XXII Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica
XI Simpósio Brasileiro de Engenheiros Geotécnicos Jovens
24 a 28 de agosto de 2026 – Brasília/DF
DOI: 10.47094/COBRAMSEG2026.6/97

Improving Cities' Resilience through Nature-Based Solutions (NbS)

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RESUMO: A intensificação das mudanças climáticas tem aumentado a frequência e a severidade de eventos extremos, como a onda de calor de 2025 na Europa e as inundações no sul do Brasil, em 2024. As Soluções Baseadas na Natureza (NBS) oferecem um caminho promissor para aumentar a resiliência da infraestrutura urbana por meio do sequestro de carbono e da restauração de ecossistemas naturais e modificados. Para examinar os benefícios da aplicação de NBS no nexo solo–água–planta no desenvolvimento de cidades resilientes, este estudo baseia-se em uma revisão da literatura e na troca de conhecimentos entre pesquisadores das áreas de recursos hídricos, biologia e geotecnia da Europa, América do Sul e América do Norte. A síntese deste trabalho demonstra que as NBS fortalecem a resiliência urbana por meio da regulação do carbono e dos processos hidrológicos, da redução dos riscos de inundações e secas, da mitigação da poluição da água e do aumento da estabilidade das encostas. O nexo solo–água–planta representa as interações dinâmicas entre a saúde do solo, os processos hidrológicos e o desempenho da vegetação, fundamentais para a eficácia das NBS na mitigação dos impactos climáticos e na construção de uma infraestrutura urbana mais resiliente.

PALAVRAS-CHAVE: Nexo Solo–Água–Planta; Cidades Sustentáveis; Impactos das Mudanças Climáticas; Restauração Hídrica; Estabilidade de Encostas

ABSTRACT: The intensification of climate change has increased the frequency of extreme events, such as the heatwave that struck Europe in 2025 and the flooding in Rio Grande do Sul, Brazil, in 2024. Therefore, there is an increased need for resilient cities. Nature-based Solutions (NBS) can enhance the resilience of urban infrastructure through carbon sequestration and the restoration of natural and modified ecosystems. Aiming to explore the advantages of utilising NBS within the Soil-Water-Plant nexus for the development of resilient cities, this research was carried out based on a literature review and on the exchange of knowledge among researchers in water resources, biology, and geotechnics from three regions of the world (Europe, South America, and North America). The synthesis presented in this review shows that NBS enhance urban resilience by supporting climate action, particularly through carbon regulation, improved water regulation, reduced flood and drought risks, mitigation of water pollution, and increased slope stability via plant root systems that

strengthen soil cohesion. The soil-water-plant nexus reflects the dynamic interactions among soil health, hydrological processes, and vegetation performance, which are essential to the success of NBS in mitigating climate impacts and creating a more resilient urban infrastructure.

KEYWORDS: Soil-Water-Plants Nexus, Sustainable Cities, Climate-related changes, water restoring, slope stability

1 INTRODUCTION

The current trend of climate change increases the frequency of extreme hydrometeorological events, significantly affecting natural systems and human infrastructure (Igwe and Una, 2019). Events such as the heatwave that struck Europe in 2025 and the flooding in Rio Grande do Sul, Brazil, which left the city of Porto Alegre underwater for more than two weeks in May 2024 and caused severe infrastructure damage across southern Brazil, are becoming more intense and more frequent. Reflecting the urgency of these impacts, the Paris Agreement promotes the incorporation of urban resilience and adaptation strategies into countries' Nationally Determined Contributions (NDCs) (Dodson et al., 2022).

Conventional strategies for resilient cities often focus on lowering surface temperatures or enhancing urban aesthetics; however, Nature-based Solutions (NBS) deliver broader environmental benefits by fostering evapotranspiration, strengthening stormwater control, and sustaining urban biodiversity. Introduced by the International Union for Conservation of Nature (IUCN) at COP15 in 2009, NBS refer to interventions that conserve, sustainably manage, and rehabilitate natural or altered ecosystems in order to address societal challenges in an effective and adaptive manner, while at the same time enhancing human well-being and supporting biodiversity (Berg et al., 2024; Choi et al., 2023). By working in harmony with ecological processes, NBS represent a holistic and effective pathway for urban climate mitigation.

