



A Decision-Support Framework for Nature-Based Solutions for Climate Adaptation and Mitigation: A Case Study of the Sardinia Region, Italy

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ABSTRACT

The study developed a framework that integrates multicriteria land suitability analysis with a decision-support tool to guide funding allocation and the spatialization of nature-based solutions (NbS) at the regional scale. The approach prioritized areas most affected by climate change impacts, environmental pressures, and conditions of exposure and vulnerability. Focusing on urban contexts, the study highlights NbS as a central strategy for sustainable development and climate change adaptation and mitigation. The proposed framework was designed as a replicable tool to support the identification of suitable areas for NbS implementation, ensuring the efficient use of financial resources; maximizing environmental, social, and economic benefits; and enabling transparent and informed decision-making. The framework was applied to a case study in Sardinia, Italy. The findings confirm its relevance for the spatialization of public policies and for enabling the integration of mitigation and adaptation strategies into urban and territorial planning.

KEYWORDS

Climate Change, Mitigation, Adaptation, Nature Based Solutions, Urban Areas, Decision Support Tool, Sustainable Development Goals, Sardinia

INTRODUCTION

In Italy, approximately 70% of the population resides in urban areas with populations between 10,000 and over 100,000 inhabitants. The concentration of population, infrastructure, and economic activities in cities makes urban areas both major contributors to climate alteration and highly exposed to its impacts (Lwasa et al., 2022). Interactions among urban form, exposure, vulnerability, and direct climatic pressures can exacerbate adverse impacts specific to individual urban contexts (Dodman et al., 2022). Concurrently, urbanization and land-use conversion processes drive ecological degradation, fragmentation, disruption of ecosystem services, and biodiversity loss (Mosisa et al., 2025).

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The Italian National Strategy for Adaptation to Climate Change (Italian Ministry for the Environment, 2015) identifies soil erosion, land degradation, flooding, localized temperature increases, and heatwaves as the main climate-related hazards affecting urban areas. These phenomena are expected to trigger further consequences, including infrastructure disruption, increased energy demand, water scarcity, reduced productivity, changes in social interaction, and declining quality of life—particularly among disadvantaged populations.

Consequently, strengthening adaptation and mitigation in urban environments is essential for advancing climate resilience and sustainable urban development. Fundamental international and European policy procedures—including the 2030 Agenda for Sustainable Development (United Nations, 2015), the New Urban Agenda (United Nations Habitat, 2017), and the Urban Agenda for the European Union (European Commission, 2021)—emphasize the need for integrated strategies addressing disaster resilience, climate mitigation, and adaptation in cities.

Aligning mitigation strategies with sustainable development goals can foster sustainable urban development trajectories. However, potential trade-offs and interactions among specific mitigation measures, as well as among mitigation, adaptation, and broader sustainability objectives generally, must be assessed (Bush & Doyon, 2019; Choi et al., 2021). Within this perspective, the study focused on the implementation of nature-based solutions (NBS; International Union for Conservation of Nature, 2021) and addressed two research questions:

- How can spatial and environmental information be structured to support the planning of NbS?
- How can a decision-support procedure be developed to guide the allocation of limited financial resources for NbS under site-specific climatic and environmental conditions?

The existing literature provides only a limited number of contributions on the development of spatial analysis-based methods for allocating climate change mitigation and adaptation measures based on an NBS approach. Moreover, most studies have focused on the municipal scale (Battisti et al., 2024; Cortinovis et al., 2022; Feroz & Rana, 2025; Longato et al., 2023) or have neglected the financial constraints imposed by the limited resources within existing programs and policy frameworks (Zaniboni et al., 2025). To respond to these questions, this study developed a procedure that combines multicriteria land suitability analysis with a decision-support tool to support funding allocation and the spatial planning of NbS at the regional scale. The procedure was designed to identify priority areas by considering climate-related impacts, environmental pressures, and conditions of exposure and vulnerability. In this respect, the study's main contributions are as follows:

- Examining the spatial dimension of climate change adaptation and mitigation in relation to NBS planning
- Developing a multicriteria method for identifying priority intervention areas at the regional scale
- Providing a structured basis for planning NbS in relation to site-specific environmental, spatial, and social conditions

The procedure was applied to the Sardinia Region, Italy, as an illustrative case study at the regional scale. In this perspective, the study contributes to the advancement of urban e-planning methods and technologies aimed at operationalizing sustainability, resilience, and climate neutrality goals in the governance of territorial transformations. The article is articulated in six sections. After the introduction, the scientific literature on NbS is reviewed along with the related concepts of green infrastructure and ecosystem services in the context of addressing climate change impacts in urban areas. The following section describes the proposed procedure, which combines multicriteria land suitability analysis with a decision support tool (DST). Subsequently, after the Results section, the

Discussion section examines the main findings. Finally, the Conclusions section outlines the study's limitations and directions for future research.

LITERATURE REVIEW

This literature review is based on the systematic selection of scientific articles investigating the interrelations between NbS, urban green infrastructure (UGI), and urban ecosystem services (UES), and the contribution of NbS and UGI to climate alteration adaptation and mitigation in urban areas. NbS, due to their capacity to deliver multiple co-benefits for life conditions, the economy, society, and the environment (Mosisa et al., 2025) are increasingly recognized as more efficient and cost-effective solutions than more traditional options (European Commission, 2015) for addressing impacts of climatic alterations in urban areas. The International Union for Conservation of Nature (IUCN) defines NbS as actions to protect, sustainably manage, and restore natural and modified ecosystems that respond to economic, social, and ecological sustainability concerns adaptively and effectively, simultaneously providing benefits in terms of biodiversity and quality of life (International Union for Conservation of Nature, 2021; Kabisch et al., 2016; Miles et al., 2021). As a result, NbS refers to multidimensional interventions that foster the adaptive capacity and resilience of urban landscapes by responding to issues related to climate alteration, food security, water resources, or disaster risk management (Dorst et al., 2019; Mosisa et al., 2025). The concept of NbS is related to the concepts of UES and UGI (Fang et al., 2023). UGI refers to a continuous infrastructure that includes natural and semi-natural spaces (forests, agricultural land, urban green areas, private gardens, ponds, streams) and engineered features (green roofs, green façades, bioretention, and permeable pavements) in and around urban areas at various scales, planned and managed to deliver multiple ecosystem services and benefits (Alves et al., 2019; Choi et al., 2021; European Environment Agency, 2021a, 2021b; Fang et al., 2023). Hence, UGI primarily underlines the strategic planning of trans-scalar and continuous spatial systems composed of natural and semi-natural areas, whereas NbS represents a broader umbrella concept that incorporates a problem-driven, solution-oriented perspective. Moreover, NbS encompasses a broader range of actions that leverage ecological processes to address sustainability concerns. Some studies regard UGI as a subset of NbS (Cohen-Shacham et al., 2016); UGI components, in fact, including green roofs, façades, rain gardens, private gardens, urban parks, and forests, are categorized as NbS (Di Pirro et al., 2023; Kabisch et al., 2016; Raymond et al., 2017). UES refers to the environmental and cultural benefits that ecosystems provide in urban areas (Kabisch et al., 2017). UES are categorized as provisioning, regulating, and maintenance services and cultural services and include local climate regulation, air pollution control, water regulation, outdoor recreation, and noise reduction (Bolund & Hunhammar, 1999; Evans et al., 2022). Despite not being a solution or action per se, UES capture the core of ecosystem-based strategies by connecting urban ecosystems and individuals' life conditions (Fang et al., 2023). More precisely, NbS, including UGI components, improve urban resilience primarily via the provision of ecosystem services. In periods of stability, cultural ecosystem services—which generate social, cultural, and community benefits as well as contribute to human well-being—are particularly significant in reinforcing resilience to the chronic stresses and gradual transformations that cities face. Provisioning, regulating, and supporting services are also recognized as crucial in contributing to resilience to sudden alteration, disruptions, and natural disasters (Cohen-Shacham et al., 2016).

Despite being central to building urban resilience, NbS implementation can be limited by persisting gaps in their conceptual framing, notably in relation to social equity, trade-offs between services and functions, and their variation across space and time (Bush & Doyon, 2019). More precisely, five dimensions of trade-offs can be identified: temporal, spatial, functional, social, and ecosystemic. Mosisa et al. (2025) and Bush and Doyon (2019) argue that urban planning is crucial in implementing NbS by managing trade-offs and conflicts across spatial, temporal, and social equity dimensions, particularly from the perspective of strategic and collaborative planning. At the same time, the effective

implementation and integration of NbS necessitate the establishment of robust and standardized protocols for evaluating cost-effectiveness. This includes comprehensive quantification of co-benefits, accurate valuation of ecosystem services, and the generation of empirical evidence that is both representative and applicable across diverse contexts (Brander et al., 2024). NbS implementation also depends on the establishment of dedicated governance mechanisms, the systematic integration of socio-environmental justice criteria, and the adoption of site-specific design principles (Bush & Doyon, 2019; Kabisch et al., 2022; Zarei & Shahab, 2025). Within this context, this study aimed to develop a decision-support procedure for the planning of NbS in urban areas. The procedure addressed one specific constraint in NbS implementation—namely, how limited financial resources can be allocated in relation to site-specific conditions.

METHODOLOGY

This study developed a procedure to support the spatial planning of NbS in urbanized areas for the mitigation of and adaptation to climate change. The study provided a transparent and replicable procedure to compare NbS implementation options across municipalities under budget constraints and site-specific conditions. It combined three main components:

- the identification of relevant NbS options for different urban domains
- a municipal-scale land suitability analysis
- a decision-support tool for budget allocation and spatial prioritization

The procedure was applied to Sardinia, Italy, as an illustrative case study.

Selection of the Area of Study

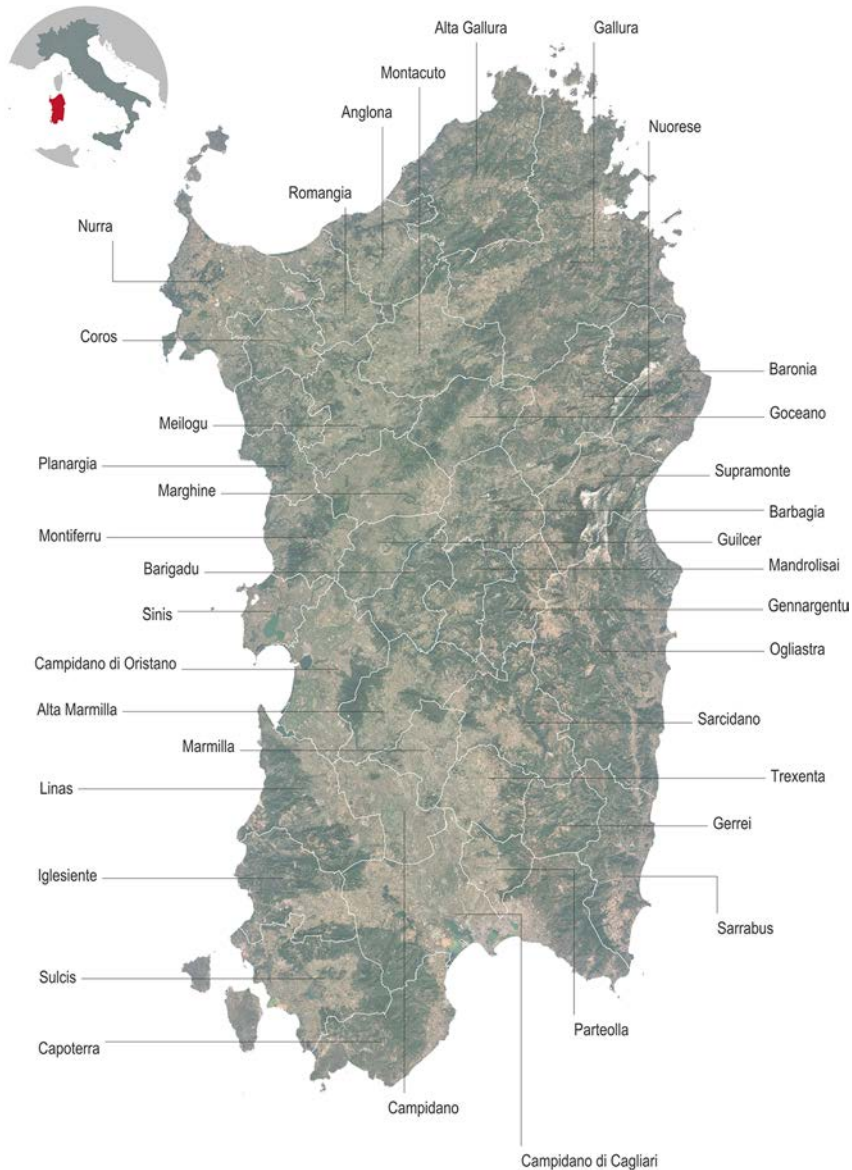
The Sardinia Region was selected as a case study because it combines elevated exposure to climate alteration impacts and significant territorial and socioeconomic vulnerability, as shown in Figure 1. The Sardinia Region covers an area of 24,127 km² and has a population of 1,561,339 inhabitants, resulting in an average population density of about 65 inhabitants per square kilometer. The population is unevenly distributed, with the main urban concentrations located along the coastal areas, particularly in and around Cagliari, Sassari-Alghero, and Olbia, while many inland areas are characterized by low density and marginality.

