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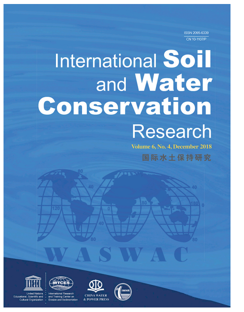

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Nature-based solutions for soil and water conservation in an era of climate extremes: Limitations and future scenarios

Perspective
International Soil and Water Conservation Research

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Paolo Tarolli: Conceptualization, Methodology, Funding Acquisition, Supervision. **Davide Rizzo:** Visualization, Funding Acquisition. **All authors:** Investigation, Writing – original draft, Writing – review & editing.

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Perspective

Abstract

Nature-based Solutions (NbS) have emerged as an effective approach to address environmental challenges while promoting sustainable development. If properly designed, they foster resilient ecosystems capable of adapting to and mitigating threats, such as soil degradation, water scarcity, natural hazards, and climate change. In soil and water conservation, NbS offer adaptive strategies that integrate ecological, social, and economic benefits. However, the unprecedented climate extremes (e.g. heatwaves, prolonged drought, drought-flood coexistence, and extreme rainfall causing destructive flash floods) threaten their functionality. If one solution is effective in the present climate regimes, it is not guaranteed that the same effectiveness will be maintained in future climates (e.g. climate zone shift from temperate to arid with record heatwaves during summer). This challenge is exacerbated when the changes in climate extremes coincide with unexpected shifts in anthropogenic activities. This perspective explores these challenges and proposes some approaches for implementing NbS in soil and water conservation, considering future climate change scenarios.

Nature-based Solutions (NbS) for soil and water conservation

Enhanced Soil Health and Fertility

Nature-based Solutions (NbS) can be defined as *"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), or, in a more operational way, as *"a collective term for solutions that are based on natural processes, in healthy or restored ecosystems, and their services to address the three pillars of sustainability, including climate-related challenges"* (Preti et al., 2022). NbS implemented for soil and water conservation, such as reforestation, agroforestry, cover cropping, and restoration of native shrubs can improve soil structure, organic matter content, and nutrient cycling. Cover crops reduce soil erosion, increase infiltration and water retention, and enhance microbial activity, fostering healthier and more fertile soils.

Drylands, in particular, pose significant challenges for NbS as they comprise an estimated 40-45% of the land surface (excluding Antarctica) supporting the livelihoods of about 2.5 billion people, many of whom live in poverty (Prăvălie, 2016; Shackelford et al., 2021). Soil water deficits in drylands are closely linked to poor soil nutrition, low carbon stocks, weak soil structure, and coarse textures that limit water holding capacity (Plaza et al., 2018). These inherent soil limitations are further compromised by anthropogenic practices, such as extensive overgrazing that compacts soils leading to excessive runoff and gullying, salinization due to poor irrigation practices, excessive cultivation, fire, woody plant removal for fuelwood, and urban sprawl (Ravi et al., 2010; Sidle et al., 2023). Despite these limitations, carefully designed NbS can help alleviate many of the problems associated with soil degradation in drylands, such as reducing water and wind erosion, enhancing soil nutrient status and structure, and mitigating inland soil salinization (Tarolli et al., 2024). Benefits from NbS can also be derived along coastal areas (Tarolli et al., 2023), and by restoring favorable hydrologic functions (Ravi et al., 2010). For example, in degraded drylands, restoration of locally adapted native woody plants enhances soil carbon stocks, soil water retention, and surface stability, supporting food security, particularly in mountain regions with few options for diverse commercial agriculture (Sidle et al., 2023). However, to be sustainable, NbS need to carefully assess local soil, climate, and geomorphic conditions and craft interventions accordingly, as well as consider socio-economic conditions. Given the wide extent of degraded drylands, restoring woody plant cover amongst other NbS holds huge potential benefits for soil carbon sequestration, addressing a significant climate change challenge (Yirdaw et al., 2017).

Water Regulation and Quality Improvement

Restoring wetlands and riparian buffers helps to regulate water flow, reduce flooding and drought risks, increase groundwater replenishment, and improve water quality. The topographical and soil conditions of wetlands, including high soil porosity and significant water-holding capacity (Smakhtin, 2001), enable them to store and retain large amounts of water, playing significant roles in regulating hydrological processes (Acreman and Holden, 2013). This allows wetlands to serve as NbS for enhancing resilience and reducing the risk of hydrometeorological extremes (Ruangpan et al., 2020). Among the regulating ecosystem services of wetlands, moderate-scale flood protection can be achieved by storing water during wet periods and releasing it during dry periods (Acreman and Holden, 2013), acting then as a “sponge”. Wetland and riparian buffer potentials of NbS can improve water quality, facilitating the remediation of contaminated waters, guaranteeing a high pollutant removal efficiency through phyto-remediation (Ferreira et al., 2023). In agricultural areas, the riparian buffer strips can create barriers and mitigate pollution along the watercourse between field management practices and freshwater resources (Cole et al., 2021).