The increasing uptake of NBS in policy, research, and development reflects a shift toward more holistic strategies to enhance climate resilience and urban sustainability. However, for this momentum to be translated into meaningful outcomes, NBS must be supported by rigorous, systematic, and multidisciplinary research. Positioning NBS as an effective climate action aligned with the Sustainable Development Goals and the Paris Agreement depends on strong scientific evidence of their effectiveness, social equity outcomes, and long-term durability. Nature-based solutions (NBS) rely on the interactions among soil, water, and vegetation. Accordingly, this study aims to review the application of NBS from a soil–water–plant nexus perspective, highlighting their potential as a strategy to enhance urban resilience.

2 METHODOLOGY

This research is based on a literature review and exchange of knowledge among researchers in water resources, biology, and geotechnics from three regions of the world (Europe, South America, and North America) from the universities of the University of Illinois Urbana-Champaign (UIUC), University of Birmingham (UoB), and the Federal University of Campina Grande (UFCG). The literature was obtained from several well-established databases, including Scopus, Springer, Elsevier, and Taylor & Francis Group, to explore the advantages of utilising NbS within the Soil-Water-Plant nexus, with a focus on climate, water restoration, and slope stability resilience.

3. NATURE-BASED SOLUTION FOR CLIMATE-RESILIENT URBANS

3.1 Climate Resilience Benefits of NBS

Nature-based solutions contribute to climate change mitigation by conserving, sustainably managing, and restoring natural and altered ecosystems, thereby strengthening ecosystem resilience while delivering co-benefits for human well-being and biodiversity. Current estimates indicate that NBS could provide 30–40% of the necessary CO_2 mitigation by 2030 and that natural climate solutions have a probability greater than 66% of limiting global warming to below 2 °C (Cotrell 2022).

Ground vegetation cover plays a central role in regulating the carbon balance, with direct consequences for both regional and global carbon budgets (Mendes et al., 2025). Evidence from Oliveira et al. (2023) indicates that vegetated areas exhibit greater water availability and carbon sequestration potential, reinforcing the importance of sustainable strategies such as Nature-Based Solutions (NBS).

Although not all NBS exhibit the same capacity for carbon sequestration. Carbon stocks vary considerably across urban green infrastructure types, with tree groups and woodlands storing the most carbon, whereas grassed areas, green roofs, and street trees generally store substantially less. (Jones et al. 2022)

Nature-based solutions may also increase certain ecosystem negative services that must be accounted for in planning and design. For example, lakes and constructed wetlands can act as sources of methane emissions, potentially offsetting part of their climate benefits (Pereira et al. 2023). Camacho-Caballero et al. (2024) showed that the expansion of urban agriculture can unintentionally increase heat vulnerability and may fail to lower nighttime temperatures in sensitive urban areas such as Barcelona. Consequently, inadequately planned NBS may intensify, rather than mitigate, climate-related risks.

Therefore, climate-resilience NBS depend on how well they are tailored to their intended function and local environmental conditions (Pereira et al., 2024). Such context-specific design is essential to maintain stable carbon storage over the long term, even under changing climatic conditions. At the same time, embedding these regulating services within a wider ecosystem-services framework enables meaningful comparison and the identification of potential trade-offs (Keith et al., 2021)

3.2 NBS in the improvement of water restoration

In water management, NBS encompasses a range of measures, including the protection and enhancement of water resources and associated ecosystems; the mitigation of impacts from natural hazards such as floods and droughts, as well as from urbanisation and human-induced pollution; and the conservation or enhancement of biodiversity. Wetlands, for example, can be restored to reduce the risks of flooding and water scarcity; they can also mitigate climate change impacts through carbon sequestration, while simultaneously delivering benefits to ecosystems and society. Similarly, restoring a channelised river to a more natural state can increase biodiversity and strengthen ecosystem resilience, while reducing flow velocity and limiting the impacts of potential flooding. The revegetation of civil engineering structures along riverbanks can also be regarded as an NBS(Rey et al. 2026).