Sardinia is identified by the Intergovernmental Panel on Climate Change as a climate change hotspot. According to the Regional Strategy for Adaptation to Climate Change, the region is expected to experience increasing temperatures, more frequent heatwaves, reduced precipitation, and an increasing intensity of extreme events (Regione Autonoma della Sardegna, 2024).

These climatic pressures interact with sociodemographic fragilities that may reduce adaptive capacity. Sardinia is affected by population decline and aging more strongly than the national average (Italian National Statistical Institute, 2024). In addition, accessibility to essential services remains uneven, especially in peripheral and inland areas. For example, 14% of the population requires more than 30 minutes to reach the nearest emergency department (Centre for North South Economic Research, 2025). These conditions increase the relevance of spatially differentiated planning approaches for climate adaptation and mitigation.

Within this context, the study explored the potential implementation of NbS in urbanized areas of Sardinia. The analysis focused on census tracts classified in 2021 by the Italian National Statistical Institute (2024) as urban centers or urbanized clusters. At this spatial scale, the study estimated the surface area of feasible spaces for NbS implementation and used this information to support the subsequent suitability analysis and funding allocation procedure.

Figure 1. Selection of the Area of Study: The Sardinia Region and Its Subdivision in Sub-Provinces



Three domains of the urban environment were considered: (1) non-forested permeable areas, (2) building surfaces, and (3) impervious urban spaces. Non-forested permeable areas, defined following Di Pirro et al. (2023), corresponded to surfaces with low tree-cover density, mapped as periodic and permanent herbaceous land by the CLCplus Backbone 2018 (Copernicus Land Monitoring Service, 2024). Building surfaces represented the ground projection of constructed structures, derived from the Building layer of the Topographic Database developed by the Territorial Information System of the Sardinia Region. Impervious urban spaces included artificial areas—vehicular and pedestrian circulation zones and road service areas—mapped through the corresponding layers. For each census

tract, a conservative share of 15% of the total impervious surface was assumed suitable for NbS implementation.

Finally, urban census tracts were aggregated at the municipal level to estimate, for each urban center, the cumulative surface of targetable domains and to define the optimal distribution of available financial resources among municipalities.

Selection of Relevant Nature-Based Solutions

The application of the procedure required the selection of one representative NbS option for each urban domain. To this end, the set of relevant alternatives was reduced via a simulated negotiation among territorial planning scholars, as described in Annex 1. This step was introduced to operationalize the subsequent stages of the procedure and to illustrate how a deliberative component can be incorporated into the selection of NbS options. Participants were asked to compare the available alternatives within each domain and identify a preferred option on the basis of a qualitative evaluation. The discussion was informed by an information base built on the scientific literature, including (1) classifications of urban Green Infrastructure, (2) the UC-ES-NbS framework that Babí Almenar et al. (2021) used to relate NbS to urban ecosystem services and urban issues, and (3) the performance scores developed by Di Pirro et al. (2022, 2023), which compared NbS typologies with respect to air quality, water management, and climate regulation.

The selected representative measures were semi-intensive green roofs for building surfaces, street trees for impervious land covers, and urban parks for non-forested permeable areas (Di Pirro et al., 2022, 2023). Estimated unit investment and annual maintenance costs (Di Pirro et al., 2022, 2023) amounted to 310 €/m² and 7.8 €/m² yr⁻¹ for semi-intensive green roofs, 125 €/m² and 3.1 €/m² yr⁻¹ for street trees, and 225 €/m² and 5.6 €/m² yr⁻¹ for urban parks. The associated mitigation potential, expressed as carbon sequestration and emission avoidance, was estimated at 2.11 kgCO₂ m⁻² yr⁻¹ (Quaranta et al., 2021), 1.03 kgCO₂ m⁻² yr⁻¹ (Lwasa et al., 2022), and 0.98 kgCO₂ m⁻² yr⁻¹ (Gómez-Villarino et al., 2021), respectively.

Development of Multi-Criteria Land Suitability Analysis

The land suitability analysis (LSA) was developed to compare municipalities in terms of the relative priority for NbS implementation. In this study, priority referred to the relative position of each municipality with respect to a set of predefined suitability conditions. Suitability was evaluated separately for each NbS type and structured around five dimensions: technical feasibility, climatic alterations, environmental pressures, exposure, and vulnerability (Malczewski, 2003).

Technical feasibility measured the physical availability of land suitable for the implementation of a given NbS option. It was represented by AV_SUR, measuring the total surface area of eligible land units for option *j* across the census tracts included in municipality *i*.

Climatic alterations measured the main projected climate-related stresses relevant to NbS planning. In line with the Regional Strategy for Adaptation to Climate Change for the Sardinia Region, this dimension was represented by indicators of temperature conditions, heatwave dynamics, and precipitation patterns. Temperature conditions were represented by I_T_MAX and I_T_MIN, which measured, respectively, the projected mean summer maximum temperature and the projected mean summer minimum temperature for the period 2021–2040, and by I_D_T_MAX and I_D_T_MIN, which measured the change in these two variables relative to 1970–2000. Heatwave dynamics were represented by I_HW and I_D_HW, which measured, respectively, the average annual duration of heatwaves in 2026–2040 and the change in heatwave duration relative to 1986–2000. Precipitation patterns were represented by I_DRY, I_D_DRY, I_Y_PREC, and I_D_Y_PREC, which measured, respectively, the mean annual number of dry days in 2021–2040, the change in the number of dry days relative to 1980–2000, the mean annual precipitation in 2021–2040, and the change in annual precipitation relative to 1970–2000. Environmental pressures measured anthropogenic environmental stress potentially relevant to NbS performance. This dimension was represented by I_CO2,

measuring annual CO₂ emission intensity, and by I_PM10 and I_PM2.5, measuring the annual mean concentrations of PM₁₀ and PM_{2.5}.

Exposure measured the concentration of population and built structures potentially affected by climate-related hazards. It was represented by I_POP_R, measuring population density, and I_BUI_VOL, measuring built-up volume density. Both indicators were computed as mean values per 100 m raster cell intersecting each census tract.

Vulnerability measured socio-territorial conditions associated with susceptibility to climate impacts. It was represented by I_ER and I_TRA, measuring, respectively, the reciprocal of the number of emergency departments and train stations, weighted by distance and service level within a 75 km radius; I_POP_T, measuring variation in population density between 2000 and 2030; and I_ELD, measuring the percentage of residents aged 65 and over. Distances to services of general interest were computed using the Attraction Reach function of the Place Syntax Toolkit (Stahle et al., 2007), while the 75 km threshold was defined in accordance with the Italian National Strategy for Inland Areas (Annunziata et al., 2024).

All indicators were normalized by range standardization, which expressed variables measured in non-homogeneous units on a 0–1 scale. In this model, values closer to 1 denoted greater relative priority for intervention (see Annex 2).

The normalized indicators were then aggregated into five composite indices: I_SUR (technical feasibility), I_CLI (climatic alterations), I_ENV (environmental pressures), I_EXP (exposure), and I_VUL (vulnerability). These composite indices were subsequently combined into synthetic suitability indices specific to each NbS type: I_SUI_BUI for NbS on built-up surfaces, I_SUI_IUS for NbS on impervious artificial land, and I_SUI_POS for NbS on permeable non-forested land. The composite and synthetic indices ranged from 0 to 1. Values closer to 1 indicated greater relative priority for intervention, as they reflected more pronounced conditions relevant to suitability across the dimensions considered, under the weighting scheme derived via an analytical hierarchy process (AHP).

Composite and synthetic indices were used to provide an operational synthesis of multidimensional evidence for comparing municipalities and supporting funding allocation. Composite and synthetic indices were computed as weighted averages of the corresponding indicators, with weights derived via the AHP (Saaty, 1980), using pairwise comparisons defined via the simulated participatory exercise described in Annex 1. Full definitions of indicators, units of measurement, data sources, and AHP-derived weights are reported in Annex 2.

Development of a Decision Support Tool

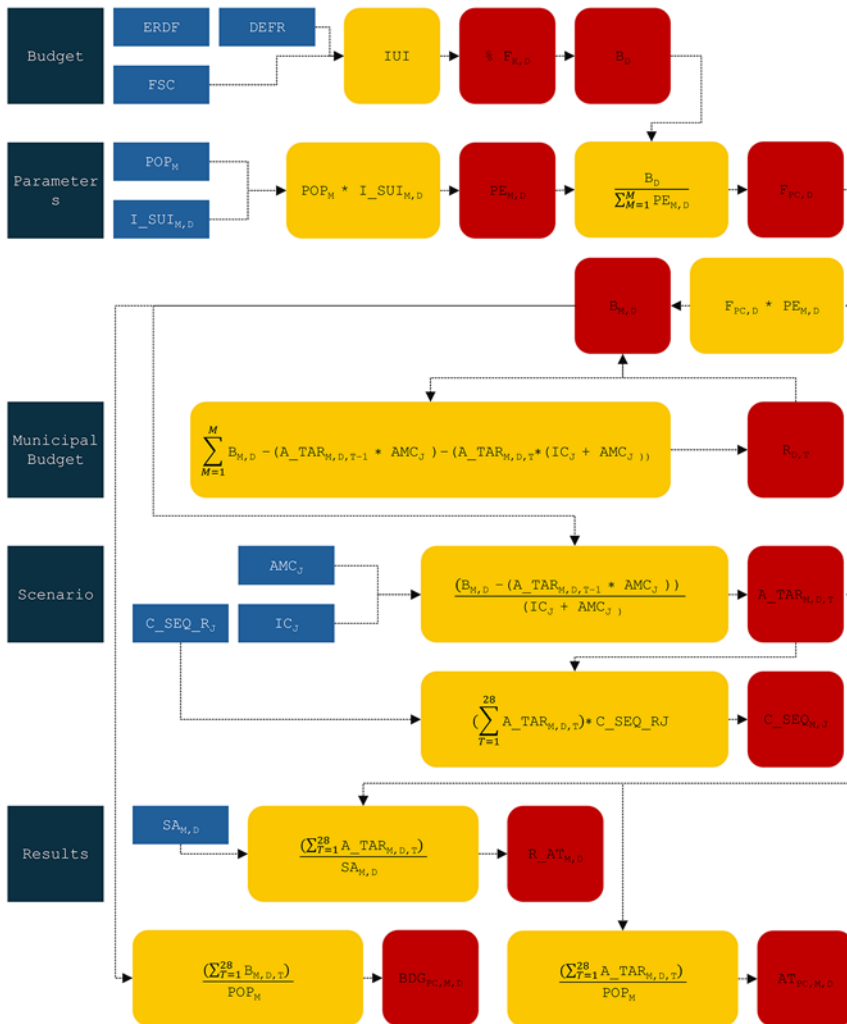
The DST was designed as a replicable and adaptable tool for planning NbS across different territorial scales. Its function was to organize available information, budgetary constraints, and explicit evaluation criteria into a structured allocation procedure. The DST was conceived as a policy-support tool that formalizes the assumptions guiding resource distribution.