Hillslope stability and soil conservation

NbS are optimal solutions to mitigate soil erosion and mass movements on hillslopes and engineered slopes like road cuts. The benefits of NbS for hillslope stability solutions range from ecoengineering to enhancing stability due to lower water pressure and increased root cohesion by plants (Preti et al., 2022; 2025; Giachi et al., 2024; Gonzalez-Ollauri and Mickovski, 2017a; 2017b; Stokes et al., 2009). While enhanced root cohesion is not a solution for all the mass movements, it can guarantee a progressive, ecologically sustainable restoration of the area (e.g. Gonzalez-Ollauri and Mickovski, 2017c; Preti, 2013) and significantly reduce shallow landslide potential (Sidle and Bogaard, 2016). Some interesting applications are related to Soil and Water Bioengineering (SWB), defined as "*Biology-oriented Engineering, in which native plants and plant fragments are used as living building material which together with the improvement of soil quality can significantly contribute to human safety and face all forms of erosion. In other words, Bioengineering is a discipline that uses plants as element of environmental construction and reconstruction*" (Sangalli et al., 2021; Preti et al., 2022). Such technology can also be applied in low- to medium-income economies with appropriate climate conditions (Preti et al., 2025; Preti and Petrone, 2013; Petrone and Preti, 2010). Successful implementation of NbS also includes forested slopes to prevent rock fall to reach populated areas or critical infrastructure (Dorren and Moos, 2022).

Carbon Sequestration and Climate Mitigation

NbS also have considerable potential for carbon sequestration and related climate change mitigation. Practices like afforestation and soil conservation agriculture store carbon in biomass and soils, reducing greenhouse gas emissions and enhancing resilience to climatic extremes (Pereira et al., 2024). This effect is mostly valid for all the NbS with a large natural component – other examples are urban gardens, and soil and water bioengineering (Pereira et al., 2024; Preti et al., 2022). Especially in urban areas, besides some biogeophysical features, the main constraints on the carbon sequestration capacity of NbS is their management and maintenance status, where poor management can jeopardize carbon sequestration benefits. Converseley, some water-related NbS may have limited carbon budgets and even emit other greenhouse gases, like methane and nitrous oxide (Pereira et al., 2024). However, NbS that focus on providing water for reforestation or afforestation purposes, like fog collection - e.g. Forzini et al., 2025; Certini et al., 2019 - still have a very positive effect in terms of carbon sequestration in vegetation and soils. Agricultural practices that are considered NbS, like conservation agriculture practices (e.g. no tillage and organic mulches), specific cover crops, biochar, or others, have considerable carbon storage potential (Sastre et al., 2020; Payen et al., 2021). However, the exact amount of C stored in each agro-ecosystem depends upon external (climatic) and internal (type of soil, crops, etc.) features. As an example, for agricultural-based NbS in vineyards, carbon storage is high in temperate climates, while it is still relevant - but lower – in hot and dry climates.

Biodiversity Conservation and Restoration

Global biodiversity is currently facing severe challenges (Loreau et al., 2001). It is estimated that about 1 million plant and animal species are facing extinction, accounting for 25% of the total species on earth (IPBES, the United Nations, 2019). The biodiversity loss from deforestation, habitat loss, climate change, pollution, and overexploitation has threatened humans' well-being (Pecl et al., 2017). Despite the great conservation efforts, biodiversity loss is accelerating, and more effective conservation measures are urgently needed. There is increasing recognition of the necessity for NbS, working with nature to cope with environmental challenges such as biodiversity loss (Chausson et al., 2020). Better management and restoration of natural ecosystems, such as degraded forests, wetlands and peatlands, brings multiple environmental benefits, including biodiversity conservation

(Griscom et al., 2017; Seddon et al., 2019). By preserving and restoring natural habitats, NbS protect and increase biodiversity at the level of genes, species and ecosystems. NbS restoration has been demonstrated to positively affect species diversity by providing conditions for the survival and reproduction of a variety of animals and plants and by restoring suitable habitats. Genetically, NbS restoration contributes to gene flow and enhances species diversity by restoring connectivity in natural ecosystems. Diverse ecosystems are more resilient to disturbances, providing long-term stability to soil and water resources. An example is China' s Loess Plateau, the most severe soil and water erosion area in the world. The native vegetation in the Loess Plateau was historically destroyed to meet the food and material supply needs of an expanding population, thereby resulting in severe soil erosion and land degradation (Fu et al., 2022). The Chinese government launched a series of nationwide conservation efforts in 1999, focusing on ecological restoration through NbS protection, such as the “Grain for Green” and the “Grazing Prohibition for Natural Restoration” projects (Fu et al., 2023). These protections have resulted in a great change in landscape and ecosystem functions, including biodiversity (plants, soil microbes and habitat quality) (Zhang et al., 2016). The improved microbial community structure and function facilitates nutrient biogeochemical cycling in soil and in turn, promotes the growth of plants. This above- and below-ground biodiversity interaction sustains ecosystem functions. At the regional scale, habitat quality in the Loess Plateau increased during the restoration, indicating an enhanced ability to provide appropriate environments for local organisms (Zhang et al., 2011; 2016).

