as fostering environments in favour of the spread of infectious diseases (Zuo et al. 2015, Yusa et al. 2015).

Table 3.

Health Impacts of Climate-Related Hazards: This table presents an overview of the health outcomes and impacts associated with various climate-related hazards. The nexus is coded (N1-N8) for subsequent analysis on how different types of NbS can address the nexus and create synergies.

Climate-related Hazards	Health Outcomes	Impact	Coding	Ref.
Air pollution	NCDs Mortality and morbidity Mental Health, stress disorders and anxiety	▪ Air quality, influenced by weather and climate change factors such as humidity, wind and temperature, harms human health. ▪ The chemical composition of pollutants affects the global climate by either cooling or warming the planet. ▪ Key pollutants impacting health, especially respiratory diseases, include nitrogen dioxide, sulphur dioxide, ozone, methane, mercury, black carbon and fine particulates. ▪ Air pollution is linked to higher mortality rates from respiratory and cardiovascular diseases. ▪ Air pollution is classified as a human carcinogen, linked to lung, nasopharyngeal, head and neck cancers and is a leading cause of cancer deaths. ▪ Both short- and long-term exposure to air pollutants is associated with various cardiovascular diseases, including heart failure, myocardial ischemia, strokes, arrhythmias, and increased mortality. ▪ High levels of stress hormones, such as epinephrine, cortisone and cortisol, have been correlated with exposure to fine air pollutant particulates.	N1	Kim et al. (2014), Hassan et al. (2016), Almetwally et al. (2020), Ivanova (2020), Muñoz-Pizza et al. (2020)
Floods/ Landslides	Food-borne diseases and malnutrition Vector-borne diseases Water-borne diseases Injury, mortality and morbidity Mental Health, stress disorders and anxiety	▪ Flood impacts change over time, from immediate injuries to longer-term issues. ▪ Reduces access to healthcare, clean water and food. ▪ Injuries from debris, burns and evacuation accidents. ▪ Infectious diseases from contaminated water due to faecal and vector transmission ▪ Post-flood respiratory issues from mould and microbial growth. ▪ Urbanisation and changes in land cover from permeable to impermeable surfaces reduce soil water infiltration and increase runoff volume during storms and rainfall. ▪ Poses health risks through direct contact with contaminated flood water.	N2	Lowe et al. (2013), Zhang et al. (2015) , Burton et al. (2016), Houghton and Castillo-Salgado (2017), Bai et al. (2018), Zhong et al. (2018)
Droughts	Injury, mortality and morbidity Food-borne diseases and malnutrition Vector-borne diseases Water-borne diseases and water scarcity Heat-related illness	▪ Droughts disrupt water supply and food security, intensify heat stress and decrease water quality, contributing to food insecurity and malnutrition. ▪ Droughts are responsible for widespread global morbidity and mortality, being the costliest and most complex climatic hazard affecting more people than any other.	N3	Kim et al. (2014), Vins et al. (2015), Yusa et al. (2015), Diasso and Abiodun (2018), Salvador et al. (2020), Sugg et al. (2020)

Climate-related Hazards	Health Outcomes	Impact	Coding	Ref.
	Mental Health, stress disorders and anxiety	▪ Hot, dry conditions during droughts can increase food-borne pathogens and facilitate mosquito breeding due to standing water. ▪ Summer droughts can elevate pollutant concentrations; winter droughts may increase particulate matter levels. ▪ Wildlife intrusion, rodents and pests during droughts can pose additional health risks. ▪ Prolonged droughts lead to socioeconomic losses, forced displacement and mental health issues due to emotional stress.		
Temperature Extremes/Heat Waves	Cardiopulmonary illness Heat-related illness Mental Health, stress disorders and anxiety Mortality and morbidity	▪ Less vegetation and man-made materials in cities raise temperatures, contributing to urban heat island (UHI) effects and heat waves. ▪ UHI is a major issue in urbanised areas, worsening human health risks from thermal stress due to higher temperatures. ▪ UHI effects, marked by higher temperatures, can intensify and prolong city heatwaves, leading to more extreme heat exposure and higher heat-related mortality. ▪ Heatwave health impacts include exhaustion and heat stress, as well as serious conditions like heart attacks and kidney failure, which increase emergency hospital visits and mortality.	N4	Kim et al. (2014), Zuo et al. (2015), Ward et al. (2016), Chapman et al. (2017), Mohajerani et al. (2017), Hsu et al. (2021)
Desertification	Heat-related illness Malnutrition Water-borne diseases and water scarcity Mental Health, stress disorders and anxiety	▪ Desertification impacts water and food security, as well as soil and air quality. ▪ It reduces access to essential resources like safe water, increasing the risk of diseases, such as diarrhoea. ▪ Climate change exacerbates desertification, affecting agricultural lands and livestock, thus compromising food security. ▪ The negative effects of desertification on agricultural lands and pastures lead to migration, as people seek to escape the economic impacts of desertification, which, in turn, affects ecosystems and human well-being.	N5	Sena and Ebi (2020), Al-Obaidi et al. (2022)
Wildfires	Cardiopulmonary illness NCDs Injury and mortality Mental health, stress disorders and anxiety.	▪ Climate change increases the frequency, intensity and scale of wildfires, leading to more intense and faster-spreading fires. ▪ Wildfire emissions, including fine particles (PM2.5), ozone and NOx, negatively impact air quality and human health, leading to acute and long-term health risks. ▪ Fine particles disperse further from the source and penetrate more deeply into the lungs, which can change lung functions, leading to respiratory and cardiovascular issues, with increased risks including asthma, mortality and morbidity. ▪ Long-lasting exposure to emissions can have delayed adverse mental health impacts.	N6	Youssouf et al. (2014), Liu et al. (2015), Black et al. (2017), Drolet et al. (2020), Gao et al. (2023), Zhang et al. (2023)
Dust Storms	NCDs Cardiopulmonary illness Injury, mortality, and morbidity.	▪ Dust storms, carrying fine particles, pathogens, pollutants and allergens, pose significant health risks. ▪ The size of particulate matter influences the type and concentration of bioaerosols, affecting the presence of different bacterial communities. ▪ These storms expose people to microorganisms and allergens absorbed by dust particles during transport, with particles smaller than 10 μm (PM10) capable of reaching deep into the lungs. ▪ High particulate levels in the air are linked to cardiovascular diseases. ▪ Desert dust is associated with increased mortality and morbidity from respiratory and cardiovascular diseases, as well as accidents caused by reduced visibility.	N7	Goudie (2014), Schweitzer et al. (2018), Soleimani et al. (2020), Williams and Samara (2023), Jasim et al. (2024)