The configuration of the DST was based on three groups of inputs. The first group included empirical inputs—namely, eligible land availability and the synthetic suitability indices presented in the previous sections. The second group included policy and financial inputs, represented by the budget lines derived from European and regional programs. The third group included deliberative parameters, which concerned the selection of one representative NbS for each urban domain and the proportion of each program budget assigned to the selected domains. In the present application, these parameters were defined via a simulated negotiation among territorial planning scholars, as reported in Annex 1. The resulting configuration of the tool reflected explicit evaluative choices concerning priorities, relevance, and allocation criteria.

The DST was organized into five sections: budget, parameters, municipal budget, scenario, and results, as shown in Figure 2. It was designed to simulate how financial resources managed at the regional level can be distributed across municipalities for NbS implementation according to explicit territorial criteria. More specifically, the tool allocated resources across the three

intervention domains at the regional level, distributed each domain budget among municipalities, and estimated the expected outcomes by 2040. The tool adopted a constraint-based logic. It estimated the results that can be achieved under predefined financial conditions rather than the total budget required to cover all suitable land units. Annual budgets assigned to each domain were assumed to remain constant over the 2026–2040 period, so that allocation effects can be compared under stable budget conditions. The assumption of constant annual budgets over the 2026–2040 period was adopted as a simplifying condition for scenario construction. This assumption provided a consistent basis for estimating the medium-term implementation capacity of NbS and the associated benefits under conditions of constrained institutional resources.

Figure 2. Structure of the Decision-Support Tool



DST STRUCTURE

The Budget section listed the actions and corresponding financial resources derived from regional and European programs, including the European Regional Development Fund in 2021–2027, the Development and Cohesion Fund in 2021–2027, and the Regional Economic and Financial Document 2024–2026. For each action, a share of the available budget was assigned to the three intervention domains. In this study, these shares were defined through the simulated negotiation described in Annex 1.

The Parameters section regulated the distribution of each domain budget among municipalities. This distribution was based on the synthetic suitability indices developed for each NbS type.

For each municipality m and domain d , a population equivalent was calculated by weighting the resident population by the corresponding suitability index. The funding per capita for each domain was then obtained as:

$$F_{pc,d} = \frac{B_d}{\sum_{m=1}^M PE_{m,d}} \quad (1)$$

where $F_{pc,d}$ is the funding per capita for domain d , B_d is the total budget of domain d , $PE_{m,d}$ is the population equivalent of municipality m in domain d , and M is the total number of municipalities in the Sardinia region. This calculation related the allocation of resources to population size and local suitability conditions.

The Municipal Budget section estimated the annual budget assigned to each municipality and domain. Municipal allocation was calculated by multiplying the funding per capita for domain d by the population equivalent of municipality m . During implementation, some municipalities may have exhausted all suitable land available for the selected NbS before using the full allocated budget. In such cases, the unspent amount was returned to the residual budget of the same domain and reallocated among municipalities where eligible land remains available. This redistribution followed a ranking rule based on three criteria: lower implementation progress, higher synthetic suitability, and, where these are equal, larger resident population. The detailed procedure is reported in Annex 2.

The Scenario section calculated, for each municipality and domain, the annual targeted surface area and the estimated carbon sequestration by 2040. The targeted area was obtained by dividing the annual budget, net of maintenance costs associated with previously targeted units, by the sum of unit investment and maintenance costs. Carbon sequestration was estimated by multiplying the cumulative targeted surface area by the sequestration rate associated with the selected action.

The Results section reported the main outputs for 2040, including cumulative and required budgets, per-capita allocated funding, total and per-capita targeted surface areas, and total and per-capita annual carbon-sequestration estimates.

Overall, the DST integrated budget programming, suitability assessment, and municipal allocation into a single procedure. Its outputs depended on empirical evidence, institutional budget constraints, and explicit evaluative criteria concerning the selection of actions, the weighting of indicators, and the distribution of resources across domains. Detailed information is provided in Annex 2.

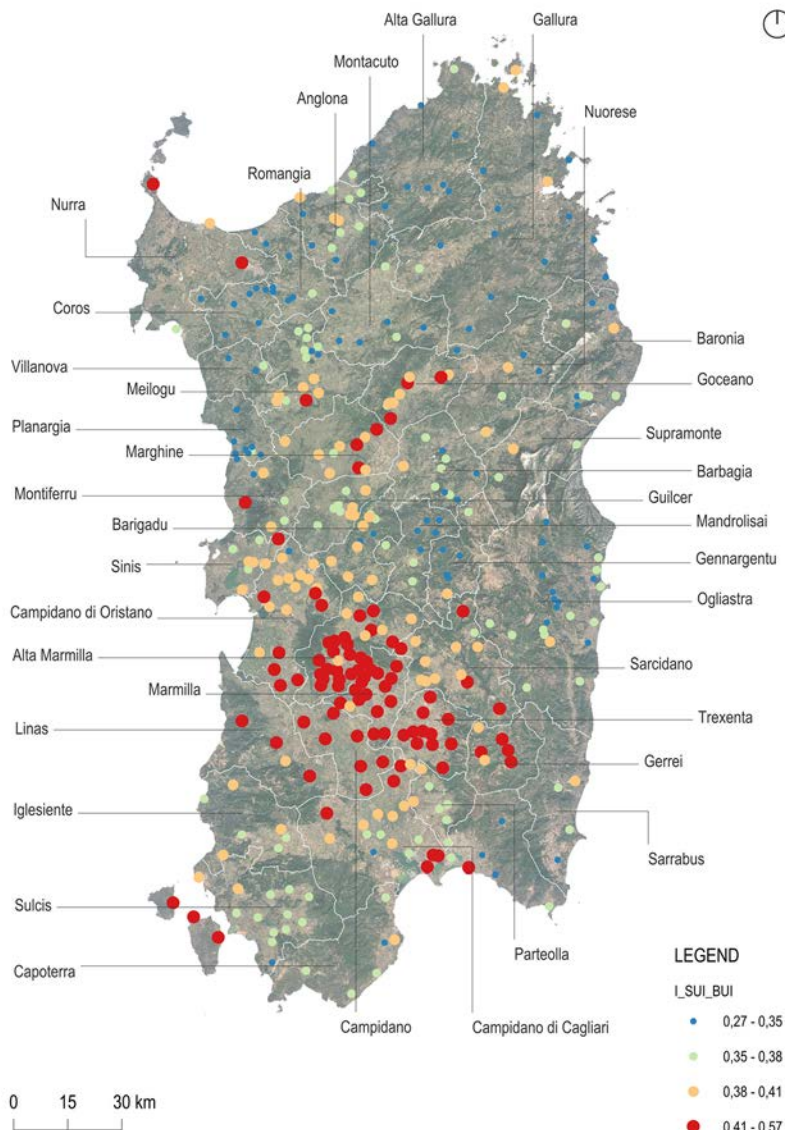
DST Implementation and Results Visualization

The implementation of the tool outlined in above required defining key input data, including the suitability index for action j in domain d , the surface area of suitable land units, the budget share of each action financed through European and regional programs, unit investment and maintenance costs, and the carbon sequestration rate of action j . Following the DST execution, output indicators were exported as a CSV table, imported into a geographic information system environment, and linked to geometries representing urban census tracts, enabling reproducible spatial analysis of NbS implementation outcomes and funding allocation results at the municipal level. The results of the LSA, of the funding allocation across the municipalities, and of the spatial distribution of the NbS implementation outcomes are presented below.

RESULTS

The LSA, conducted at the municipal level for each urban domain, underlined substantial spatial variability in the priority levels for implementing the selected NbS. In the building-surface domain, elevated suitability levels for semi-intensive green roofs—identified by I_{SUL_BUI} values above the upper quartile—were concentrated in clusters of urbanised municipalities in Campidano, Marmilla, Trexenta, and Gerrei. Intermediate suitability levels were observed in Nurra, Marghine, Meilogu, Goceano, Barigadu, Sarcidano, and Sulcis, whereas lower levels prevailed in Planargia, Gallura, Coros, Mandrolisai, Gennargentu, and Ogliastra, as shown in Figure 3.

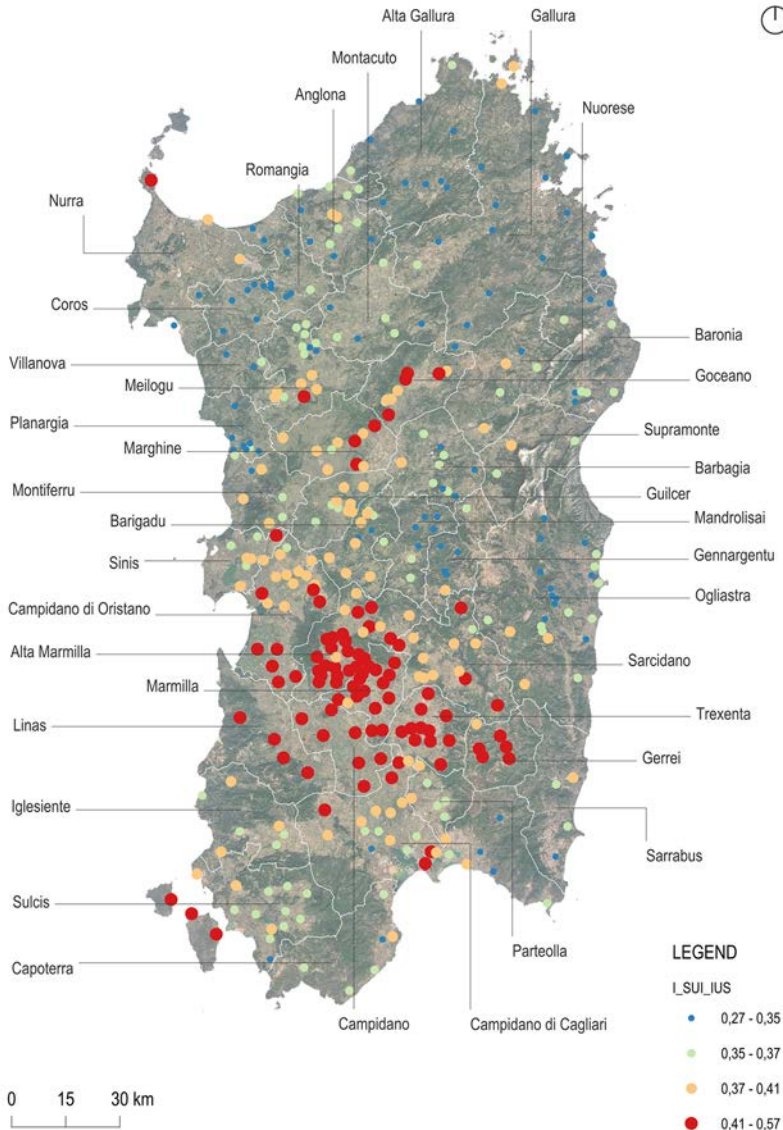
Figure 3. Spatial Variation of the Levels of Suitability to Nature-Based Solutions Targeting the Domain of Building Surfaces



A comparable spatial pattern emerged for street trees in the impervious artificial land domain and urban parks in the non-forested permeable land domain.