Cost-Effectiveness and Sustainability

NbS are often seen as being not as easy to implement as the traditional engineered alternatives, and this is predominantly due to the abundance of widely used standards and calculatable costs of the latter. NbS, however, can be very cost-effective if we can broaden our perspectives of “costs” and “benefits” beyond the traditional domains, e.g., construction costs, avoided damages or protected properties. Here we argue that these solutions can provide innovative and cost-effective alternatives, particularly in water management and climate adaptation. Unlike conventional engineered measures, such as levees that require substantial upfront investments and rigid designs, alternatives such as restoring mangroves and floodplains offer dynamic, multifunctional benefits that evolve with environmental conditions (Temmerman et al., 2013). The latter not only buffers coastal areas against storm surges and reduces erosion but also supports biodiversity, enhances carbon sequestration, and improves water quality (Keech et al., 2023). Admittedly these nature-based approaches may require larger spatial footprints and longer timeframes to achieve full functionality, but their cumulative long-term benefits frequently outweigh initial disadvantages. Furthermore, the adaptive capacity of NbS enables ecosystems to self-regenerate and adjust to changing climatic conditions, thereby reducing the need for continuous, costly maintenance that is often associated with engineered solutions (Barbier et al., 2011). However, in the short and mid-term future, we do not foresee NbS as a complete replacement of traditional infrastructures, but rather as *retrofitting tools* to further promote the compound benefits. For instance, by integrating NbS into coastal management alongside investments of levees, policymakers can harness ecosystem services that provide not only flood protection but also additional co-benefits, including recreational opportunities, improved air quality, and enhanced community resilience while immediately offsetting flood risks. This holistic approach promotes sustainable development by valuing both economic savings and ecological integrity. Ultimately, a comprehensive cost-benefit analysis that accounts for immediate expenditures as well as long-term environmental and social benefits is essential for informed decision-making in climate adaptation and disaster risk reduction (Barbier et al., 2011). Such an integrated perspective underscores the promise of NbS as a resilient and versatile alternative to conventional infrastructure investments. Future research should further quantify these benefits, thereby encouraging broader policy integration and investment in nature-based approaches as a sustainable strategy for long-term risk reduction (Preti et al. 2025).

Community Engagement and Livelihood Enhancement

NbS began as local actions informed by traditional ecological knowledge to manage natural resources for human purposes (figure 1), only later considered for use at larger scales (Cohen-Shacham et al., 2019). This evolution of NbS from local practices to a system-level approach resembles the transition observed in the story of agroecology, namely the application of ecological principles focusing on agricultural systems and practices (Wezel & Soldat, 2009). NbS and agroecology are intrinsically connected to community engagement as they are based on the shared management of local resources for livelihood enhancement (Aguilera et al., 2020; Boivin & Crowther, 2021). In recent decades, these approaches have been re-engineered with scientific expertise to increase traditional knowledge's replicability and integrate technological innovation (Preti et al., 2022; figure 1b). However, NbS deployment often requires coordination among different stakeholders; therefore, it is crucial to ensure inclusive decision-making and community engagement in both the design and implementation phases (WWAP, 2019).

NbS provide direct socioeconomic benefits through job creation and sustainable resource management, while simultaneously addressing critical challenges like food security, water access, and disaster risk reduction. For instance, NbS provide functional integration of hydrological and biological processes both to address climate resilience in water-limited ecosystems (Belete, 2023) and improve flood and sediment management through runoff attenuation features (Robotham et al., 2023); in both cases, localized solutions benefit the entire community that lives in the watershed. The holistic nature of NbS related to natural resources management ensures they deliver multiple benefits that support sustainable development while strengthening the relationship between people and nature, as well as among the different stakeholders that depend on the managed resources. This approach helps identify and resolve conflicting interests among stakeholders, leading to innovative solutions that enhance both ecosystem resilience and human well-being (Snelder et al., 2018). Finally, by aligning environmental conservation with cultural values and societal needs, NbS contribute to more equitable and sustainable outcomes in resource management (Boivin & Crowther, 2021).