Climate-related Hazards	Health Outcomes	Impact	Coding	Ref.
Heavy rainfall	Water-borne diseases Vector-borne diseases	▪ Heavy rainfall can lead to wildlife disease outbreaks by changing host physiology and environments, facilitating pathogen transmission. ▪ Excessive wet weather can trigger outbreaks by causing latent carrier animals to shed pathogens. ▪ Water infiltration into aged sewer systems during rainstorms can cause sanitary sewer overflows, increasing the risk of water-borne disease transmission. ▪ Both temperature and rainfall influence water-borne diarrhoeal pathogens, with higher temperatures boosting pathogen survival and rainfall flushing faecal material into waterways. ▪ Increased rainfall is linked to higher risks of diseases like leptospirosis and can enhance mosquito-borne disease transmission by creating more breeding sites.	N8	Carlton et al. (2014), Chowell et al. (2019), Deshpande et al. (2020), Shender et al. (2022)

Additionally, land degradation and desertification reduce water availability and agricultural productivity, leading to malnutrition and mental health issues (Al-Obaidi et al. 2022). Wildfires and dust storms contribute to cardiopulmonary diseases and NCDs due to airborne particles and pollutants (Black et al. 2017). Heavy rainfall increases the risk of water-borne diseases and vector-borne diseases by changing pathogen dynamics and habitat conditions (Chowell et al. 2019). Overall, these hazards indicate the need for climate-health strategies to enhance resilience and protect human health against the various impacts of climate change (Seddon et al. 2020b). Fig. 2 shows the interconnected roles of various NbS in addressing the climate-health nexus, emphasising the importance of integrated solutions to mitigate climate impacts and enhance human health resilience.

NbS Contribution to Climate and Health

NbS have proven effective in mitigating climate-related risks by reducing exposure and sensitivity to hazards, while simultaneously enhancing adaptive capacity within the climate-health nexus. By addressing both environmental and health vulnerabilities, NbS help to reduce the adverse impacts of climate change on human health. Agroforestry, for example, regulates microclimates, improves soil structure and lowers ambient temperatures, which collectively reduce exposure to extreme weather impacts (Alikhanova and Bull 2023). Afforestation and reforestation projects sequester carbon and mitigate droughts by enhancing water retention and reducing runoff, thereby lowering the exposure to adverse climate effects, such as flooding and soil erosion (Moomaw et al. 2019, Alikhanova and Bull 2023). Wetlands absorb floodwaters, reduce peak flood levels and improve water quality, directly reducing exposure to flooding and water-borne diseases (Wolff et al. 2023).

Sensitivity to climate impacts is addressed through NbS by enhancing ecosystem resilience. Agroforestry systems, for instance, support carbon sequestration in less fire-prone trees and reduce fire risks, thereby reducing sensitivity to wildfires (Damianidis et al. 2021). Urban green spaces mitigate the urban heat island effect, providing cooler environments that reduce sensitivity to heat waves and related health risks (Xing et al.

2017, Zhou et al. 2023). Green-built environments, such as green roofs, improve air quality, which lowers sensitivity to air pollution and heat stress (Schindler et al. 2019).