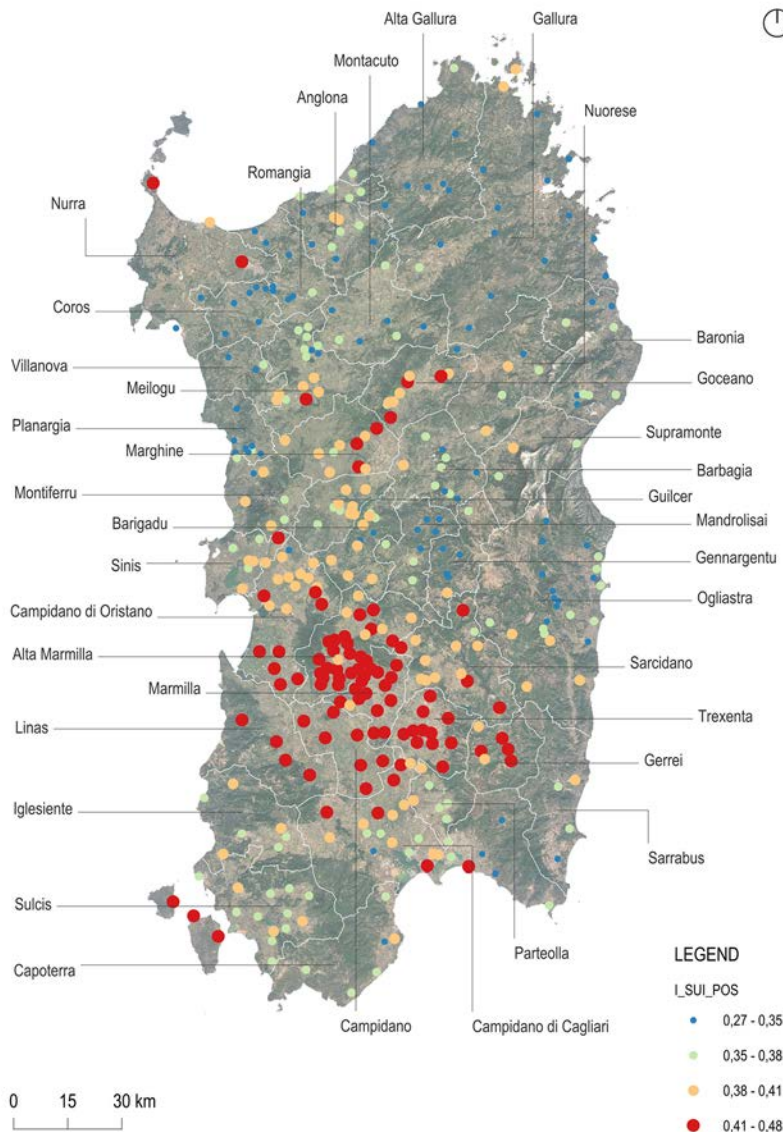
Municipalities with high suitability for street trees (i_SUI_IUS above the upper quartile) were concentrated in central Sardinia, particularly in Campidano, Linas, Marmilla, Trexenta, and Gerrei, while areas with low suitability (i_SUI_IUS below the first quartile) were found in Planargia, Coros, Romangia, Anglona, Montacuto, Gallura, Baronia, Barbagia, Mandrolisai, Gennargentu, and Ogliastra, as shown in Figure 4.

Figure 4. Spatial Variation of the Levels of Suitability to Nature-Based Solutions Targeting the Domain of Artificial Impervious Land



Similarly, municipalities with elevated suitability levels for the non-forested permeable land domain were located mainly in Campidano, Linas, Marmilla, Trexenta, Gerrei, Sarcidano, Marghine, Goceano, and Nurra, whereas marginal suitability levels were concentrated along the eastern coast and inland mountainous areas, including Planargia, Coros, Romangia, Montacuto, Anglona, Gallura, Baronia, Barbagia, Mandrolisai, Gennargentu, and Ogliastra, as shown in Figure 5.

Figure 5. Spatial Variation of Suitability Levels for the Implementation of Nature-Based Solutions Targeting the Domain of Non-Forested Permeable Land

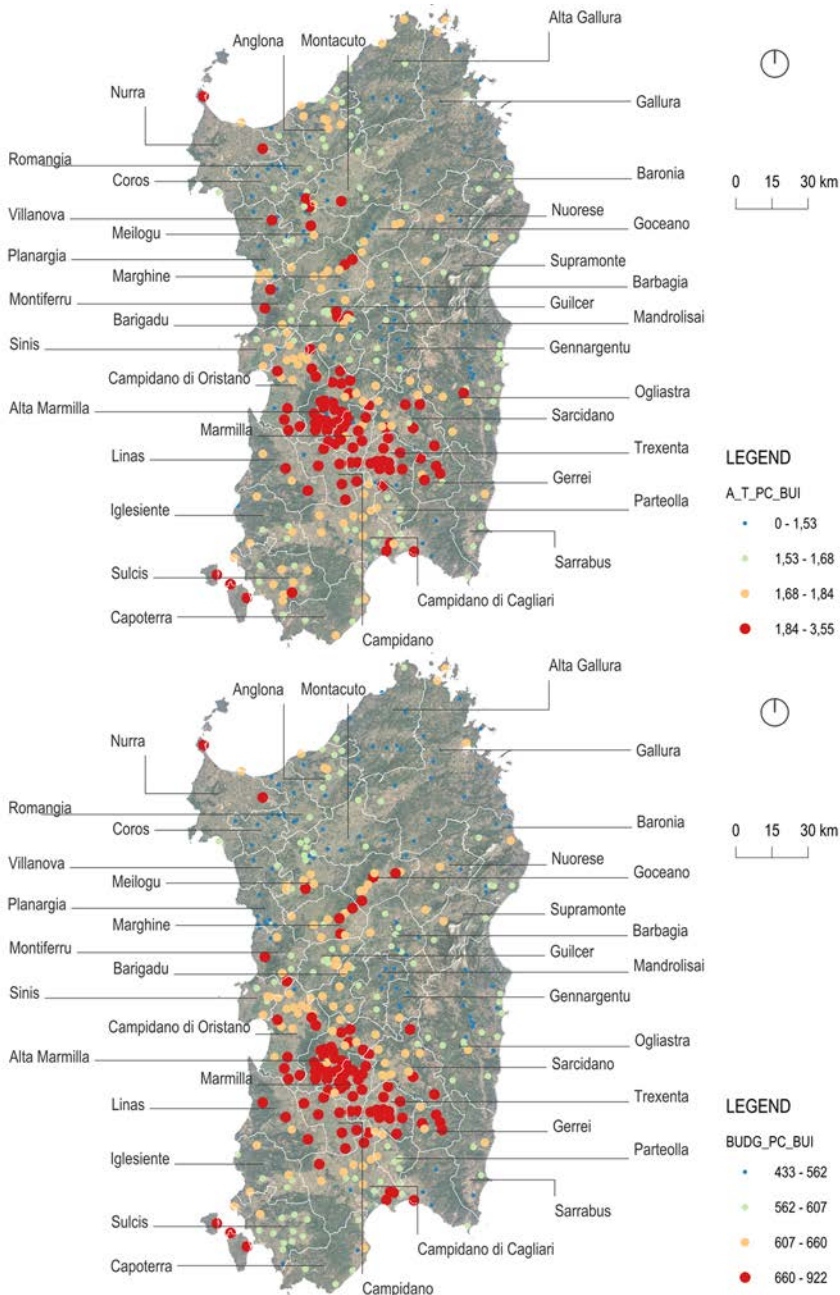


Analysis of climatic indicators revealed stronger projected increases in air temperature, precipitation variability, and extreme temperatures in Campidano, Marmilla, and Trexenta, and milder effects in Gallura, Baronìa, Barbagia, Mandrolisai, Gennargentu, Nuorese, Supramonte, Ogliastra, and Sarrabus.

Higher environmental impact levels (i_ENV above the upper quartile) occurred in Campidano, Linas, Parteolla, Trexenta, Marmilla, and Sulcis. Elevated exposure values (i_EXP) were also evident in Campidano, Parteolla, Trexenta, Iglesiasiente, Coros, Romangia, and Nurra. Lastly, elevated I_VUL values were observed in inland and marginal sub-regions such as Gerrei, Alta Marmilla, Sarcidano, Sarrabus, Ogliastra, Gennargentu, Barbagia, Baronìa, Nuorese, Goceano, and peripheral municipalities in Alta Gallura, Sulcis, and Iglesiasiente. In this study, higher I_VUL values reflect greater vulnerability related to limited access to services, demographic aging, and population decline. The DST used the suitability patterns identified by the LSA and the available program budgets to estimate the spatial distribution of funding and the corresponding implementation outcomes. In the scenario developed here, it was assumed that, for each policy priority financed through European and regional program, the sum of the budget shares assigned to the three selected intervention domains did not exceed 50% of the total available budget for that policy priority. On this basis, the annual budgets amounted to approximately €71 million for building surfaces, €47 million for artificial impervious land, and €148 million for permeable non-forested land. In the building-surface domain, the model estimated the greatest implementation levels for semi-intensive green roofs in municipalities located in Gerrei, Trexenta, Marmilla, Barigadu, and Goceano, where 55% to 100% of suitable land was targeted. Per-capita targeted surface area above the upper regional quartile was observed in Campidano, Sulcis, Gerrei, Trexenta, Marmilla, and Sarcidano. Per-capita funding values between €660 and €922 were concentrated in Campidano, Linas, Gerrei, Trexenta, Marmilla, Marghine, and Goceano, as shown in Figure 6.

These municipalities presented a higher average suitability index than the remaining municipalities. Under the funding-constrained scenario, the model estimated the transformation of about 5.5% of suitable building surfaces, with annual carbon sequestration reaching about 5,600 tCO₂ by 2040 and cumulative expenditure amounting to €990 million. Under the demand-driven scenario, full implementation would require cumulative expenditure of €17.9 billion and would yield annual sequestration of about 103,000 tCO₂ by 2040.

Figure 6. Spatial Variation of the Variables Surface Area of Targeted Land Per Capita and Funding Per Capita for the Domain of Buildings Surfaces

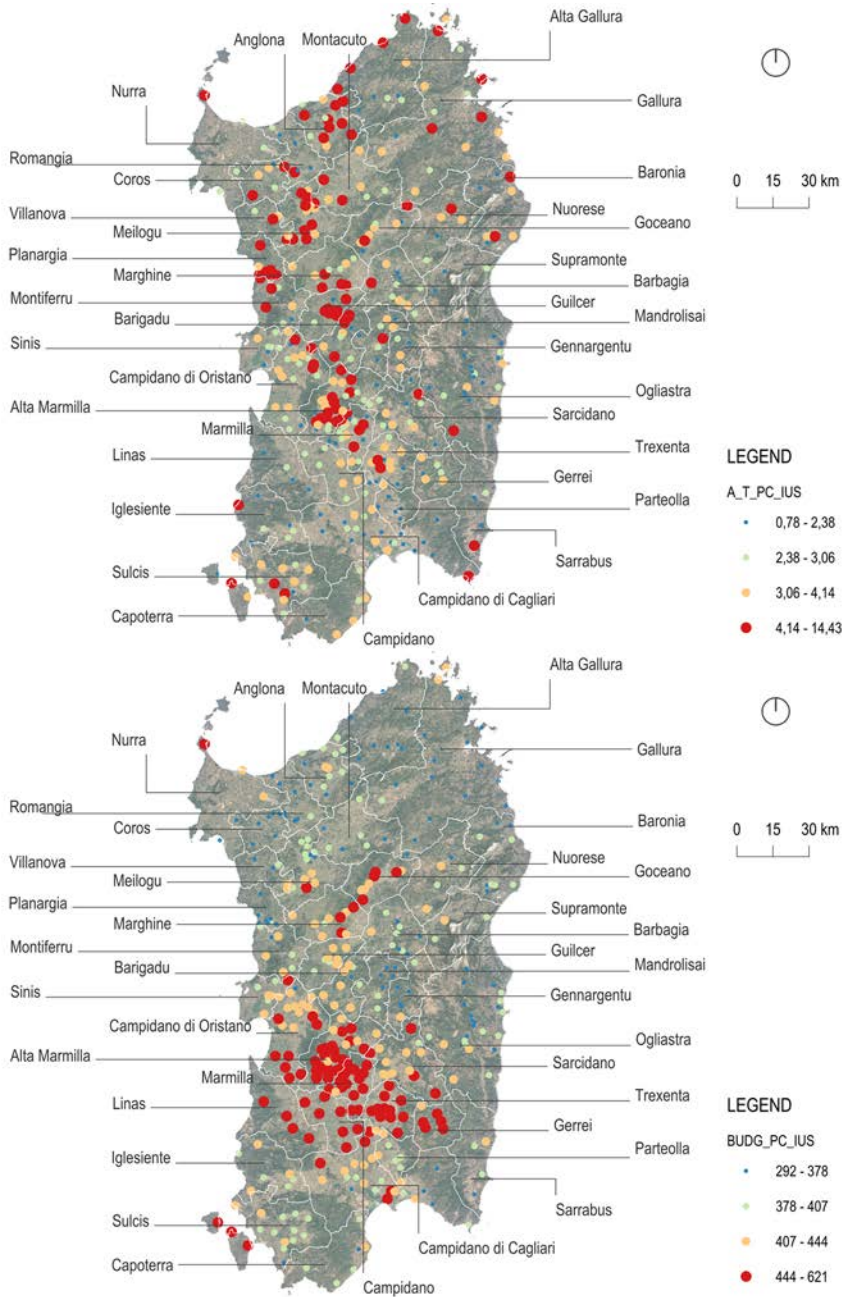


Note. *A_T_PC_BUI* = surface area of targeted land per capita; *BUDG_PC_BUI* = funding per capita for the domain of buildings surfaces.

In the impervious surface domain, the largest per-capita targeted surface areas for street trees were found in Marmilla, Guilcer, Marghine, Planargia, Meilogu, Anglona, and Gallura (Figure 7).

Per-capita funding values ranging from €444 to €621 were concentrated in Linas, Campidano, Gerrei, Trexenta, Marmilla, Marghine, and Goceano.

Figure 7. Spatial Variation of the Variables Surface Area of Targeted Land Per Capita and Funding Per Capita for the Domain of Artificial Impervious Land

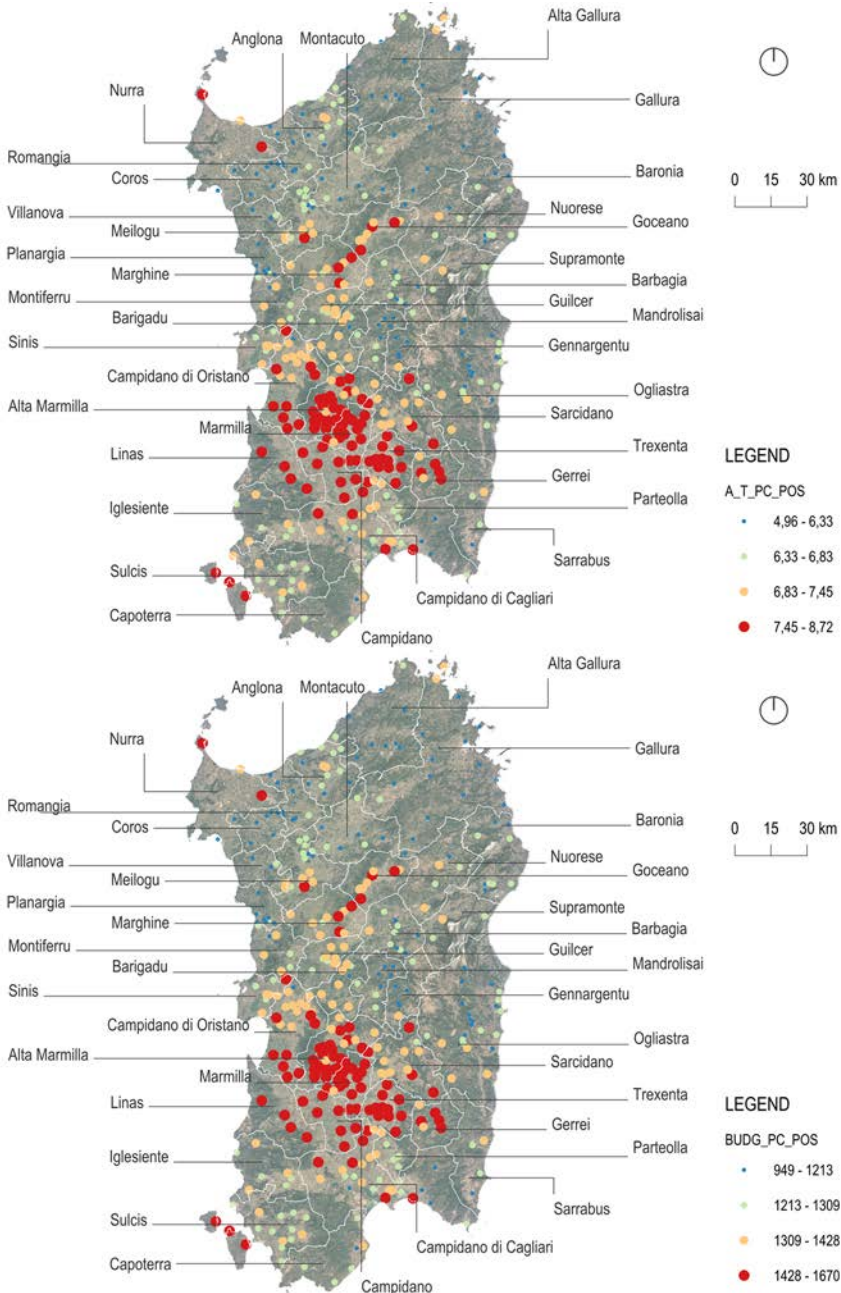


Note. A_T_PC_IUS = surface area of targeted land per capita; BUDG_PC_IUS = funding per capita.

These municipalities were characterized by greater mean suitability, vulnerability, climatic alteration, and environmental pressure values than the regional average. Under the funding-constrained scenario, the model estimated street tree implementation on 86.2% of suitable land, corresponding to annual carbon sequestration of about 4,500 tCO₂ by 2040. Under the demand-driven scenario, implementation across the full suitable area would raise annual sequestration to about 5,200 tCO₂, with total expenditure increasing from €652 million to €750 million.

In the permeable non-forested land domain, municipalities with the highest per capita surface area of targeted land were concentrated in Campidano, Marmilla, Trexenta, Gerrei, Sarcidano, Marghine, Goceano, and Nurra, as shown in Figure 8.

Figure 8. Spatial Variation of the Variables Surface Area of Targeted Land Per Capita and Funding Per Capita for the Domain of Non-Forested Permeable Land



Note. A_T_PC_POS = surface area of targeted land per capita; BUDG_PC_POS = funding per capita.

Per-capita funding presented a similar spatial distribution, with values ranging from €949 to €1,213 in Planargia, Coros, Romangia, Anglona, Gallura, Mandrolisai, Ogliastra, and Gennargentu, and from €1,428 to €1,670 in Campidano, Marmilla, Trexenta, Gerrei, Sarcidano, Marghine, Goceano, and Nurra. Under the funding-constrained scenario, the model estimated the

conversion of about 4% of suitable areas into urban parks, with annual carbon sequestration of about 7,500 tCO₂ by 2040 and cumulative expenditure of €2.1 billion. Full conversion under the demand-driven scenario would increase annual carbon sequestration to about 177,000 tCO₂ and total expenditure to €34.4 billion. Overall, the results indicate that the spatial distribution of simulated funding is consistent with variations in suitability and socio-environmental conditions across municipalities. They also underline that the gap between funding-constrained and demand-driven scenarios varies significantly across domains. This deviation is particularly pronounced for green roofs and urban parks, where the estimated benefits remain limited under current financial conditions, whereas the street-tree domain presents a modest gap between partial and full implementation. These findings provide a clearer basis for assessing the interdependencies between financial constraints, territorial prioritization, and expected mitigation outcomes.

DISCUSSION

The study proposed a procedure to support NbS planning at the municipal level by guiding the allocation of financial resources according to criteria based on local suitability and socio-environmental conditions. The procedure defined a budgetary relation between the regional and municipal levels, whereby resources derived from E.U., national, and regional programs and managed at the regional level were distributed across municipalities for NbS implementation according to explicit territorial criteria. It allocated resources across the three intervention domains, distributed each domain budget among municipalities, and estimated the expected outcomes by 2040. Several considerations emerge from the results of the model application. A first point concerns the relation between the modelled distribution of per-capita funding and the spatial distribution of projected climatic anomalies. In this respect, the Campidano sub-region—identified in the Regional Strategy on Climate Change Adaptation as particularly exposed to climatic alterations—receives substantial per-capita funding for NbS implementation across the selected domains. More broadly, the simulated distribution of municipal budgets generated by the procedure reflects the spatial variation of environmental pressures, projected climatic anomalies, exposure, and vulnerability.

The resulting allocation pattern directs greater per-capita resources to the sub-regions of Campidano, Marmilla, Trexenta, Gerrei, Sarcidano, Marghine, Goceano, Linas, and Sulcis. These areas combine stronger climatic and environmental pressures with greater urbanization intensity than the rest of the region, with greater population density, built-up volume, and infrastructure density. As a result, the simulated allocation of regional resources across municipalities reflects territorial conditions rather than population size alone.

This point is relevant from a distributive perspective. Since the procedure generates municipal budget allocations directly from regional policy funding lines according to explicit territorial criteria, it provides an alternative to systems based primarily on competitive access to resources (Thompson et al., 2023). In contexts where administrative capacity is unevenly distributed across municipalities (Grundel & Magnusson, 2023; Thompson et al., 2023), competitive procedures may favor larger municipalities with greater technical and institutional resources. By contrast, the present procedure relates municipal allocations to measured territorial conditions, thereby rendering the allocation rule more explicit, place-sensitive, and open to scrutiny (Thompson et al., 2023; Toxopeus & Polzin, 2021).

A further point concerns participation. The procedure was designed to incorporate participatory and deliberative activities in three stages: the distribution of regional resources across domains, the selection of the representative NbS for each domain, and the weighting of the criteria and sub-criteria used to assess suitability at the municipal level. In the present study, these steps were operationalized via a simulated negotiation exercise, as described in Annex 1. In an applied planning context, these stages could be conducted through structured deliberative processes involving public institutions and relevant stakeholder groups.

A second central implication of the results concerns the financing conditions required to extend NbS implementation beyond the levels feasible under the available public financial resources. The comparison between the demand-driven and funding-constrained scenarios indicates a substantial gap between the investment required to intervene across all suitable land units and the financial capacity represented by existing regional and European program funding. This gap is particularly pronounced for green roofs and urban parks and milder for street trees. More precisely, under the demand-driven scenario—assuming full conversion of all suitable land units during 2026–2040—the required investment reaches €3.8 billion (12.8% of regional GDP). By contrast, the funding-constrained scenario yields only €265 million annually (6.9% of the required amount), rising to about €995 million (26.2%) even if all resources within relevant policy priorities were assigned to NbS. The results thus suggest that public funding alone is sufficient to support only a limited proportion of the potential implementation identified by the suitability analysis. Under these conditions, broader deployment requires instruments capable of mobilizing private resources in forms consistent with the structural and spatial constraints, ownership structure, and implementation requirements of the selected NbS.

From this perspective, the results point to the policy relevance of combining institutional funding with complementary private contributions, particularly where NbS implementation depends partly on interventions undertaken on private land or buildings. For NbS integrated into built structures, the intervention of private capital can be pursued via a combination of regulatory and incentive-based instruments. Regulatory measures may include amendments to building codes and planning regulations requiring the integration of vegetated surfaces in new developments or major regeneration projects, for example, via minimum green-roof ratios, energy-performance standards, or hydraulic and hydrologic invariance requirements. These provisions can be complemented by incentive instruments designed to improve the economic feasibility of private intervention, including expedited permitting, reductions in permit fees, density bonuses, and fiscal measures aimed at supporting retrofitting in existing buildings. For NbS targeting artificial impervious and permeable land, the same objective can be pursued through land-based and development-related instruments capable of redirecting part of the value generated by urban transformation towards public green infrastructure (Colavitti & Serra, 2023; Longato et al., 2024; Morano et al., 2023; Mouton et al., 2024).

These include negotiated public–private agreements, betterment levies, transferable development rights, and developer obligations related to development permits or regeneration procedures. In operational terms, these instruments posit that public institutions can secure land, infrastructure, or financial contributions and use them for the implementation of urban parks, street-tree systems, and other forms of green infrastructure. Betterment levies consist of supplementary contributions imposed on private developers conducting urban development or regeneration projects, proportionate to the land-value gains generated by modifications in land use (Colavitti & Serra, 2023). Transferable development rights involve the transfer of baseline building rights, determined by local urban plans, to designated receiving areas deemed suitable for development; this instrument enables the public acquisition of non-buildable areas for public purposes, including the creation of green infrastructure, while ensuring an equitable redistribution among private operators of the benefits generated by urban plans (Organisation for Economic Co-operation and Development & The Lincoln Institute of Land Policy, 2022).

Additional mandatory financing instruments include developer obligations—such as development permit fees and exactions—which may take the form of monetary contributions or the provision of land and infrastructure required by new development. Community fundraising and the purchase of carbon credits associated with urban forests may provide additional, though more limited, sources of support (Toxoepus & Polzin, 2021).

A further implication concerns the assessment of NbS co-benefits in relation to climate-change mitigation, adaptation, and broader sustainable development objectives. Even under the demand-driven scenario, per-capita carbon sequestration remains limited relative to current per-capita emissions,

amounting to only $0.2 \text{ tCO}_2 \text{ y}^{-1}$, equivalent to 1.6% of the per-capita emissions estimated for 2022 ($11.8 \text{ tCO}_2 \text{ y}^{-1}$; Italy for Climate, 2025).

This result indicates that the relevance of NbS cannot be assessed solely in terms of mitigation performance. Their contribution lies more broadly in the multiple co-benefits they provide for urban adaptation and sustainable development (Alves et al., 2024; Babí Almenar et al., 2021; Choi et al., 2021; Jones et al., 2022; Kabisch et al., 2016; Mosisa et al., 2025). In this respect, the three NbS considered in this study are associated with distinct but complementary benefits. Green roofs contribute to stormwater regulation and can support social interaction and psychological restoration (Jones et al., 2022); street trees contribute to air-quality improvement, urban cooling, carbon storage, and stress reduction; urban parks, implemented on permeable non-forested land, contribute to air-pollution removal, noise attenuation, climate and water regulation, biodiversity conservation, and physical and mental well-being (Babí Almenar et al., 2021; Jones et al., 2022).

These results reinforce the need to evaluate NbS through a broader ecosystem-services perspective rather than through carbon sequestration alone.

From this perspective, the economic valuation of ecosystem services is relevant for assessing the cost-effectiveness of NbS, informing investment priorities, supporting cost-benefit analysis, and improving the transparency of decisions concerning the distribution of costs and benefits among different actors (Biasin et al., 2023; Brander et al., 2024; Quagliolo et al., 2022; Raymond et al., 2009). It is also relevant for reinforcing the integration of NbS into spatial planning and policy instruments across governance levels (Bush & Doyon, 2019; Fang et al., 2023; Mosisa et al., 2025; Raymond et al., 2017; Ronchi et al., 2020) and for supporting the mobilization of private capital, where implementation depends partly on non-public actors (Liberalezzo et al., 2020; Toxopeus & Polzin, 2021). Indicative estimates derived from value-transfer methods suggest that the economic value of water, climate, and air-quality regulation may be substantial under both scenarios, with larger cumulative values under the full implementation scenario. For example, estimated annual benefits amount to about €0.2 million and €3.2 million for the water-regulation services provided by green roofs under the funding-constrained and demand-driven scenarios, respectively; about €1.4 million and €1.6 million for the climate-regulation services related to street trees; and about €8.5 million and €201 million for the air-quality regulation services provided by urban parks (Brander et al., 2021, 2024).

In this respect, databases such as the Ecosystem Services Valuation Database provide a useful basis for rapid and low-cost co-benefits evaluation, particularly in contexts where technical expertise, financial resources, and institutional capacity are limited. At the same time, the robustness of these estimates remains constrained by the limited standardization of valuation methods and by uneven coverage of ecosystem types and services in the available literature (Brander et al., 2024). For this reason, economic valuation should be interpreted as a supporting element in NbS assessment rather than as a definitive measure of their overall effectiveness.

Overall, the results suggest that NbS planning requires forms of evaluation capable of integrating mitigation performance, adaptation effects, and broader ecosystem-service benefits. This integration is essential for informing climate policies that allocate resources efficiently while remaining responsive to local climatic, environmental, and social conditions.

CONCLUSION

Based on the results and preceding discussion, this study addressed two primary questions:

- How can information be structured and organized to effectively support decision-making in the planning and implementation of NbS?
- How can a DST for NbS planning be designed to support funding allocation, ensuring responsiveness to site-specific conditions?

This study addressed existing gaps in the literature on the implementation of NbS for climate-change adaptation and mitigation, particularly the limited use of multicriteria decision-analysis methods for the spatial allocation of NbS and the predominance of demand-driven, municipality-centered procedures in optimization models. To overcome these limitations, the study developed a procedure that integrates a multicriteria LSA with a decision-support tool that aligned financial allocation and the spatial distribution of mitigation and adaptation measures with clearly defined intervention priorities. These priorities were articulated across five dimensions—feasibility, climatic alterations, environmental pressures, exposure, and vulnerability—each operationalized via quantitative indicators selected for their relevance, validity, replicability, and suitability to the spatial scale of analysis. The objective was to identify and prioritize areas presenting significant intensities of climatic impacts and environmental pressures, elevated levels of exposure, and pronounced socio-territorial vulnerability. The results indicate that the proposed procedure allocates regional resources towards municipalities presenting greater climatic and socio-environmental fragility. At the same time, the comparison between the funding-constrained and demand-driven scenarios indicates that currently available public resources remain inadequate to support extensive NbS implementation and substantial mitigation outcomes across all suitable land units. While the mitigation impact of local NbS interventions remains limited in the context of global emission trajectories, their contribution is relevant for improving territorial resilience, reducing local climate risks, and supporting the alignment of local responses with regional, national, and E.U. adaptation and mitigation strategies.

The proposed procedure is broadly consistent with several priorities identified in European, national, and regional strategies for climate-change adaptation and mitigation. These include the role of NbS in local adaptation, the need for evidence-based and transparent decision-support tools, the integration of adaptation and mitigation criteria into sectoral policies and programs, and the expansion of access to financial instruments capable of supporting climate-related interventions. In this respect, the funding-constrained perspective adopted in the study is also consistent with the mainstreaming of climate objectives within ordinary policy and expenditure frameworks.

The proposed procedure is consistent with selected IUCN (2020) principles concerning transparent governance, economic feasibility, and responsiveness to societal needs. Moreover, it contributes to addressing several barriers to NbS implementation, including the need for decision-support tools that enable evidence-based decision-making for integrating NbS—and, more broadly, climate-change adaptation and mitigation criteria—into spatial planning procedures and policy initiatives, as well as the currently insufficient incorporation of socio-environmental justice considerations in the planning and financing of NbS (Bush & Doyon, 2019; Choi et al., 2021; Kabisch et al., 2016; Mosisa et al., 2025). The study is also consistent with a global-to-local-to-global perspective, according to which climate change operates via interrelated processes across spatial scales. Within this perspective, local climatic impacts and socio-environmental fragilities are determined by broader global dynamics, while the cumulative effects of local responses contribute to wider regional and global trajectories (Baldos et al., 2023). Consequently, by integrating multicriteria spatial analysis with interactive decision-support environments, the proposed procedure is relevant to the research on urban e-planning methods and technologies. The study contributes to research on geospatial analysis and interactive decision-support tools for NbS planning, supporting the integration of climate adaptation and mitigation objectives into data-informed territorial planning.

Two main limitations are identified. First, the limited availability of fine-scale climatic and socio-economic data constrains the capacity to capture intra-urban variability in impacts, environmental pressures, and vulnerability. Second, the quantification of the ecosystem services provided by NbS—and the estimation of their economic value—remains essential for comprehensively assessing the cost-effectiveness of NbS in contributing to climate-change mitigation and adaptation objectives, as well as broader sustainable development goals. This component is, in turn, central to raising stakeholder awareness of the role of NbS in improving urban resilience, incentivizing private

investment in NbS, and supporting evidence-based decision-making in setting policy priorities and developing plans, programs and projects that integrate NbS.

Future research will therefore focus on deepening the analysis of territorial, social, and economic drivers of vulnerability, expanding the set of indicators for assessing climatic impacts at the sub-urban scale, and incorporating multiscale evaluations of the efficiency and economic value of NbS, including their co-benefits for adaptation, resilience, and sustainable development.

DATA AVAILABILITY STATEMENT

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

AUTHORS' CONTRIBUTION

This paper is the result of the joint work of the authors. The abstract, literature review, results and conclusions were written jointly by all authors. Francesco Scorza wrote the introduction, Chiara Garau wrote the discussion, and Alfonso Annunziata wrote the methodology.

COMPETING INTERESTS

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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APPENDIX 1

Simulated Negotiation Process

The proposed framework involves a simulated negotiation process (Kesting & Smolinski, 2023) designed to address three primary concerns: i) determining the proportion of funding to be allocated within these investment lines to the identified domains; ii) the selection of specific Nature-Based Solutions (NbS) options within defined urban landscape domains—namely building surfaces, impervious land covers, and non-forested permeable areas; and iii) the assignment of weights to sub-criteria and criteria for calculating synthetic suitability indices using the Analytical Hierarchy Process (AHP).

The simulated negotiation exercise involved a total of eighteen participants with differentiated academic profiles. These included four professors specializing in Urban and Territorial Planning, one professor in Real Estate Evaluation and Life Cycle Assessment, two postdoctoral researchers (one in Urban and Territorial Planning and one in Real Estate Evaluation and Life Cycle Assessment), three doctoral students in Urban and Territorial Planning, and nine students enrolled in the Master's Degree Course in Environmental Engineering. All participants were affiliated with either the Department of Engineering at the University of Basilicata or the Department of Civil and Environmental Engineering and Architecture at the University of Cagliari.

Participants were selected based on their knowledge and expertise in four interrelated domains relevant to the development of climate change adaptation and mitigation actions in urbanized areas: i) urban planning regulations and incentive mechanisms supporting public–private cooperation in public action; ii) drivers and impacts of climate change in Mediterranean contexts; iii) European Union, national, and regional strategies and plans for climate change adaptation and mitigation; and iv) nature-based solutions (NbS) and urban ecosystem services.

Task 1: Allocation of Financial Resources

For the task concerning the allocation of investment resources across three intervention domains, participants were randomly assigned to three distinct working groups. Group composition was subsequently reviewed and adjusted to ensure a balanced distribution of expertise across the four predefined knowledge domains. Each group was asked to determine the fraction of funding allocated to each domain for a set of policy priorities financed through European and regional programmes, including Green Transition, sustainable urban mobility, social inclusion, sustainable and integrated urban and territorial development, energy, environment and natural resources, urban regeneration, and land use and housing.

Group activities were structured around a consensus-building approach, aimed at achieving agreement through negotiation and discussion. The exercise was divided into three segments. In the first segment, lasting 30 minutes, general instructions and background information were provided to all participants. These materials outlined the objectives of the exercise, a working definition of the three intervention domains, and a description of the relevant European Union and regional policy priorities. The task was framed as the identification of a suitable allocation of available funding to mainstream nature-based solutions into existing policy priorities and initiatives, subject to the constraint that no more than 50% of the funding associated with each policy priority could be allocated to NbS implementation within the three domains.

The second segment, lasting 45 minutes, consisted of intra-group negotiations aimed at reaching a consensual decision on the allocation of funding shares across the three domains for each policy priority. In this study, consensus is defined as an outcome of the negotiation process in which group members, through structured discussion and argumentation, converge on a shared solution that none of the participants actively opposes and to which all declare their willingness to commit (Haug, 2015; Susskind, 2006). In the third segment, the final allocation of funding was computed, for each policy priority, as the average of the shares determined independently by the three groups. The resulting

allocation scheme was then reviewed to verify compliance with the funding constraint and discussed collectively with the participants.

Task 2: Selection of NbS

A second simulated negotiation exercise focused on the selection of one representative Nature-Based Solution (NbS) within each of the three predefined domains: building surfaces, impervious land covers, and non-forested permeable areas. The NbS alternatives considered for each domain were identified on the basis of previous studies by Di Pirro et al. (Di Pirro et al., 2022, 2023). For building surfaces, the options included extensive, semi-intensive, and intensive green roofs, green façades, vegetated pergolas, and green wall systems. For impervious land covers, the alternatives included street trees, raingardens, vegetated grid pavements, pocket gardens or parks, and vertical mobile gardens. For non-forested permeable areas, the options included private gardens, swales, retention ponds, infiltration basins, green corridors, large urban parks, community and heritage gardens, urban forests, urban orchards, and constructed wetlands. Participants were again randomly assigned to three working groups, with group composition adjusted to ensure balanced expertise. Each group was assigned one domain and asked to compare the relevant NbS options in order to identify a representative solution through a qualitative comparison of alternatives.

The exercise was structured into two segments. In the first segment, participants received background information based on the scientific literature, including descriptions of the available NbS alternatives, their relationships with ecosystem services and selected urban issues, and their expected contribution to environmental functions such as climate regulation, water management, and air quality improvement. Reference materials included urban green infrastructure typologies, the Urban Challenges–Ecosystem Services–NbS analytical framework (Babí Almenar et al., 2021), and a performance scoring system developed by Di Pirro et al. (Di Pirro et al., 2022, 2023). In the second segment, lasting 45 minutes, each group engaged in an intra-group negotiation aimed at reaching a consensual decision on the preferred NbS option within its assigned domain. The option selected by each group was adopted as the representative NbS for the corresponding domain.

Task 3: Weights of criteria and sub-criteria

Lastly, the third exercise focused on the assignment of weights to criteria and sub-criteria for the calculation of synthetic suitability indices using the Analytical Hierarchy Process (AHP). Participants were assigned specific stakeholder roles, based on their expertise across the four knowledge domains, and divided into four groups. Professors specializing in Urban and Territorial Planning assumed the role of political and administrative representatives of the Regional Government. Postdoctoral researchers and doctoral students represented professional and business trade associations, including engineering associations, associations of architects and planners, and confederations of industry and commerce. Master's students were divided into two groups, representing municipal administrations and citizen associations, respectively.

The exercise was organized into three sequential segments. The first segment, lasting 45 minutes, was dedicated to providing all participants with general information concerning the objectives of the exercise, the principles of qualitative pairwise comparison among variables, and their translation into quantitative dominance factors for the construction of pairwise comparison matrices within the Analytical Hierarchy Process. During this phase, participants were also provided with a working definition of the criteria and sub-criteria selected to quantify the priority level for Nature-Based Solution (NbS) implementation across clusters of urbanized land units. The task was framed as the weighting of a set of criteria and sub-criteria aimed at supporting the spatial allocation of NbS for climate change adaptation and mitigation, in accordance with climatic impacts, environmental pressures, levels of exposure, and socio-territorial vulnerability.

The AHP hierarchy was structured across three levels. The first level corresponded to the overall goal of optimizing the spatial allocation of NbS. The second level comprised five dimensions formalizing intervention priority: feasibility, climatic alterations, environmental pressures,

exposure, and vulnerability. The third level included the variables selected to operationalize each of these dimensions.

The second segment, lasting 75 minutes, consisted of an intra-group negotiation process aimed at reaching a consensual assessment of the relative importance of each criterion and sub-criterion through pairwise comparisons within the same hierarchical level and category. To limit cognitive burden and reduce uncertainty associated with an excessive number of comparisons, the number of elements within each category was restricted to a maximum of ten, in accordance with established AHP methodological guidelines (R. W. Saaty, 1987; T. L. Saaty, 1980, 1990; T. L. Saaty & Vargas, 1991).

The third segment, lasting 45 minutes, consisted of an inter-group negotiation process coordinated by the authors, who acted as facilitators. The facilitation role of the authors was limited to supporting convergence and methodological consistency, without influencing the substantive judgments expressed by participants. In this phase, adjusted comparison matrices were proposed for each group of criteria by averaging the dominance factors resulting from the qualitative evaluations agreed upon within each group. These adjusted matrices were discussed with the participants and further refined through collective deliberation until a shared version was accepted. Based on the finalized comparison matrices, weight scores for each criterion and sub-criterion were then computed by normalizing the matrices and calculating the average value of each corresponding row. Finally, the Consistency Ratio was calculated to assess the internal coherence of the pairwise comparison matrices.

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APPENDIX 2

Land Suitability Analysis

The land suitability analysis (LSA) was developed to assess, for each municipality and NbS type, the relative priority of intervention for funding allocation. Separate suitability analyses were carried out for each NbS type at the municipal level. The assessment was structured around five dimensions: technical feasibility, climatic alterations, environmental pressures, exposure, and vulnerability, which together describe the opportunities and constraints affecting NbS implementation (See Table 1).

Technical feasibility represents the availability of land suitable for implementing each option and is expressed through the AV_SUR metric, which measures the total surface area of eligible land units for the *j*-th option across the *n* census tracts within the *i*-th municipality. Climatic alterations reflect the intensity and frequency of climate change impacts. Based on the Regional Strategy for Adaptation to Climate Change for the Sardinia Region, three key phenomena are considered: temperature rise, heatwaves, and changes in precipitation. Average temperature variations are represented by I_T_MAX, I_D_T_MAX, I_T_MIN, and I_D_T_MIN, measuring respectively: i) projected mean maximum summer temperature (2021–2040); ii) variation in mean maximum summer temperature between 2021–2040 and 1970–2000; iii) projected mean minimum summer temperature (2021–2040); and iv) variation in mean minimum summer temperature between the same periods. Heatwave dynamics are captured through I_HW and I_D_HW, indicating respectively the average annual duration of heatwaves (2026–2040) and its change relative to 1986–2000. A heatwave is defined as a period of at least two consecutive days when both maximum apparent temperature (Tappmax) and minimum temperature (Tmin) exceed their monthly 90th percentiles (Copernicus Climate Change Service Climate Data Store, 2019).

Alterations in precipitation are described by I_DRY, I_D_DRY, I_Y_PREC, and I_D_Y_PREC, corresponding respectively to: i) mean annual dry days (precipitation <2 mm, 2021–2040); ii) change in mean dry days between 2021–2040 and 1980–2000; iii) mean annual precipitation (2021–2040); and iv) its variation from 1970–2000. Data on heatwaves and dry days were obtained from Heat Waves and Cold Spells in Europe (Copernicus Climate Change Service Climate Data Store, 2019) and Downscaled Bioclimatic Indicators for Selected Regions from 1950 to 2100 (Copernicus Climate Change Service, 2021), both provided by the Copernicus Climate Data Store (CDS). Temperature and precipitation data were retrieved from WorldClim (Fick & Hijmans, 2017), using the GISS-E2-1-G Global Climate Model under the SSP 3–7.0 scenario for 2021–2040.

The environmental pressures dimension assesses anthropogenic pressures, quantified through I_CO2, I_PM10, and I_PM2.5. These indicators express, respectively, the annual CO₂ emission intensity and the annual mean concentrations of particulate matter PM₁₀ and PM_{2.5}, measured in µg/m³. Data sources include the Copernicus Atmosphere Monitoring Service (Copernicus Atmosphere Monitoring Service, 2020) for CO₂ and European Environment Agency (2023) air quality datasets for PM₁₀ and PM_{2.5} (European Environment Agency, 2023).

Exposure refers to the density of population and built structures potentially affected by climate-related hazards. It is represented by I_POP_R (population density) and I_BUI_VOL (built-up volume density), both computed as mean values per 100 m raster cell intersecting each census tract.

Data were derived from the Global Human Settlement (GHS) population grid and built-up volume grid (Pesaresi et al., 2024; Pesaresi & Politis, 2023). Using density metrics ensures comparability across spatial units of varying size.

Vulnerability captures socio-economic and territorial conditions influencing susceptibility to climate impacts, including accessibility to essential services, demographic ageing, and depopulation trends. Vulnerability is quantified through I_ER, I_TRA, I_POP_T, and I_ELD, representing respectively: i) the reciprocal of the number of emergency departments, weighted by distance and service level, within a 75 km radius; ii) the reciprocal of the

number of train stations under the same criteria; iii) variation in population density (2000–2030); and iv) the percentage of residents aged 65 and over.

Distances to Services of General Interest were computed using the Attraction Reach function of the Place Syntax Toolkit (Stahle et al., 2007). The 75 km threshold aligns with the definition of ultra-peripheral areas in the Italian National Strategy for Inland Areas (SNAI) (Annunziata et al., 2024).

These indicators are selected as proxies of the impact of remoteness, ageing, and population decline on vulnerability to climate risks (Graus et al., 2024; Linares et al., 2020).

All indicators were normalized through range standardization, as reported in Equation 1.

$$I_n = \frac{(I_i - I_{min})}{(I_{max} - I_{min})} \quad (1)$$

where I_n is the normalised value, I_i the original value for the i -th spatial unit, and I_{max} and I_{min} the maximum and minimum values of the original variable across all spatial units.

Range standardisation converts the values of each variable into the 0–1 interval.

After normalization, values closer to 1 indicate greater relative priority for intervention in relation to the variable considered.

The normalized indicators are subsequently aggregated into five composite indices: I_SUR (technical feasibility), I_CLI (climatic alterations), I_ENV (environmental pressures), I_EXP (exposure), and I_VUL (vulnerability). These indices were then integrated into synthetic suitability indices specific to each NbS type: I_SUI_BUI for NbS on built-up surfaces (e.g., green roofs), I_SUI_IUS for NbS on impervious artificial land (e.g., street trees), and I_SUI_POS for NbS on permeable non-forested land (e.g., urban parks). The values of the composite and synthetic indices range from 0 to 1, with values closer to 1 indicating greater priority for intervention across the dimensions considered and according to the weights derived via AHP.