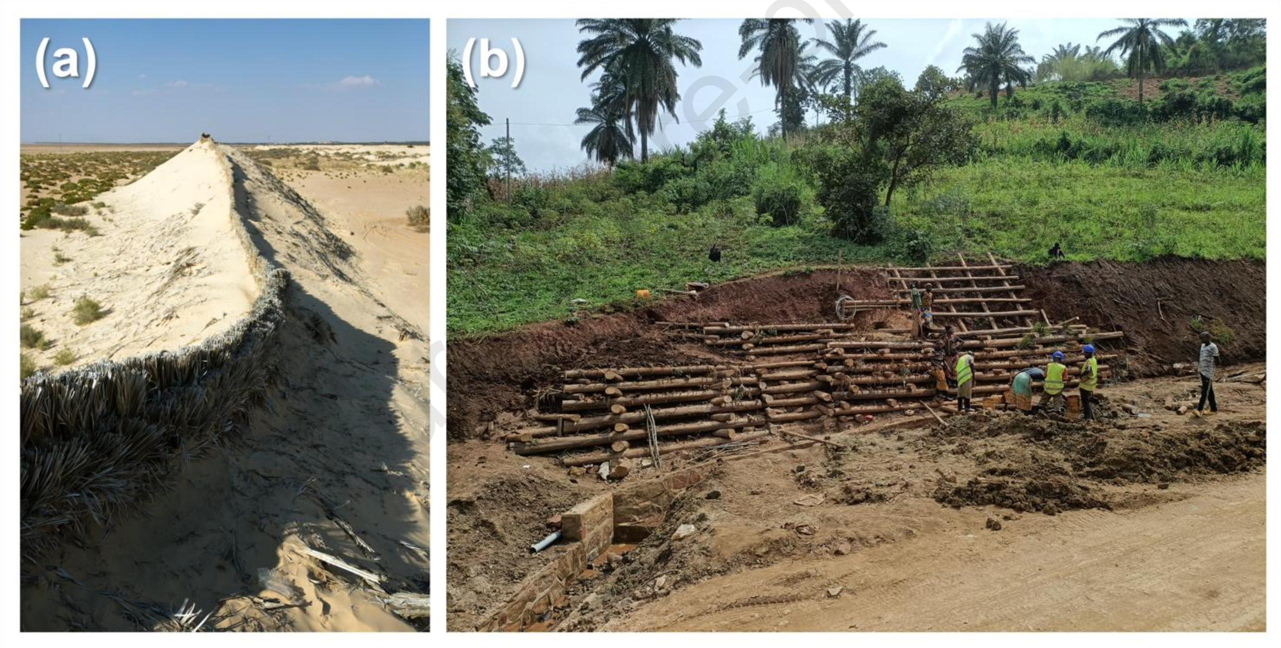

Fig. 1 – Examples of NbS (a) dune restoration and (b) soil and water bioengineering (© IRD - IRA - Christian Lamontagne; Giulio Castelli)

Limitations under climate-change threats

Context-Dependency and Site-Specificity

In contrast to grey infrastructures, NbS are tailored to local physiographic and climatic conditions (Fig.2). A diverse selection of native plant species is typically advocated as the most sustainable and resilient option for NbS in soil and water conservation (Preti et al., 2025). However, shifting climate zones can stress vegetation selected for NbS. This may result in reduced photosynthesis and growth, decreased resistance to pests, or changes in species composition, as exotic species outcompete traditional vegetation due to evolutionary advantages (Seddon et al., 2020; Sidle et al., 2023). Such forest degradation can reduce the effectiveness of rockfall trapping and become less reliable as a mitigating measure (Albrich et al., 2018). Another example, in cases of increased wetness, waterlogging affects root systems, root cohesion, and pore pressure generation, consequently increasing the probability of slope failure. During climate extremes, such as prolonged heatwaves and droughts, entire ecosystems may be lost—for example, due to the migration of invasive pests, abnormally high-intensity wildfires, or a combination of these factors. The effects of climate change on ecosystems are further exacerbated by anthropogenic activities, such as monoculture forestry or forest management in peri-urbanized areas that prevent natural forest fire regimes and, consequently, natural regeneration (Mahli et al., 2020). In general, a landscape, including the ecosystem, is in quasi-equilibrium with its local climate and climate variability. The resilience of the natural system will adapt to gradual changes; however, shocks like unprecedented extremes disrupt the ecosystem to a level that compromises the effectiveness of the NbS (Duffaut et al., 2022). Moreover, NbS cost time to fully deliver the expected benefits. For instance, reforestation efforts may require more than a decade before trees can effectively prevent soil erosion or enhance water retention, while climate change is accelerating. In a constructed wetland, it will take up to 2-5 years for the biodiversity to stabilize with a mature plant and microbial community. It then also reaches peak efficiency in nutrient removal (nitrogen, phosphorus), sediment trapping, and biological filtration. In this adjustment period, if climate extremes occur, NbS may not mitigate devastating floods or other hazards.

Scaling Challenges

Currently, NbS can also be considered as “an umbrella concept that covers a whole range of ecosystem-related approaches, all of which address societal challenges” (Cohen-Shacham et al., 2016, p. 10). This perspective helps to frame the challenges that climate change poses to scaling these interventions (Cohen-Shacham et al., 2019). Scaling NbS is a dynamic process to expand solutions geographically and to integrate them into broader systems. As such, scaling requires balancing relevance, adaptability, and effectiveness of NbS across spatial, temporal, analytical, and jurisdictional scales (Odongo et al., 2022). We focus here on spatial scaling as an illustration of challenges stemming from biophysical dimensions to scale NbS up, down, and out (Fig.2), even though socio-ecological dimensions would also require scaling considerations (Sarkki et al., 2024).

Scaling up extends the amplification of proven local NbS, such as the farmer-managed natural regeneration, a type of agroforestry that involves finding, protecting and managing trees and shrubs from stumps, roots, and seeds to combat land degradation (Kandel et al., 2022), or innovative rainwater management for rainfed agriculture (FAO, 2020). Effective upscaling requires a preliminary study to identify optimal locations based on biophysical features and sociotechnical systems (Préau et al., 2022; Pacetti et al., 2022). However, the replication across large extents of anthropic homogeneous interventions can be vulnerable to extreme events (Phillips et al., 2024). From a wider perspective, scaling up is part of the inclusion of NbS in landscape planning and management. Rigid upscaling strategies risk overlooking the relationships between solution and system characteristics, thus reducing the solution effectiveness, as illustrated by Muñoz et al. (2024) for vegetative barriers and Thorslund et al. (2017) for wetlands at the landscape scale.