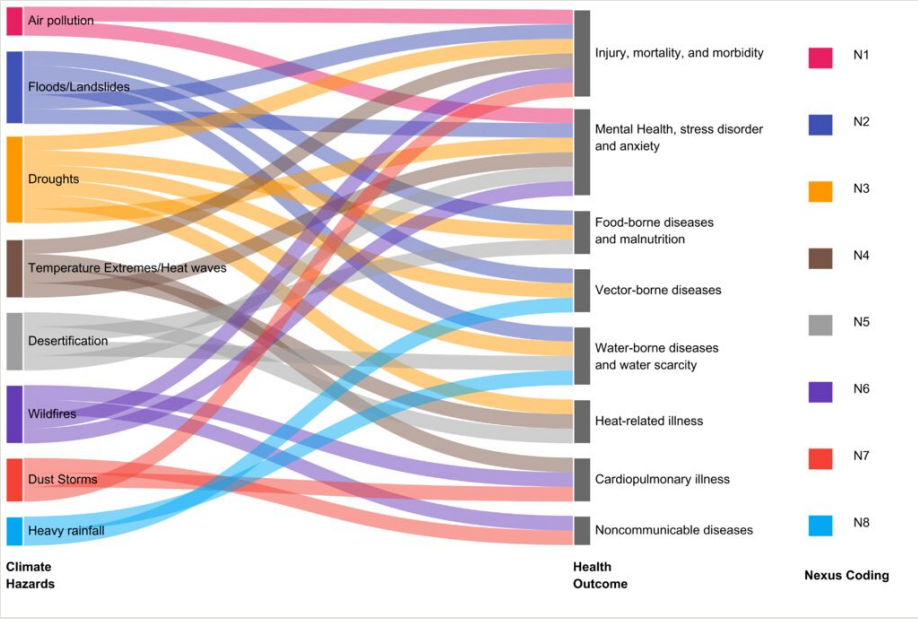

Figure 2.

Health Impacts of Various Climate-Related Hazards: This Sankey diagram illustrates the relationship between key climate hazards (left) and their corresponding health outcomes (centre). The right side displays a "Nexus Coding" (N1–N8) assigned to each health outcome for reference in analysis. The coloured flows indicate the connections and pathways between each hazard and specific health outcomes.

Lastly, NbS have been found to enhance adaptive capacity by fostering sustainable practices and improving environmental quality. Organic farming enhances soil health and biodiversity, increasing resilience to external shocks (Keesstra et al. 2018). Blue-green space restoration alleviates the urban heat island effect and supports sustainable urban planning, improving overall adaptive capacity (Yu et al. 2020). By integrating these solutions, communities can better adapt to the challenges posed by climate change, ensuring long-term resilience and sustainability (Chausson et al. 2020).

Table 4 provides the definitions of the NbS types considered in this study, forming the basis for the subsequent analysis of their relationships with the climate-health nexus. Table 5 and Fig. 3 explain and visualise the connections between various NbS types and their roles in addressing the climate-health nexus, highlighting the pathways through which they reduce exposure and sensitivity and enhance adaptive capacity. In the table, a downward arrow (↓) indicates a reduction in exposure or sensitivity, an upward arrow (↑) indicates an enhancement of adaptive capacity and a dash (–) denotes that no explicit relationship was identified in the reviewed literature. The connections in the Sankey diagram further illustrate where each NbS demonstrated a positive contribution within the

vulnerability framework, indicating whether it reduced exposure or sensitivity, enhanced adaptive capacity or simultaneously contributed to more than one of these dimensions.

Table 4.

Definitions of the NbS types studied in this review

NbS	Definition	Reference
Agroforestry	Land-use systems that intentionally integrate trees and woody shrubs with crops and/or livestock on the same land management unit.	Damianidis et al. (2021)
Afforestation/ Reforestation	Afforestation is the establishment of forests on land that has not been forested for a long period, while reforestation is the re-establishment of forest cover on land that was previously forested.	Doelman et al. (2020)
Wetlands	Ecosystems where water covers or saturates the soil permanently or seasonally, creating low-oxygen conditions and supporting plant species adapted to such environments.	Dworrak et al. (2022)
Urban Green Spaces	Vegetated areas within urban environments, including parks, gardens and street trees, are designed to provide ecological and social benefits.	Zhou et al. (2023)
Green Built Environment	Refers to the integration of natural elements and processes into the design, construction and operation of buildings and urban infrastructure.	Xing et al. (2017)
Blue-Green Space Establishment or Restoration	Integrated networks of natural and semi-natural aquatic (blue) and terrestrial (green) elements within urban and peri-urban areas.	Yu et al. (2020)
Organic farming	An agricultural system that relies on ecological processes, biodiversity and cycles adapted to local conditions, avoiding the use of synthetic fertilisers, pesticides and genetically modified organisms.	Selvan et al. (2023)

Table 5.

Role of NbS in Tackling Climate-Health Nexus: This table presents the roles of various NbS in mitigating climate impacts and improving human health, identifying the specific nexus (N1-N8) they address from Table 1. Each NbS type is analysed in terms of its potential to reduce exposure and sensitivity to climate hazards and enhance adaptive capacity. The framework columns indicate whether the NbS reduces exposure and sensitivity and/or enhances adaptation.