Composite and synthetic indices were computed as weighted averages of the corresponding indicators, with weights derived through the Analytical Hierarchy Process (AHP) (Table 2) (T. L. Saaty, 1980). AHP integrates a pairwise-comparison technique within a multi-level hierarchical structure: the hierarchy represents the problem decomposition, while pairwise comparisons determine the relative importance of variables within each level. The pairwise comparison matrix was developed through a simulated participatory process involving territorial planning scholars (Annex 1), and all subjective judgements regarding the relative importance of criteria and sub-criteria were established through consensus among participants.

Decision Support Tool

The Decision-Support Tool (DST) is designed as a replicable and adaptable tool for supporting the planning of Nature-Based Solutions (NbS) for climate change mitigation and adaptation across different territorial scales. It is structured around three stages: i) allocation of funds among the three domains at the regional level; ii) distribution of financial resources across municipalities within each domain; and iii) visualization of projected policy outcomes, including the proportion of domains targeted, expected mitigation benefits, and the iterative adjustment of budget allocations. The tool is applied to generate a scenario for the year 2040.

The DST follows a constraint-based logic and estimates the outcomes of implementing selected NbS under fixed financial conditions. A fundamental assumption is the stationarity of annual budgets, whereby allocations per domain remain constant over the 2026–2040 period.

Structurally, the DST comprises five sections: Budget, Parameters, Municipal Budget, Scenario, and Results. The Budget section lists all actions and corresponding financial resources derived from regional and European programmes, including the European Regional Development Fund (ERDF) 2021–2027, the Development and Cohesion Fund (FSC) 2021–2027, and the Regional Economic and Financial Document (Documento di Economia e Finanza Regionale, DEFR) 2024–2026. This section

provides an interactive interface that allows users to define the percentage of each action’s budget allocated to the three domains. This stage entails the mainstreaming of climate-change adaptation and mitigation strategies grounded in NbS implementation within financial programmes related to the Green Transition, sustainable urban mobility, social inclusion, sustainable and integrated urban and territorial development, energy, environment and natural resources, urban regeneration, and land use and housing. The proportion of funding to be allocated within these investment lines to the identified domains is determined through a simulated negotiation among territorial planning scholars (Annex 1). For example, the ERDF-financed action “Sustainable and Integrated Urban and Territorial Development” (€32,185,431) assigns 15% to NbS on building surfaces, 5% to NbS on artificial impervious land, and 15% to NbS on permeable non-forested land, yielding the annual domain-specific budgets. The Parameters section distributes each domain’s budget among municipalities according to criteria of context-specificity and socio-environmental justice, operationalised via the synthetic suitability index for each NbS type. For each municipality and domain, a population equivalent is computed as the resident population weighted by the corresponding suitability index. The funding per capita parameter is then derived by dividing the total domain budget by the sum of all population-equivalent values (see equation 2).

$$F_{pc,d} = \frac{B_d}{\sum_{m=1}^M PE_{m,d}} \quad (2)$$

Where $F_{pc,d}$ refers to the funding per capita for domain d , B_d is the total budget of domain d , $PE_{m,d}$ is the population equivalent of municipality m in domain d , and M is the total number of municipalities in the Sardinia Region. The Municipal Budget section estimates, for each municipality m and domain d , the share of the domain budget to be allocated. The municipal allocation is obtained by multiplying the funding per capita for domain d by the population equivalent of municipality m . During implementation, some municipalities may use only part of the allocated budget because all suitable land units available for the selected NbS within that domain have already been transformed. In such cases, the unspent amount is treated as a residual budget.

This residual amount is not transferred to other domains. Instead, it is returned to the residual budget of the same domain and redistributed among municipalities that still have suitable land available for intervention. In this way, financial resources remain coherent with the original policy objective while avoiding underutilization of the domain budget. For each year of implementation, the section therefore computes: i) the total residual budget of domain d ; and, for each municipality, ii) the progress status of action j ; iii) a priority parameter; and iv) the percentage of the residual budget assigned to municipality m .

The redistribution is based on a priority rule designed to direct residual resources toward municipalities where implementation is less advanced and where the intervention remains comparatively more relevant. More precisely, municipalities are ordered according to three criteria: i) lower progress in the implementation of the selected action within the domain; ii) greater synthetic suitability index; and iii) larger resident population, where the previous two criteria are equal. This ordering generates a ranking in which municipalities with lower coverage levels and greater relative suitability are placed first. The ranking is then converted into a priority score, so that municipalities in higher positions receive a larger share of the residual budget. Municipalities whose implementation progress has already reached the predefined threshold are excluded from this redistribution step. The share of residual budget assigned to each eligible municipality is calculated as (equation 3):

$$\alpha_{m,d} = \frac{P_{m,d}}{\sum P_{m,d}} \quad (3)$$

Where $\alpha_{m,d}$ is the share of residual budget assigned to municipality m in domain d , and $P_{m,d}$ is its priority score.

Through this procedure, the DST reallocates unspent municipal resources within the same domain in a transparent and reproducible way. The rule ensures continuity of expenditure, limits budget fragmentation, and privileges municipalities where the selected NbS still has greater margin for implementation.

The Scenario section calculates, for each municipality m and domain d , the surface area of land units targeted annually (A_TAR_t) and the estimated carbon sequestration benefit by 2040 (C_SEQ). A_TAR_t is computed by dividing the annual budget, net of maintenance costs of land units targeted in previous years, by the sum of unit investment and maintenance costs. C_SEQ is obtained by multiplying the cumulative targeted surface area by the carbon sequestration rate of action j .

Finally, the Results section reports, for 2040, key performance metrics: cumulative and required budgets, per capita allocated funding, total and per capita targeted surface areas, and total and per capita annual carbon sequestration estimates.

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Table A1. List of Criteria and Sub-criteria selected for the Land Suitability Analysis

Dimension	Indicator	Variable measured	Unit of measurement	Data source
Technical feasibility	AV_SUR	Total surface area of eligible land units for option <i>j</i> within municipality <i>i</i>	m ²	Derived from spatial processing of eligible land units
Climatic alterations	I_T_MAX	Projected mean maximum summer temperature (2021–2040)	°C	WorldClim (Fick & Hijmans, 2017)
Climatic alterations	I_D_T_MAX	Variation in mean maximum summer temperature between 2021–2040 and 1970–2000	°C	WorldClim (Fick & Hijmans, 2017)
Climatic alterations	I_T_MIN	Projected mean minimum summer temperature (2021–2040)	°C	WorldClim (Fick & Hijmans, 2017)
Climatic alterations	I_D_T_MIN	Variation in mean minimum summer temperature between 2021–2040 and 1970–2000	°C	WorldClim (Fick & Hijmans, 2017)
Climatic alterations	I_HW	Average annual duration of heatwaves (2026–2040)	days/year	Heat Waves and Cold Spells in Europe (Copernicus Climate Change Service Climate Data Store, 2019)
Climatic alterations	I_D_HW	Variation in heatwave duration relative to 1986–2000	days/year	Heat Waves and Cold Spells in Europe (Copernicus Climate Change Service Climate Data Store, 2019)
Climatic alterations	I_DRY	Mean annual dry days (2021–2040; precipitation < 2 mm)	days/year	Downscaled Bioclimatic Indicators for Selected Regions from 1950 to 2100 (Copernicus Climate Change Service, 2021)
Climatic alterations	I_D_DRY	Variation in mean annual dry days between 2021–2040 and 1980–2000	days/year	Downscaled Bioclimatic Indicators for Selected Regions from 1950 to 2100 (Copernicus Climate Change Service, 2021)
Climatic alterations	I_Y_PREC	Mean annual precipitation (2021–2040)	mm/year	WorldClim (Fick & Hijmans, 2017)
Climatic alterations	I_D_Y_PREC	Variation in annual precipitation relative to 1970–2000	mm/year	WorldClim (Fick & Hijmans, 2017)
Environmental pressures	I_CO2	Annual CO ₂ emission intensity	t km ⁻² y ⁻¹	Copernicus Atmosphere Monitoring Service (Copernicus Atmosphere Monitoring Service, 2020)
Environmental pressures	I_PM10	Annual mean concentration of PM ₁₀	µg/m ³	European Environment Agency (European Environment Agency, 2023)

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Table A1. Continued

Dimension	Indicator	Variable measured	Unit of measurement	Data source
Environmental pressures	I_PM2.5	Annual mean concentration of PM _{2,5}	µg/m ³	European Environment Agency (European Environment Agency, 2023)
Exposure	I_POP_R	Population density	inh/ha	Global Human Settlement population grid (Pesaresi et al., 2024).
Exposure	I_BUI_VOL	Built-up volume density	m ³ /ha	Global Human Settlement built-up volume grid (Pesaresi et al., 2024; Pesaresi & Politis, 2023).
Vulnerability	I_ER	Reciprocal of the number of emergency departments weighted by distance and service level within 75 km	index	Place Syntax Toolkit + service data (Stahle et al., 2007)
Vulnerability	I_TRA	Reciprocal of the number of train stations weighted by distance and service level within 75 km	index	Place Syntax Toolkit + service data (Stahle et al., 2007)
Vulnerability	I_POP_T	Variation in population density (2000–2030)	%	Global Human Settlement population grid (Pesaresi & Politis, 2023).
Vulnerability	I_ELD	Share of residents aged 65 and over	%	Census Data (ISTAT (Italian National Institute for Statistics), 2023)

Table A2. Weights derived from the AHP method

Indicator	Definition	Weight
I_CLI	Composite Indicator of Climatic Alterations	0.297
Sub-Indicator	Definition	Weight
I_T_MAX	Projected Mean Maximum Summer Temperature (2021–2040)	0.049
I_D_T_MAX	Variation In Mean Maximum Summer Temperature between 2021–2040 and 1970–2000	0.049
I_T_MIN	Projected Mean Minimum Summer Temperature (2021–2040)	0.088
I_D_T_MIN	Variation In Mean Minimum Summer Temperature between 2021–2040 and 1970–2000	0.088
I_HW	Average Annual Duration Of Heatwaves (2026–2040)	0.156
I_D_HW	Variation In Average Annual Duration Of Heatwaves between 2026–2040 and 1986–2000	0.156
I_DRY	Mean Annual Dry Days (precipitation <2 mm, 2021–2040)	0.156
I_D_DRY	Variation In Mean Dry Days between 2021–2040 and 1980–2000	0.156
I_Y_PREC	Mean Annual Precipitation (2021–2040)	0.049
I_D_Y_PREC	Variation In Mean Annual Precipitation between 2021–2040 and 1970–2000	0.049
Indicator	Definition	Weight
I_ENV	Composite Indicator of Environmental Pressures	0.158

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Table A2. Continued

Indicator	Definition	Weight
Sub-Indicator	Definition	Weight
I_CO2	Annual CO ₂ Emission Intensity	0.333
I_PM10	Annual Mean Concentration of particulate matter PM ₁₀	0.333
I_PM2.5	Annual Mean Concentration of particulate matter PM _{2.5}	0.333
Indicator	Definition	Weight
I_VUL	Composite Indicator of Socio-Territorial Vulnerability	0.297
Sub-Indicator	Definition	Weight
I_ER	Reciprocal of The Number of Emergency Departments, weighted by distance and service level, within a 75 km radius	0.351
I_TRA	Reciprocal of The Number of Train Stations weighted by distance and service level, within a 75 km radius	0.188
I_POP_T	Variation in Population Density (2000–2030)	0.109
I_ELD	Percentage of Residents Aged 65 and Over	0.351
Indicator	Definition	Weight
I_EXP	Composite Indicator of Exposure	0.088
Sub-Indicator	Definition	Weight
I_POP_R	Population Density	0.750
I_BUI_VOL	Built-Up Volume Density	0.250
Indicator	Definition	Weight
I_SUR	Total Surface Area of Eligible Land Units	0.158

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