Out-scaling replicates context-specific NBS (e.g., wetland restoration) across new regions or sectors while maintaining ecological integrity (e.g., adapting riparian buffer designs from temperate to tropical agroecosystems). These strategies collectively enhance the precision, scalability, and resilience of sustainable soil-water management, ensuring NBS remain effective across diverse spatial, institutional, and climatic contexts. In this framework, the challenge is to define a set of descriptors to enable the comparison of solutions that can be suited to different levels and require connection and adaptation to the specific sociotechnical context, such as ditches and wetlands in an agricultural landscape (Rizzo et al., 2023). The ex-ante evaluation of the relevance and adaptation of NbS for soil and water conservation to new locations can benefit from ecohydrology (Belete, 2023). For NbS in croplands, the potential can be also evaluated based on the services they can provide within the field (Blanco-Canqui, 2024), on the hydrological functioning of watersheds (Lalonde et al., 2024), or at wider scales (Miralles-Wilhelm, 2023). Out-scaling should also be assessed against climatic scenarios to identify the criteria of adaptation to new locations (Pignalosa et al., 2022; Zougmoré et al., 2014).

Down-scaling tailors broad-scale policy interventions to local conditions, such as in the case of the Great Green Wall Initiative in the Sahel region in Africa inspired by the United Nations Convention to Combat Desertification and refined for its deployment by the different member countries to account for local biophysical and sociotechnical specificities (Dia and Niang, 2012). The local implementation of NbS from broader programs faces several site-specific challenges that complicate their downscaling. The effectiveness of NbS varies significantly based on local agricultural and environmental conditions, requiring careful adaptation to specific contexts, often limited by a lack of local data. Limited local knowledge and insufficient site-specific data often hinder proper implementation, as the variability of local conditions can affect short-term success and long-term community engagement (Snelder et al., 2018). For example, an NbS regional program can be scaled down easily on lost parcels of land to be attractive from a political and socioeconomic perspective, but landownership must be addressed in advance (Winterwerp et al., 2025). At the community level, challenges include addressing land ownership issues (Smit et al., 2017), empowering local actors with relevant skills, and integrating traditional practices early in the design and implementation phases. These factors emphasize the need for tailored approaches that consider potential trade-offs.

Potential Trade-Offs

As with all land, water, and environmental management solutions, NbS also involve different trade-offs related to their implementation (Fig.2). The first category of trade-offs is related to competition for land use: implementing medium- to large-scale NbS requires land, and conflicts may arise, specifically over the decision of allocating land for food production or carbon sequestration (Gurgel et al., 2024). These kinds of trade-offs are evident in Africa and, in general, in areas with high land availability and high potential for climate mitigation interventions. This dynamic also encompasses the case of food production-oriented NbS versus climate mitigation-oriented NbS, as they both need land to be implemented and since they have a clear functional trade-off (Gurgel et al., 2024). Functional trade-offs are always present because, despite NbS being conceived to provide different ecosystem services, a one-size-fits-all solution does not exist (Sidle et al., 2023). For instance (see section on carbon sequestration and climate mitigation) water-oriented NbS have high potential to provide water-related ecosystem services as water retention and flood reduction, but, in turn, they cannot have high performances in sequestrating CO_2 from the atmosphere (Pereira et al., 2024). Trade-offs can also involve multi-functionality. In particular, within the same domain, trade-offs can exist among NbS targeting one function and others with multi-functionality. One example related to NbS is afforestation and reforestation for climate mitigation, where policies can create an enabling environment only for mono-species forestation projects targeting only carbon storage, while multi-functional forestation with multiple species and an ecosystem approach are penalized (Seddon et al., 2020). Finally, planning and governance trade-offs exist, in particular for urban areas. Their analysis involves environmental justice considerations, considering how many solutions are installed, where, in which temporal frameworks, and if targeting certain vulnerable social groups or other parts of urban/rural areas (Stijnen et al., 2024; Pacetti et al., 2020).