NbS	Nexus	Role of NbS	Framework			Ref.
			Exp.	Sen.	Adp.	
Agroforestry	N3	• Agroforestry can rehabilitate marginal and salt-affected irrigated lands. • Through tree shading and increased evapotranspiration, agroforestry can regulate microclimate by altering air temperature, solar radiation and wind speed. • Trees improve soil structure, enhance water retention and infiltration and reduce soil compaction. • They also lower ambient temperatures, decreasing water evaporation from the soil and crop transpiration. • This is expected to build more resilient food systems and produce higher crop yields.	↓	−	↑	Abbas et al. (2017), Keesstra et al. (2018), Rosenstock et al. (2019), Seddon (2022), Alikhanova and Bull (2023), Silva et al. (2023)

NbS	Nexus	Role of NbS	Framework			Ref.
			Exp.	Sen.	Adp.	
	N6	▪ Agroforestry systems mitigate wildfire risk by reducing fuel loads, altering fuel characteristics and serving as extensive fuel breaks. ▪ They support carbon sequestration in trees less likely to be affected by fire. ▪ Acting as "productive fuelbreaks", extensive agroforestry systems protect communities near fire-prone areas. ▪ By breaking up shrubland continuity and increasing tree spacing, agroforestry reduces forest understorey biomass, further diminishing fire risk.	↓	−	↑	Damianidis et al. (2021), Wolpert et al. (2022)
	N1	▪ Agroforestry systems have the potential to sequester a substantial amount of carbon in both above-ground biomass and soil, playing a key role in regulating the carbon cycle.	↓	−	−	Ghale et al. (2022)
Afforestation/ Reforestation	N7	▪ Afforestation projects, while combatting desertification and enhancing topsoil quality, can also significantly reduce dust storms and wind erosion within a few years of reaching maturity, functioning as well in sequestering carbon and improving air quality.	↓	↓	−	Middleton (2019), Smith et al. (2019), Lyu et al. (2020), Alikhanova and Bull (2023)
	N1	▪ Growing existing forests to their biological carbon sequestration potential optimises carbon dioxide removal, while limiting climate change. ▪ Forests annually sequester large quantities of atmospheric carbon dioxide (CO_2) and store carbon above and below ground for long periods.	↓	−	−	Moomaw et al. (2019)
	N3	▪ Forested areas can mitigate droughts by altering local climate conditions. These areas, whether reforested or afforested, help increase rainfall and reduce warming. ▪ They decrease runoff and increase evapotranspiration, allowing more water to be retained in the soil. ▪ Forested areas can enhance carbon sequestration and moisture penetration, potentially affecting larger areas beyond their boundaries.	↓	↓	↑	Diasso and Abiodun (2018), Reisman-Berman et al. (2019), Omer et al. (2020), Takata and Hanasaki (2020), Holátko et al. (2022)
	N6	▪ Afforestation restores burnt soils and ecosystems post-wildfire and, paired with treatments like mulching or contour felling, leads to more effective erosion control and seed protection. ▪ Choosing suitable native plant species and seeding methods accelerates ecosystem recovery and enhances ecological resilience in areas affected by wildfires.	−	↓	↑	Wittenberg and Shtober-Zisu (2023)
Wetlands	N2 N8	▪ Historically, wetlands have proven to combat flooding and food production challenges. ▪ They act as a sponge, absorbing water, slowing its flow, and reducing peak flood levels. ▪ They can store water, responding to longer wet and dry periods and improve water quality by treating various wastewater streams	↓	↓	↑	Acreman and Holden (2013), Smith et al. (2019), Hobbie and Grimm (2020), Van Hullebusch et al. (2021), Wolff et al. (2023)
Urban green spaces	N4	▪ Urban green spaces, with more vegetation and fewer hard structures, mitigate the UHI effect and create resilient, sustainable cities. ▪ Green spaces, such as parks, are cooler than surrounding urban zones due to their high evaporative cooling and low heat storage and this cooling benefit extends beyond the parks' boundaries. ▪ Planted areas can lower ambient air temperature and offer relief from heatwaves	↓	↓	−	Xing et al. (2017), Lafortezza and Sanesi (2019), Hobbie and Grimm (2020), Badura et al. (2021), Zhou et al. (2023)
	N2	▪ Green spaces play a role in urban flood control, which can complement sewer systems to manage runoff. ▪ Planning green areas along with impermeable surfaces, such as roads and rooftops, can slow down runoff and enhance water absorption, reducing surface runoff and mitigating flood risks.	↓	↓	−	Zhang et al. (2015), Bai et al. (2018), Abass et al. (2020), Zhao and Yue (2023)