NBS enables the natural treatment of stormwater and supports aquifer and stream recharge. They can reduce the required capacity of collection and conveyance systems, as well as of associated wastewater treatment plants, thereby lowering costs (Lafforgue, 2016). A case study from Bozcaada (Türkiye), conducted by Şamiloğlu et al. (2025), showed that strategically located rainwater ponds, a type of NBS, enhance seasonal water availability, reduce reliance on external water sources, and provide year-round support for native species. Lafforgue (2016) says that the interaction among soil, vegetation, root systems, and associated mycorrhizae enables the retention and/or remediation of a wide range of pollutants (Lafforgue, 2016). In this way, Engelke et al.(2025) evaluated Constructed Floating Wetlands (CFWs) on two urban waterways in Seattle, Washington, USA, over four years. Monitoring data from the organic plant root substrate showed that the CFWs efficiently removed heavy metals and nutrients from water under both freshwater and brackish conditions, whereas results for carbon sequestration were mixed.

Additionally, according to Ramírez-Agudelo et al. (2020), natural elements in urban environments can help control surface runoff and mitigate the impacts of drought by enhancing infiltration capacity, providing temporary water storage, increasing evapotranspiration, and supporting urban biodiversity.Therefore, well-designed water NBS can enhance resilience to water scarcity and pollution, mitigate hydrological problems, and promote biodiversity and quality of life.

3.3 NBS in the improvement of slope stability

Landscapes have become increasingly vulnerable to extreme events, a condition further intensified by changes in land use and management practices, particularly in fragile environments such as agricultural and forested areas. The abandonment of these territories has led to the loss of traditional land management practices,

especially water and vegetation control systems (e.g., dry-stone walls, channels, drains, and drainage networks), which were essential for maintaining stability in these areas.(Tarolli et al., 2014)
Soil bioengineering that employs vegetation has proven to be an ecologically sound, environmentally sustainable, and cost-effective approach for mitigating shallow landslides. (Mickovski et al., 2005; Yan et al., 2010). Therefore, according to Leug et al. (2023), NBS have been recognised as sustainable and environmentally friendly approaches for enhancing slope performance through root reinforcement and changes in soil matric suction induced by plant transpiration.
Sonnenberg et al. (2010) were among the first to investigate how willow roots of different ages influence soil pore-water pressure and slope deformation under varying groundwater levels. Their results showed that vegetated slopes exhibited less progressive failure than bare slopes. Similarly, Askarinejad and Springman (2015) demonstrated that slopes reinforced by *Avena sativa* roots present higher infiltration capacity and greater resistance to deformation when compared with unvegetated slopes.
Prasetyaningtiyas et al. (2024), in a centrifuge study evaluating the effect of Vetiver (*Chrysopogon zizanioides*) on slope stability, observed that slope failure initiated at the crest, where root density was low. In contrast, near the slope toe, where a denser root network was present, little to no failure occurred. This behavior was likely due to the effective mobilisation of root–soil interfacial resistance and the tensile strength of the roots, which enhanced resistance to shear and sliding mechanisms. The same author also showed that, for a numerical model to realistically represent failure, the change in soil properties induced by the root should be considered.
Li et al. (2024) also studied the influence of vetiver root on soil properties using triaxial tests. They found that roots improve soil cohesion more effectively than the soil friction angle, resulting in a higher safety factor for grass-covered slopes than for bare slopes. Similar results were obtained by Rahim and Naveed (2026) using Festuca arundinacea (tall fescue), alone and with symbiosis with mycorrhizal fungi (MF)
Kang et al. (2026) showed, using direct shear tests and numerical simulations, that the roots of herbaceous vegetation reduce progressive failure by increasing soil strength and altering the shallow subsurface hydrological regime, thereby improving slope stability.Therefore, the integration of vegetation properties into the engineered design of green infrastructure, such as slopes, is essential for improving the stability and resilience of green infrastructure.

3.4 Soil-water plant nexus

The soil–water–plant nexus provides an integrated, interdisciplinary lens for designing and evaluating urban NBS (Negm et al., 2019). It can be interpreted through the combined perspectives of hydrology, hydropedology, ecohydrology, and hydrogeomechanics, because this nexus integrates soil hydromechanical behaviour, plant water-uptake strategies, evapotranspiration, and nutrient cycling into a tightly coupled system governed by reciprocal feedbacks.
Vegetation alters soil structure and moisture dynamics, while soil properties determine how effectively plants can access water and nutrients. Within this system, root development reshapes soil pore networks and aggregation, plant physiology regulates transpiration, and water is continuously redistributed through the soil profile. Together, these interacting processes promote nutrient retention, improve infiltration, improve soil strength, and preserve soil structure, thereby strengthening overall resilience. Therefore, this nexus has the potential to regulate urban microclimates, sequester carbon, support biodiversity, contribute to land restoration by limiting soil erosion and landslides, and promote social equity through improved access to urban green spaces and green infrastructure (Figure 1).

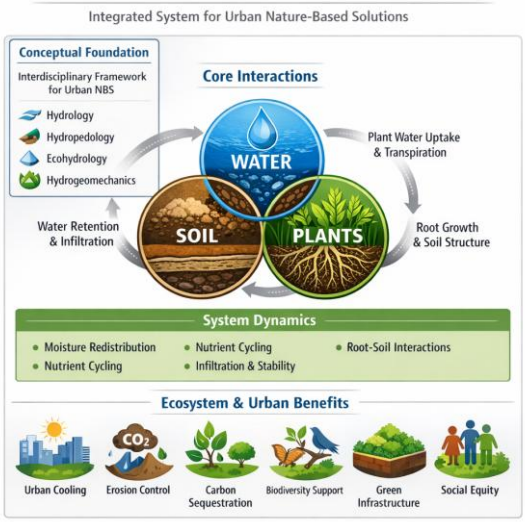


Figure 1- NBS in the optic of the Soil-Water-Plant nexus

Its functions are synergistic: healthy soils retain more water and provide a solid base for infrastructure; dynamic hydrologic processes, especially soil moisture, improve soil health and support vegetation; robust plant systems provide cooling through evapotranspiration and shade, stabilise soils, and promote infiltration. Additionally, plants propagate and expand their root systems, creating favourable conditions for biodiversity growth, and as the root systems develop, they also enhance soil resistance and cohesion over time, thereby increasing the resilience of human infrastructure (DiBiagio et al., 2024)

From a climate-resilience perspective, the soil–water–plant nexus acts as a key stabilising system against hydrological extremes. It supports drought resistance by maintaining soil moisture, reduces flood impacts by regulating runoff, and promotes ecosystem functioning through improved nutrient cycling.

Therefore, by capturing the interdependence of soil properties, water dynamics, and vegetation function, this framework underpins the effectiveness of NBS in reducing climate-related stresses. (Aboelata and Sodoudi, 2020; Morakinyo et al., 2020).

4. FINAL CONSIDERATIONS

Nature-Based Solutions (NBS) represent an innovative approach to urban resilience because they promote “design with nature” rather than “design against nature.” The synthesis presented in this review highlights several key findings. (i) Soil structure and root system dynamics play a decisive role in regulating ecosystem responses, particularly with respect to soil erosion and slope stability. (ii) Although NBS can support climate-resilience strategies through carbon sequestration and climate regulation, their effectiveness depends on being carefully planned and designed according to local environmental and socio-ecological conditions. (iii) The increasing occurrence of landslides under climate change can be mitigated through NBS, as plant root systems enhance soil cohesion and infiltration capacity. (iv) NBS can naturally reduce flood and drought risks, improve water quality, and enhance infiltration, thereby promoting aquifer and stream recharge. (v) More broadly, nature-based solutions demonstrate how soil–water–plant interactions can be harnessed for both climate mitigation and adaptation.

The soil–water–plant nexus, therefore, provides a fundamental basis for climate-resilient land and water management, as it governs water fluxes, nutrient cycling, and vegetation dynamics that underpin ecosystem services essential to both human well-being and ecological integrity.

Nevertheless, deploying NbS is complex due to the need for upfront capital, multidisciplinary expertise, and coordinated actions to enable integrated resource management.

ACKNOWLEDGMENTS

The author would like to thanks the BRIDGE Project from University of Illinois Urbana-Champaign (UIUC) and University of Birmingham (UoB).

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