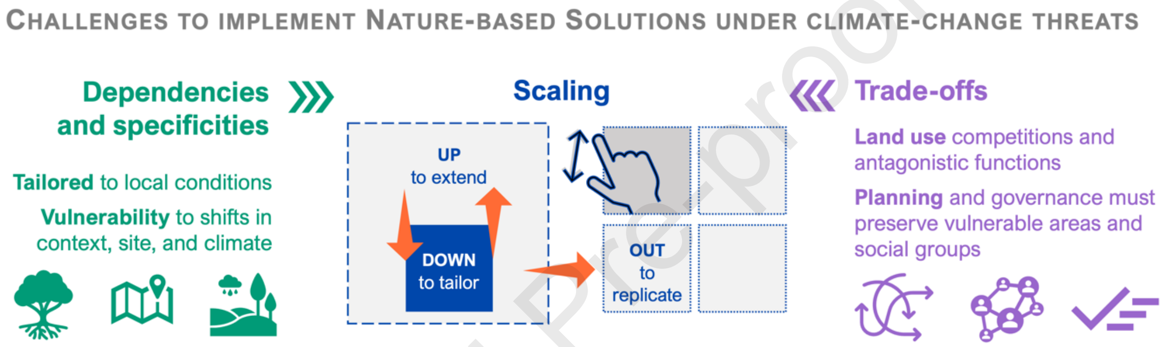

Fig. 2 – Conceptual diagram of NbS limitations under different aspects

Perspectives and Future Scenarios

Integration with Technology

Technology advances can enhance the design and monitoring of NbS (Fig.3). Remote sensing, GIS, and AI-driven models can optimize site selection, assess ecosystem performance, and predict future scenarios under varying climatic conditions. Remote sensing technologies, including satellite imagery, aerial drones, and LiDAR, provide high-resolution spatial and temporal data that aid in assessing land cover, vegetation health, hydrology, and soil conditions (Straffelini et al., 2023; Xue et al., 2024). For example, multispectral and hyperspectral sensors can detect vegetation stress, soil moisture levels, and water quality, which are critical for wetland restoration and afforestation projects. Drones equipped with thermal and infrared sensors allow for localized and real-time monitoring of NbS projects, detecting changes in ecosystem dynamics that are otherwise difficult to measure. For instance, in urban green infrastructure projects, drones can track the cooling effects of green roofs and tree canopies, helping to assess their contribution to mitigating the urban heat island effect. Such analyses can be realized by directly inferring ground-level variables (such as temperature, Tucci et al.,2019), or via normalized difference indices (e.g. Bonifazi et al., 2023; Castelli et al. 2019a; 2019b). Although controversial, it will be interesting to investigate whether AI and machine learning models could enhance the ability to predict how NbS will perform under different climatic and environmental scenarios. Effectiveness of NbS can be monitored in terms of biodiversity, soil quality, water conservation, and greenhouse gases emission. Based on the data and results of published detailed scientific studies, larger scale experiments and case studies, these models could potentially identify patterns and trends, improving forecasting capabilities for ecosystem responses to climate change, pollution, and land-use changes. For example, AI-driven hydrological models can predict the effectiveness of constructed wetlands in filtering pollutants under varying precipitation patterns. Similarly, AI-based climate models can assess how urban green spaces will contribute to temperature regulation in future climate scenarios, helping city planners optimize green infrastructure strategies. Moreover, AI-enhanced image processing techniques enable automated detection of ecosystem changes over time, reducing the need for manual assessments and improving the efficiency of long-term monitoring. This is particularly useful in large-scale conservation projects, where traditional monitoring methods may be labor-intensive and costly.

Resilience Planning and Climate Adaptation

Planning resilient NbS in a warming climate requires a thoughtful articulation of the desired ecosystem services that can be delivered as well as their respective priorities – e.g., disaster risk reduction, enhancing biodiversity and food security, mitigating climate change, and soil and water conservation, or some combination of these. Such planning decisions should be based on local biophysical and socioeconomic conditions, as well as how NbS may benefit 'downstream' areas, recognizing that anthropogenic interventions and climate footprints exert different spatial and temporal effects on hydrologic processes and sediment transport and connectivity (Sidle et al., 2017). Given that water stress is a major limitation in successful NbS implementation in agricultural drylands, practices such as contour cultivation, limited tillage, mulching, climate-smart agriculture (e.g., water-saving irrigation methods, selecting drought-adapted seeds), rotational grazing, crop rotations, off-channel watering points for livestock, and selecting salinity and drought tolerant species are potential effective measures when combined with spatially explicit climate information (Delgado et al., 2013; Sidle et al., 2023). NbS that incorporate trees need to be carefully planned in accordance with granular climate data and projected changes to ensure long-term success of plantations. Many drylands are projected to experience increasing drought and fire in future years, necessitating precise tree selection, water conservation measures, and nursery preparations (Ramo´n Vallejo et al., 2012). Agroforestry NbS offer multiple benefits where applicable, particularly on hillslopes, where slope stability, soil hydrology, soil nutrients, and organic matter produced enhances soil properties and carbon sequestration (Zhu et al., 2020).

Policy and Governance Frameworks

The adoption of NbS requires robust policy support and sound governance mechanisms (Fig.3). Policy instruments can be classified as (i) Legislative, regulatory and strategic instruments, such as urban planning mechanisms or construction standards; (ii) Economic and fiscal instruments, for instance, incentives or payment for ecosystem services; (iii) Agreement-based or cooperative instruments, of which Private-Public partnerships are examples; and (iv) Knowledge, communication, and innovation strategies (Davis et al., 2024). Davis et al. (2024) also identifies key criteria for assessing NbS-related policies which should be: (1) Effective, (2) Inclusive, (3) Innovative, (4) Locally appropriate, (5) Supportive of multifunctional NbS, (6) Sustainable in the long term, and (7) Upscalable.

We highlight how such criteria aim to resolve part of the trade-offs typically encountered in NbS implementation, indicating that policies should favor an inclusive environment (i.e., targeting different social groups) and support multifunctional solutions (Frascaria-Lacoste et al., 2025).

Besides this classification, a key element of NbS policies is to support stakeholders with a sound framework to define what is and what is not an NbS (Preti et al., 2022). Additionally, from a solution-oriented perspective, NbS and similar measures can be framed within the Sustainable Development Goals to focus on their contribution to specific goals (Rodrigues et al., 2024). Specific attention in agricultural contexts can be given to ecosystem services provided to communities and cities located elsewhere, such as supporting the management of sediment flows - also involved in the distribution of pollutants - making NbS eligible for targeted subsidies and other schemes such as Payment for Ecosystem Services (Robotham et al., 2023). Finally, supporting adaptive and transformative management projects to assess and promote the development, assessment, and deployment of hybrid solutions (Uzielli et al., 2025; Preti et al., 2025) can facilitate shifts toward greater adoption of NbS even in contexts where gray solutions were usually the only option considered by stakeholders (Anderson et al., 2022).