NbS	Nexus	Role of NbS	Framework			Ref.
			Exp.	Sen.	Adp.	
	N1	▪ Green spaces can mitigate air pollution and enhance human health. ▪ Trees, for instance, filter particulates and absorb gaseous pollutants. ▪ Tree coverage also reduces PM10 levels. ▪ They capture particles through deposition on the tree surface and absorb gases through the stomata	−	↓	↑	Matos et al. (2019), Muñoz-Pizza et al. (2020), Qiu et al. (2021)
Green Built Environment	N1 N4 N8	▪ Green roofs control stormwater, reduce energy consumption and air pollution, sequester CO2, enhance biodiversity, alleviate the urban heat island effect and boost solar panel efficiency. ▪ Extensive green roofs, with a thin layer of vegetation and minimal irrigation, offer cooling and insulation, outperforming conventional roofs. ▪ The cooling effect of green roofs results from increased albedo, evapotranspiration and plant shading, with certain plants maximising these benefits. ▪ These roofs benefit both the building and its surroundings by improving stormwater management, water runoff quality, urban air quality, reducing heat island effects and dampening noise pollution.	↓	↓	−	Mees et al. (2013), Schindler et al. (2019), Schade et al. (2021), Yan et al. (2022)
Blue-Green Space Establishment or Restoration	N4	▪ Blue-green spaces play a crucial role in alleviating the UHI effect through their significant cooling impact. ▪ Blue-green space planning reduces heat storage and increases solar radiation reflection, enhancing urban albedo and mitigating the UHI effect.	↓	↓	−	Yu et al. (2020), Pritipadmaja et al. (2023)
Organic Farming	N5	▪ Organic farming combines strategies to reduce soil erosion, enhance biodiversity, protect traditional cultivars and achieve sustainability, using methods like mulching and catching crops to improve soil health. ▪ Adapting to local environments without synthetic inputs, organic farming favours resilient, traditional species and diverse crops, enhancing resistance to external shocks. ▪ Organic practices, such as crop rotation and manuring, effectively restore degraded soils, improve rural livelihoods under climate change and offer significant climate mitigation through increased soil carbon storage.	−	↓	↑	Scialabba and Müller-Lindenlauf (2010), Keesstra et al. (2018), Selvan et al. (2023)
	N1	▪ It boosts carbon sequestration through practices like cover cropping and minimum tillage, aiding in climate change mitigation. ▪ Organic agriculture minimises land preparation by burning, reducing greenhouse gas emissions like CH_4 and N_2O and preserving sequestered carbon.	−	↓	↑	

Trade-offs and Health Impacts of NbS

NbS offer significant benefits, but they also present several trade-offs and limitations that can have direct and indirect impacts on human health outcomes. For instance, in afforestation and reforestation projects, introducing non-native species can disrupt local biodiversity and increase susceptibility to diseases and pests (Zhang et al. 2022). High water demands that are sometimes required for NbS projects can lead to water scarcity (Cao et al. 2016). Additionally, afforestation requires significant land resources, reducing the availability of agricultural land and potentially leading to higher food prices (Doelman et al. 2020). Wetland restoration can improve flood control and water quality, but may also increase greenhouse gas emissions and create habitats for disease vectors like mosquitoes (Hu et al. 2023). This can raise public health concerns related to vector-borne diseases and air pollution (Catry et al. 2018).

Green infrastructure (e.g. urban parks, green roofs) can reduce Urban Heat Island effects and potentially support biodiversity. However, if such projects use only a few plant species, they may reduce local biodiversity (Felappi et al. 2020). Planting non-native species can affect local health due to high pollen concentrations, contributing to cardiopulmonary illnesses and NCDs (Russo et al. 2017). Table 6 and Fig. 4 illustrate the trade-offs and health impacts associated with different NbS types, emphasising the need for careful planning and management to balance benefits and minimise negative health outcomes. In the trade-offs table, a downward arrow (↓) indicates a reduction in adaptive capacity, an upward arrow (↑) indicates an increase in exposure or sensitivity and a dash (–) denotes that no explicit relationship was identified in the reviewed literature.

To visualise and better understand the interactions among NbS, climate events and health outcomes, we used a Sankey diagram (Fig. 5). This diagram represents how various NbS interventions (e.g. agroforestry, urban green spaces, wetlands) influence different climate events (e.g. droughts, floods, wildfires), which, in turn, impact multiple health outcomes, such as mental health disorders, cardiopulmonary illnesses and heat-related illnesses. The diagram represents these interactions, emphasising the interconnected role that NbS play in addressing climate-related health vulnerabilities, based on relationships identified in literature.

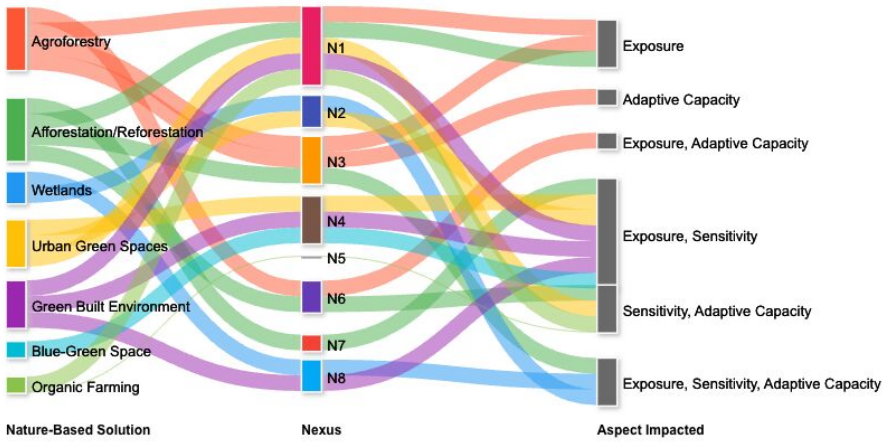

Figure 3.