Blended (Hybrid) Approaches

Combining NbS with traditional engineering approaches on grey infrastructure provides a hybrid strategy for soil and water conservation in both agricultural and urban settings. However, the transition towards greener grey infrastructure varies significantly between rural and urban areas due to historical, socio-technical, and biophysical factors. Consequently, the prospects for NbS in these two contrasting contexts differ (Recalde et al., 2024). In cities, water management has been governed for decades by a hygiene approach (Workman et al., 2021), prioritizing underground water transport through pipes and storage in grey infrastructure. While there remains significant potential for expanding NbS in urban areas (UNESCO, 2018), climate adaptation efforts incorporating NbS have rapidly increased. This is largely because their implementation can be swiftly decided by a single public authority that owns the necessary land for an integrated infrastructure network. NbS in urban environments often involve vegetation planted on technosoils, leading to artificial surface structures such as vegetated urban ditches (Koning et al., 2023). While these interventions immediately enhance urban biodiversity alongside their intended functions, such as water retention (Oral et al., 2020), further research is needed to assess their sustainability and long-term efficiency. Key concerns include pollution mitigation in soil and waters (Seddon et al., 2020), the resilience of artificially introduced vegetation on NbS, which does not form part of a pre-existing ecosystem (Sjöman et al., 2024), the impact of fluctuating anthropogenic pressures (Seddon et al., 2020) and the increasing frequency of extreme climatic events (Oral et al. 2020). The concept of greening grey infrastructure for soil and water conservation in rural areas is more debatable. Vegetated infrastructure for these purposes, created through the relocation of local soil materials (Rizzo et al., 2025), has existed for centuries worldwide. Hybrid approaches and NbS are therefore deeply rooted in rural practices, where farmers have long relied on adaptive and hybrid strategies. As a result, purely grey infrastructure is rare, except in cases such as the modernisation of drip-irrigation systems. Even sparsely vegetated rural infrastructure, such as dry-stone terrace walls, creates synergistic effects that enhance soil and water conservation while providing habitats for specific species (Manenti, 2014). Indeed, blended approaches to soil and water conservation are not new to farmers. However, in the era of agroecology, their value in enhancing biodiversity is increasingly recognised. In this context, their resilience to global change must be further explored, particularly regarding shifts in biotic processes. Additional research is therefore required in three key areas: (i) understanding ecosystem dynamics within NbS under both climate stress and anthropogenic interventions (Rudi et al., 2020), and how these dynamics influence the services and efficiency of NbS, in line with functional ecology theories (Ramachandran et al., 2024); (ii) identifying the factors influencing infrastructure maintenance, as upkeep by farmers and other local stakeholders is a key determinant of its lifecycle and effectiveness (Rizzo et al., 2025); and (iii) developing an interdisciplinary approach to identify appropriate policy support and governance mechanisms for the long-term sustainability of hybrid infrastructures in rural areas, where land-sharing involves complex landscape interdependencies (Giroux et al., 2020) and land tenure issues remain challenging (King et al., 2023).

Community-Based Approach

A community-based approach to NbS in landscape planning offers transformative potential but faces critical challenges: governance barriers, such as fragmented policies and institutional inertia, must be addressed through participatory research to align NbS with local priorities (Albert et al., 2019; Preti et al., 2025). Effective co-development requires reconciling diverse stakeholder interests—from farmers to indigenous groups for example—while bridging knowledge gaps about NbS effectiveness across spatiotemporal scales (Cohen-Shacham et al., 2019). For instance, unclear representation of soil multifunctionality into maps complicates adaptive planning, and can increase institutional agendas conflicts (Courteille et al., 2024), weakening community voices. Yet, empowering communities as codevelopers of NbS through decentralized decision-making and iterative learning could foster resilient, culturally grounded strategies, such as integrating traditional agroforestry with modern hydrology models, ultimately transforming these challenges into pathways for equitable, climate-smart landscapes (Arheimer et al., 2024).

Market-Based Mechanisms

Future scenarios of NbS implementation could see greater involvement of the private sector through market-based mechanisms. Payment for Ecosystem Services represents one of the most interesting market-based solutions for NbS financing (Davis et al., 2024), especially for those that target soil and water conservation in a rural context, where communities can benefit from the payment for protecting valuable assets (e.g., cities) located downstream (Pacetti et al., 2022; Gallay et al., 2021). Carbon credits are another possible solution, especially for afforestation projects, even if they could lead to the risk of favoring monofunctional NbS (Pereira et al., 2024). Finally, and specifically for the domain of water conservation, water funds for watershed management can attract investments and ensure financial sustainability for NbS initiatives (Castelli et al., 2017; Kaufmann et al., 2014). Such a solution, however, is still only at the pilot level in many regions of the world.

In this sense, future developments in Marked-based Mechanisms should identify financial solutions that facilitate investment in NbS, and similar initiatives, translating them into products that are viable for markets. At the same time, it is necessary to select suitable environmental evaluation criteria for the effects of investments, which could be integrated in Environmental, Social, and Governance (ESG) schemes, also aligning them with the objectives of the Paris Agreement (CPI, I4CE, 2024).