NbS addressing Climate-Health Nexus: This Sankey diagram visualises how various NbS address different components of the climate-health nexus, categorised into exposure, sensitivity and adaptive capacity. Each NbS type is linked to a specific nexus (N1-N8), showing the interconnected roles NbS play in mitigating climate impacts and enhancing human health. The left side lists different types of NbS, the right side categorises the impacts into exposure, sensitivity and adaptive capacity and the coloured flows represent the pathways and extent of each NbS type's influence.

Table 6.

Trade-offs and Health Impacts of NbS: This table outlines the trade-offs associated with different NbS and their corresponding health impacts. The table details the negative consequences that arise from the implementation of NbS. The table serves as a reminder that, while NbS offer benefits in addressing climate impacts and enhancing human health, they can also create trade-offs.

Type of NbS	Trade-offs/Limitations	Health Impact	Framework			Ref.
			Exp.	Sen.	Adp.	
Afforestation/ reforestation	▪ Afforestation projects, unlike reforestation ones, require the introduction of new trees that have not naturally occurred before and are considered invasive alien species. ▪ Non-native monocultures are of limited value in reviving local biodiversity and can lead to an increased susceptibility to diseases and pests.	Vector-borne diseases	↑	–	↓	Zhang et al. (2022), Alikhanova and Bull (2023)
	▪ Vegetation with low water-use efficiency or more water demand requires extra water input that may require supplemental irrigation to survive and function. ▪ Water consumption by one ecosystem will reduce the availability of sufficient water to support other ecosystem components. ▪ A disrupted ecosystem's water balance may lead to continuing desertification in other areas and can have negative consequences for farmers and residents.	Water Scarcity	–	↑	↓	Cao and Zhang (2015), Zhang et al. (2015), Cao et al. (2016), Jia et al. (2017)
	▪ Afforestation requires significant land resources, reducing the availability of land for agriculture. ▪ This reduction in agricultural land could lead to increased competition for land and food production, which results in higher food prices. ▪ Shift in land use from agriculture to afforestation can increase the population's hunger.	Malnutrition	–	↑	–	Kreidenweis et al. (2016), Doelman et al. (2020)

Type of NbS	Trade-offs/Limitations	Health Impact	Framework			Ref.
			Exp.	Sen.	Adp.	
Wetland Restoration	▪ Upstream developments like dams, irrigation or industrial use create a conflict by diverting water for specific uses, reducing water availability for downstream ecosystems and communities. ▪ The trade-off involves upstream water diversion versus downstream flooding benefits, which support farming, fishery, forestry and groundwater recharge.	Water availability and scarcity	-	√	↓	Barbier (2011)
	▪ Constructed Wetlands are complex in their impact on GHGs, as they can produce substantial amounts of CO_2, CH_4 and N_2O as by-products. ▪ Combining wetland hydrology with ongoing agricultural nitrogen (N) inputs enhances denitrification and can increase N_2O emissions. ▪ Flooded soils in wetlands typically exhibit lower rates of soil respiration, leading to potentially lower CO_2 emissions, which could offset the increased N_2O and CH_4 emissions. ▪ Warmer and wetter conditions, along with decreased hydroxyl (OH) levels over wetlands, contribute to rising methane concentrations.	Health outcomes of air pollution	↑	-	↓	Morse et al. (2012), Peng et al. (2022), Hu et al. (2023)
	▪ Rewetting in wetlands can create stagnant water pools, forming ideal habitats for mosquito larvae. ▪ The presence of mosquitoes in wetlands is a concern due to their role as nuisances and carriers of infectious diseases, raising public health concerns. ▪ Wetlands significantly influence mosquito abundance and West Nile Virus infection rates due to their extensive habitat offerings for larval mosquitoes and attraction of disease-competent birds, stemming from high primary productivity.	Vector-borne diseases	↑	↑	–	Johnson et al. (2012), Skaff and Cheruvelil (2016), Catry et al. (2018), Lugassy et al. (2021), Dworrak et al. (2022)

Type of NbS	Trade-offs/Limitations	Health Impact	Framework			Ref.
			Exp.	Sen.	Adp.	
Green Infrastructure	▪ Lacking minimal biodiversity requirements, some green spaces are reduced to basic lawn areas, which can result in "green deserts" that do not support urban biodiversity effectively. ▪ Human preferences for the aesthetics of green spaces can negatively affect the ability of these areas to support urban wildlife.	Health trade-offs from biodiversity loss	-	↑	-	Garmendia et al. (2016), Felappi et al. (2020)
	▪ The adaptation of foreign plants to new climatic conditions and environments is unpredictable, with potential health impacts due to high pollen concentrations in specific local conditions. ▪ A significant portion of airborne pollen-causing symptoms originates from species commonly used in urban forests and green areas. ▪ Pollen emission by higher plants during pollination is a major ecosystem disservice, affecting human health by prompting allergic responses. ▪ The emission of pollen also contributes significantly to biotic air pollution.	Cardiopulmonary illness NCDs	↑	↑	↓	Lorenzoni-Chiesura et al. (2000), Cariñanos et al. (2014), Russo et al. (2017)

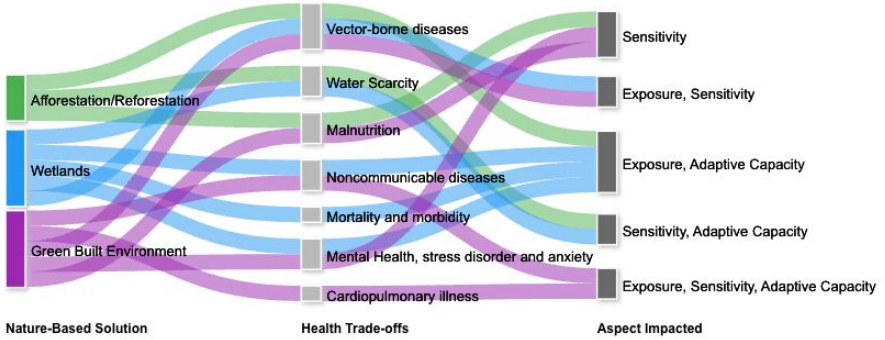

Figure 4.

NbS Trade-offs: Health Impacts: This Sankey diagram visualises the trade-offs and health impacts associated with various NbS. The left side lists different types of NbS, while the right side shows the specific health impacts they can have. The coloured flows represent the connections between each NbS type and its associated health impact

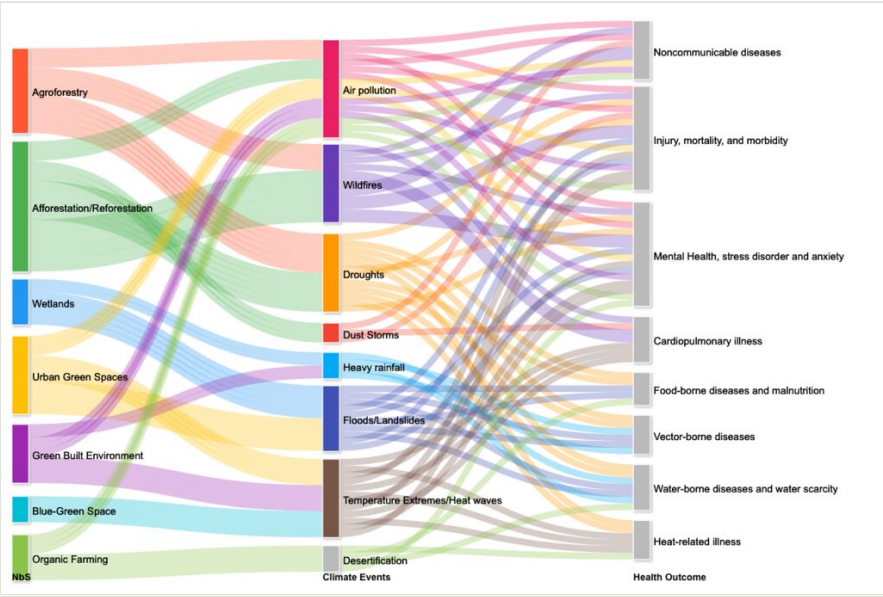

Figure 5.

Sankey diagram showing relationships between NbS, climate hazards and health outcomes. Connections represent the interactions identified in literature, illustrating NbS roles within the climate-health nexus.

Discussion

The Climate-Health Nexus

The study reveals that NbS play an important role in creating synergies in the climate-health nexus; however, potential trade-offs can arise if this nexus is not considered holistically. Our research aims to understand the impact of climate change on human health and the associated outcomes. While NbS can be a powerful intervention, neglecting the climate-health nexus may lead to unintended consequences, such as increased health risks or environmental degradation. It is essential to assess these trade-offs to ensure that NbS interventions are well-suited to both climate mitigation and health improvement. Recognising the fundamental role of natural ecosystems in achieving global climate and enabling sustainable development (Seddon et al. 2020b), we emphasise centring climate and health solutions on natural systems. Restoring and managing ecosystems through NbS as primary strategies can simultaneously mitigate climate impacts and deliver health benefits (Kabisch et al. 2017). This underscores the value and importance of integrating health considerations into NbS design and implementation.

Global attention is increasingly focusing on the critical importance of the climate-health nexus, with recent reports highlighting the need for integrated solutions that address

environmental and human health concerns (Romanello et al. 2023). It is widely stressed that health should be integrated into climate policies to effectively assess health risks associated with climate change and enhance health responses (Colléony and Shwartz 2019).

The climate-health cases gathered in this research illustrated the health risks associated with climate change. Studies showed that, as extreme weather events grow more intense and frequent, human safety and well-being are increasingly at risk. These events can cause changes in land structure, affecting crop yields and leading to food insecurity. Climatic variations also support the breeding of infectious pests, enhancing disease spread and health risks. Additionally, land degradation caused by climate change and human activity results in biodiversity loss and disrupts water systems, limiting essential benefits for people. Air quality and climate events directly impact human health, causing immediate physical harm and creating environments conducive to disease spread.

Opportunities and Challenges of the Nexus

We have provided insights into how NbS contribute to the climate-health nexus by mitigating the adverse effects of climate change on human health. This study identified various types of NbS and their roles in modifying environmental conditions. Through interventions, such as ecological rehabilitation, enhancing resilience and improving ecosystem services and environmental quality, NbS can address both human needs and ecological health. By placing people at the core of planning and development, human and ecosystem health can progress together (Colléony and Shwartz 2019).

Following the climate change vulnerability framework, our assessment found that each type of NbS uniquely reduces exposure and sensitivity while enhancing adaptive capacity. NbS build resilience against climate events by reversing desertification, improving air quality, regulating local climates, enhancing food production and improving water conservation and quality. These solutions improve land structures, provide essential resources and offer sustainable water management, crucial for overall ecosystem health and human well-being.

Proper land-use planning incorporating NbS restores ecosystems, mitigates climate change, provides natural infrastructure for flood control and promotes biodiversity (Turner et al. 2022). NbS help local communities adapt to climate impacts and ensure well-being through benefits, like improved livelihoods and ecosystem services (Alikhanova and Bull 2023). They provide natural infrastructure for flood and drought protection, enhancing ecosystem resilience and reducing community vulnerability (Seddon 2022). NbS also offer co-benefits, such as improved food security, livelihoods and health, which enhance social resilience and reduce vulnerability to climate change. Heat mitigation, improved air quality and control of vector-borne diseases from NbS reduce health issues associated with climate change (Catry et al. 2018, Van Hullebusch et al. 2021). Additionally, NbS restore ecosystems and enhance biodiversity conservation, leading to increased carbon sequestration (Smith et al. 2019, Alikhanova and Bull 2023).

NbS interventions can lead to more resilient and sustainable outcomes if they concurrently support biodiversity and human well-being (Seddon et al. 2020a). The results of this study also reveal trade-offs, highlighting the importance of considering the nexus from all angles. Neglecting these trade-offs can lead to unintended negative consequences for nature and people (Kato-Huerta and Geneletti 2022). For example, carbon offsetting projects that focus solely on climate impact without considering community well-being can increase competition for agricultural land, decrease soil fertility and reduce food production (Edstedt and Carton 2018, Woroniecki et al. 2023). Practitioners must understand and anticipate these trade-offs by learning from case studies and recognising that, while NbS can strengthen resilience, they may also create new vulnerabilities to certain climate events or health conditions if not carefully designed and assessed. This helps to ensure that NbS enhance resilience and reduce vulnerability to climate and health impacts.

Evidence shows that NbS can cause competition for land, increase water demand and even promote the spread of invasive species and disease vectors. Regional case studies are crucial for identifying suitable strategies that align with local contexts. Global examples may not always be applicable due to regional and cultural differences. Anguelovski and Corbera (2023) note that, while localised benefits and changes are evident, the large-scale and long-term effects of NbS remain understudied. It is essential to consider trade-offs alongside synergies to develop comprehensive and sustainable solutions.

Conclusions

Nature offers numerous benefits to people and, through effective management and interaction with the environment, these benefits can be fully realised (Tzoulas et al. 2021). Health considerations should be integrated into climate policy to address climate-related risks. Solutions inspired by nature can play a key role in this process by reducing vulnerabilities and enhancing resilience. Incorporating NbS into policy and decision-making processes paves the way for creating sustainable and resilient communities capable of addressing climate and health challenges (Cohen-Shacham et al. 2019). This approach enhances ecosystem services, promotes biodiversity and improves human well-being, ensuring the well-being of both ecosystems and human populations under changing climatic conditions.

In this study, we analyse the role of NbS in addressing the climate-health nexus, with a focus on identifying synergies and trade-offs. The findings aim to provide evidence-based insights for practitioners to provide information for the design and implementation of NbS initiatives. This evidence-based approach helps to ensure that planned projects do not have long-term negative consequences for ecosystems and people, despite NbS often yielding positive outcome. Solutions must be studied in the local context, considering social aspects and evaluated for long-term impacts, as short-term assessments alone cannot predict all outcomes. Moreover, many projects fail to report potential trade-offs due to inadequate outcome monitoring (Donatti et al. 2022). Future research should

address this gap to minimise trade-offs in upcoming initiatives. Building on these insights, the study also illustrates how practitioners and planners can apply this understanding when selecting and implementing NbS in real-world contexts.

Recognising the climate-health nexus allows planners and practitioners to identify where NbS can create synergies or where they may lead to unintended trade-offs. For instance, in areas exposed to flooding, wetland restoration can regulate runoff, improve water quality and lower flood risk, while also reducing the spread of water-borne diseases. In drought-prone regions, agroforestry practices enhance soil stability and food security, supporting both livelihoods and resilience. However, certain interventions designed for climate mitigation, such as large-scale reforestation for carbon sequestration, can unintentionally introduce invasive species that disrupt ecosystems and increase health risks. Understanding these potential consequences enables decision-makers to design NbS that are locally adapted, ecologically balanced and socially beneficial.

Understanding the nexus also enables urban planners to consider and design cities that enhance both resilience and well-being. Integrating parks, urban forests, green roofs and corridors within city layouts can reduce heat stress, improve air quality, support mental health and contribute to carbon mitigation. Considering nature as an important component of urban infrastructure ensures that NbS are treated as structural elements of resilient cities. Embedding NbS in land-use and zoning plans, alongside health and climate objectives, allows planners to anticipate synergies and manage trade-offs, building cities that are both adaptive to climate change and supportive of human health and quality of life.

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Conflicts of interest

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