Scaling Up and Replication

Scaling up successful NbS from pilot projects to full-scale implementations requires not only rigorous evaluation of local performance but also a robust framework for adapting these initiatives to diverse environmental, social, and economic contexts (Maxwald et al., 2022; Preti et al., 2025). Such local pilots have evidently showcased how NbS can effectively address challenges such as flood risk management, biodiversity loss, and climate change adaptation while respecting the localities (Temmerman et al., 2013). However, replicating these successes at larger scales necessitates a detailed understanding of local ecosystems and communities to ensure that the interventions are tailored to meet specific needs and conditions (Seddon et al., 2020). Knowledge exchange through international partnerships plays a critical role in this process. By sharing best practices and lessons learned, stakeholders can identify common pitfalls and opportunities, thereby streamlining the adaptation process across different regions (Cohen-Shacham et al., 2016). Collaborative networks that bring together scientists, policymakers, practitioners, and community members are instrumental in developing innovative approaches that are both context-sensitive and scalable. Moreover, policy support at both national and international levels is essential to foster an enabling environment for NbS implementation. Incentives, capacity-building initiatives, and cross-border collaborations can accelerate the adoption of NbS and ensure that they are embedded in broader sustainable development strategies. As climate change and urbanization continue to exert pressure on natural systems, scaling up NbS is not merely an option but a *necessity*. Nevertheless, wide upscaling of NbS without embracing the environmental and social nuances at granular scales is not advisable (Forzini et al., 2022). Looking forward, we herewith highlight the need of acceptable standards and adaptable frameworks to facilitate the transfer of successful NbS from local projects to regional solutions, ultimately contributing to a more resilient and sustainable future. Additionally, it is imperative that evaluation metrics and monitoring protocols be standardized to accurately assess the long-term impacts and co-benefits of NbS. Such data-driven insights will not only validate the effectiveness of these solutions but also provide a foundation for continuous improvement and adaptive management in diverse global settings.

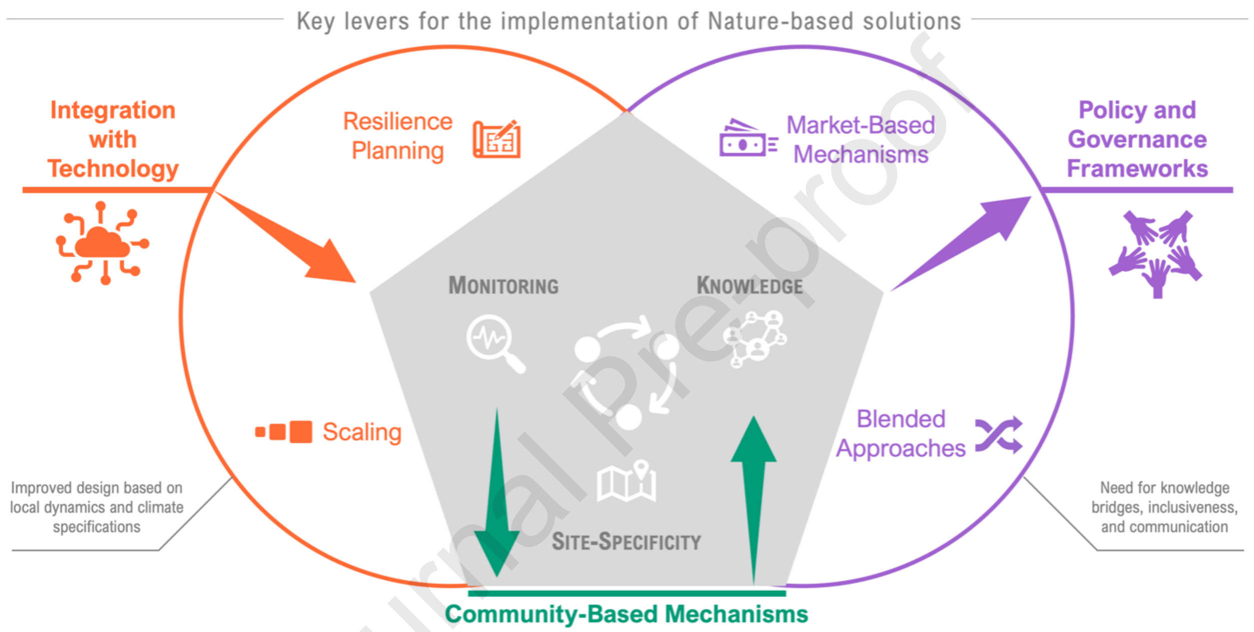

Fig. 3 – Conceptual diagram of the perspectives/solutions proposed to deal with future criticalities

Conclusion

Nature-based Solutions have significant potential for conserving soil and water resources while addressing broader environmental challenges. Their multifaceted benefits, including enhanced biodiversity, climate mitigation, and community well-being, make them an essential component of sustainable development strategies. However, their implementation faces several challenges, including site-specific limitations, scalability issues, and potential trade-offs. These challenges are worsened by the growing climate extremes. To maximize the potential of NbS, future efforts should focus on integrating advanced technologies, developing supportive policies, and promoting community engagement. We need to provide innovative funding mechanisms and, overall, a new framework to further improve their effectiveness and scalability.

CRediT authorship contribution statement

Paolo Tarolli: Conceptualization, Methodology, Funding Acquisition, Supervision. **Davide Rizzo:** Visualization, Funding Acquisition. **All authors:** Investigation, Writing – original draft, Writing – review & editing.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: