IIS

INSTITUTO INTERNACIONAL PARA SUSTENTABILIDADE

INTERNATIONAL INSTITUTE FOR SUSTAINABILITY

Prêmio MapBiomas 2025

A nature-based solutions framework for managing environmental disaster risks

Viviane Dib, Fernando Resende, Stella Manes, Julia Niemeyer, Luiz Oliveira, Fernanda D. Gomes, Agnieszka Latawiec, Rafael Loyola, Juliana M. de Almeida-Rocha.

Abstract

Biodiversity and ecosystem services (BES) play a crucial role in addressing global change drivers, such as climate change and economic growth. Nature-based Solutions (NbS) serve as effective adaptation strategies, mitigating risks while preserving nature's contributions to people. Given the increasing threats of floods, heat waves, and coastal erosion, identifying priority areas for NbS implementation is essential to ensure human well-being, especially considering increased societal risks due to the climate emergence. We developed a decision-support framework for managing environmental disaster risks through NbS. Applicable across diverse contexts, the framework identifies priority areas to optimize BES under different future scenarios. It includes a decision tree to guide users in scenario development—such as land-use and climate projections—along with a list of practical examples. As a case study, we applied the framework to Rio de Janeiro state, Brazil's second most urbanized and economically significant region. We modeled land-use scenarios for 2050 based on business-as-usual, optimistic, and pessimistic narratives and considered extreme climatic events. We assessed impacts on three key BES: flood-risk reduction, thermal comfort, and coastal protection. We then identified priority areas for NbS—specifically, restoring and conserving native vegetation—to maximize the BES benefits in socially vulnerable areas. Finally, we estimated NbS implementation costs and potential co-benefits for biodiversity conservation and carbon sequestration. The proposed framework provides a scientifically robust, spatially intelligent approach to integrating NbS into disaster risk management and climate adaptation. It supports decision-making at local and regional scales, offering a replicable method that combines future policy-relevant scenarios with BES modeling.

Keywords: Environmental Disaster, Risk Management, Nature-based Solutions, Ecosystem Services, Extreme events, Climate change, Biodiversity.

Introduction

Global change, driven by climate and land-use shifts, poses severe threats to biodiversity, ecosystem services (BES), and human well-being. These impacts are already evident, with rising deforestation rates and global temperatures having already exceeded a 1°C increase due to observed climate change (IPCC 2021). Future projections indicate a troubling outlook, with widespread BES losses at regional and global scales (Manes et al. 2022, Prado et al. 2024). Beyond rising mean temperatures, sea-level rise, and shifting precipitation patterns, extreme climatic events are expected to become more frequent and intense (Myhre et al. 2019). The growing climate emergency demands urgent action, especially given the unpredictability of extreme events, which hampers societal preparedness (IPCC 2012). In this context, efforts solely focused on reducing climate and land-use change—such as deforestation control and climate change mitigation—are no longer sufficient. More ambitious strategies are essential to sustain nature's benefits for society (Pörtner et al. 2022).

Fortunately, there is growing recognition of nature's role in addressing global challenges. Nature-based solutions (NbS) leverage ecosystem protection and restoration to enhance resilience, delivering benefits for both people and nature (IUCN, 2020). By harnessing biodiversity and ecosystem services, NbS help mitigate the risks of unchecked global change while promoting human well-being (Cohen-Shacham et al., 2016). Certain BES play a particularly crucial role in reducing climate-related risks. The concept of 'climate adaptation services' underscores how ecosystems resist, adapt to, or transform under climate change, highlighting the growing importance of ecosystem services directly linked to climatic hazards (Lavorel et al., 2019).

Ecosystem-based disaster risk reduction, such as flood mitigation, thermal regulation, and coastal protection, will be indispensable in a future of intensified global change. For instance, climate change-driven shifts in precipitation patterns, combined with urban expansion, are expected to increase flood risks by reducing natural water absorption in impermeable urban landscapes. NbS that enhance flood control offer a 'no-regrets' adaptation strategy, mitigating these risks while providing co-benefits such as water purification and biodiversity conservation (Jones et al., 2012). By harnessing nature's contributions, NbS function as a natural insurance policy, strengthening societal, economic, and ecological resilience against environmental disasters. Integrating NbS into insurance mechanisms enables the sector to bolster climate adaptation, reduce financial losses, and promote sustainable land-use practices, ultimately fostering a more resilient and risk-informed society.

Selecting priority areas for implementing NbS is crucial for maximizing benefits to people. By strategically targeting areas where NbS can deliver the greatest impact—such as regions with high social vulnerability and exposure to climate hazards—decision-makers can enhance climate adaptation services provision. This targeted approach not only improves resilience in at-risk communities but also optimizes financial resources, reducing overall implementation and maintenance costs. Furthermore, prioritization fosters climate justice by addressing historical and systemic inequalities that leave marginalized populations disproportionately exposed to environmental risks. Many socially vulnerable communities, particularly in urban peripheries and low-income rural areas, suffer from environmental racism, where inadequate infrastructure and limited access to green spaces exacerbate climate change impacts (Holifield, 2001). Implementing NbS in these areas helps redress these injustices by integrating nature into urban planning, improving quality of life, and ensuring equitable distribution of environmental benefits. Additionally, well-planned NbS can generate co-benefits such as biodiversity conservation, carbon sequestration, and economic opportunities. Ultimately, selecting priority areas for NbS implementation is not only a matter of efficiency but also a fundamental step toward building fairer, more resilient, and climate-adaptive societies.

We propose a spatial intelligence-based decision-support framework to guide local and regional policies on environmental disaster prevention and risk reduction through prioritizing areas for NbS. Applicable across diverse environmental and socioeconomic contexts, the framework identifies priority areas for NbS implementation to optimize ecosystem service provision under different future scenarios. As a case study, we applied the framework to the state of Rio de Janeiro, Brazil. We modeled land-use change scenarios based on business-as-usual (BAU), optimistic, and pessimistic policy-relevant narratives. To assess the scenarios' benefit for climate adaptation, we considered extreme climatic events of temperature, precipitation, and sea-level rise. We assessed the impacts of these scenarios on three key climate adaptation services: flood-risk reduction, thermal comfort, and coastal protection. We then identified priority areas for NbS to maximize disaster prevention benefits in socially vulnerable areas. Finally, we estimated implementation costs and potential co-benefits for biodiversity conservation and carbon sequestration in the region. This framework offers a comprehensive and adaptable tool to inform decision-making, providing valuable insights for advancing NbS strategies in the face of escalating climate risks.

Methods

Framework development

The framework was developed by a multidisciplinary team, ensuring a comprehensive and integrative approach. Its development involved three key phases: (i) designing an operational framework that outlines the essential steps for managing environmental disaster risks through NbS implementation; (ii) creating a decision tree to guide users in developing future scenarios, such as land-use and climate projections; and (iii) formulating a conceptual framework that provides a high-level overview of the methodology, highlighting its major steps and overall structure.

To ensure that the operational framework provides a replicable and adaptable methodology for any region of interest, we designed a four-stage structure, with each stage consisting of a set of steps. The framework systematically explores the socio-environmental context of the target area, examines potential future scenarios and their impacts on BES provision, and ultimately identifies priority areas for NbS implementation to enhance or sustain BES provision. This approach draws inspiration from the Driver-Pressure-State-Impact-Response (DPSIR) framework (Martins et al. 2012, Tscherning et al. 2012) and the IPBES Nature Futures Framework (PBL 2018).

To support the scenario-planning process, we designed a decision tree guide that helps users navigate scenario development based on the availability of data on environmental laws, socioeconomic factors, and climate change trends. The conceptual framework was designed to highlight the key elements that should be considered in projects or public policies focused on managing environmental disaster risks through NbS implementation. As a simplified version of the operational framework, it aims to reach a broader audience and serves as a useful tool for engaging local stakeholders.

This structure was discussed and validated by an international panel of experts participating in the *Biodiversity and Ecosystem Services (BES) Scenarios Modelling Initiative*, led by the Swiss Re Foundation, in partnership with the AXA Research Fund, WWF, Swiss Re Institute, and Ernest & Young. The initiative, aimed at improving our understanding of the societal and economic impacts of biodiversity loss and ecosystem degradation, brings together researchers from Switzerland, Germany, Peru, Belize, and Brazil. Their contributions improved the framework’s clarity, usability, and applicability across diverse contexts.

Study case

Our study region is the state of Rio de Janeiro, located in Southeastern Brazil, encompassing 43,802 km^2 within the Atlantic Forest biome—one of the world's most critical biodiversity hotspots and a global priority for terrestrial conservation (Mittermeier et al. 2005). Currently, only 30% of the state's original native vegetation remains, fragmented into small, isolated patches within a pasture-dominated landscape (SEA/INEA 2018). Approximately two-thirds of the state's land area consists of non-natural land uses, including pastures, croplands, mining, and other degraded areas (Rezende et al. 2018). This highly altered landscape presents significant opportunities for native vegetation restoration (Strassburg et al. 2020).

Rio de Janeiro is one of Brazil's most urbanized, industrialized, and densely populated states, home to 16 million people (IBGE 2022), the majority of whom reside in the capital city and its metropolitan region. The state's population is highly vulnerable to natural disasters linked to extreme events due to historical and ongoing changes in its physical landscape, including its mountainous terrain, river and stream modifications, deforestation of the original Atlantic Forest cover (SOS Mata Atlântica 2018), and unplanned occupation of hillsides and coastal zones. Additionally, Rio de Janeiro lies in a transitional area between atmospheric systems, increasing the likelihood of intense rainfall events that trigger flooding, inundation, and landslides, leading to societal disruptions and significant socioeconomic losses (SEA/INEA 2018).

The state's high population density further exacerbates climate change vulnerability. Its capital ranks among the most climate-vulnerable cities in Latin America, where rising sea levels, flooding, increased precipitation, and urban heat islands are expected to intensify in the coming years (Castellanos et al. 2022). Addressing these challenges requires adaptive mechanisms that leverage NbS to enhance the state's resilience to extreme events. Despite its climate adaptation deficit, Rio de Janeiro possesses a strong foundation for NbS implementation, benefiting from both natural and social capital (SEA/INEA 2018). Given these factors, the state serves as an excellent case study for applying the proposed framework.

Results

Framework for managing disaster risks

The operational framework consists of a four-stage structure (Figure 1), with each stage comprising a set of steps detailed in Table 1. In Stage A ("Setting the Context"), users define the socio-environmental context by identifying the drivers of environmental disasters, local pressures, and the state of nature in the region. The state of nature, shaped by local pressures, reflects environmental conditions from multiple perspectives, including biodiversity, ecosystem services, and social and cultural values. Additionally, users determine the climate adaptation BES to be enhanced or sustained through NbS, the type of NbS to be implemented, and its associated co-benefits. Engaging local actors and key stakeholders at this stage is crucial, as their involvement integrates local knowledge, values, and priorities, ensuring more relevant and widely accepted outcomes (Reed 2008).

In Stage B ("Modelling Future Scenarios"), users develop land-use and/or climate change scenarios based on neutral, optimistic, and/or pessimistic policy-relevant narratives, considering a combination of key trends (related to the local pressures identified in Stage A) and specific time spans. A decision tree (Figure S1) can be used to support the scenario-planning process. As in Stage A, engaging local stakeholders is essential for validating the scenarios, ensuring their realism and relevance to the local context while fostering stakeholder buy-in and support for potential future actions. Examples illustrating the implementation of Stages A and B can be found in the supplementary material (Table S1). In Stage C ("Estimating BES Provision"), users assess the impacts of future scenarios on the provision of the climate adaptation BES identified in Stage A. This is done by comparing BES provision across alternative scenarios (optimistic and/or pessimistic) and a business-as-usual scenario (neutral) within the same time span. Users can also build graphs to visualize the variation in BES provision over time, as indicated at the bottom of Panel C (Figure 1).

In Stage D ("Identifying Priority Areas for NbS"), users identify priority areas for NbS implementation by mapping gains and losses in BES provision, considering the impacts of both optimistic and pessimistic scenarios alongside the location of socially vulnerable areas. To achieve this, users should normalize and integrate the spatially explicit outputs from scenario impact assessments for each BES (if multiple BES are considered). Next, areas with the most significant changes in BES provision should be identified. These results should then be overlaid with spatially explicit social vulnerability indicators, which reflect socio-economic factors influencing a community's capacity to prepare for, cope with, and recover from environmental events. Examples of social vulnerability indicators can be found in the supplementary material (Table S1).

Priority areas for enhancing BES provision through NbS are zones where high social vulnerability overlaps with potential significant gains in BES provision under optimistic scenarios, if NbS is implemented. Conversely, priority areas for sustaining BES provision are zones where high social vulnerability overlaps with significant losses in BES provision under pessimistic scenarios. This spatial analysis ensures that NbS interventions are strategically placed to maximize benefits, enhance climate resilience, and address critical socio-environmental challenges. Once these priority areas are identified, users should estimate implementation costs and potential co-benefits of NbS interventions. Examples of co-benefits and cost analysis can be found in the supplementary material (Table S1). Finally, engaging local stakeholders in validating the framework's results is crucial to ensuring their relevance, feasibility, and acceptance. Ultimately, the outcomes of this framework can inform decision-making processes, supporting evidence-based planning and policy development for sustainable and climate-resilient solutions.

The conceptual framework (Figure 2) consists of a graphical synthesis of the operational framework, providing a general overview of the approach adopted. The starting point is the identification of local pressures and drivers of natural disasters.

These will determine the BES of interest, depending on how they interfere with the status of nature (considering biodiversity, ecosystem services, and cultural aspects). The provision of the BES of interest, analysed from the perspective of future scenarios, determines areas of greater gain or loss of these services. Finally, the distribution of areas of greater gain or loss of BES, weighted by social vulnerability, determines the priority areas for the implementation of NbS.

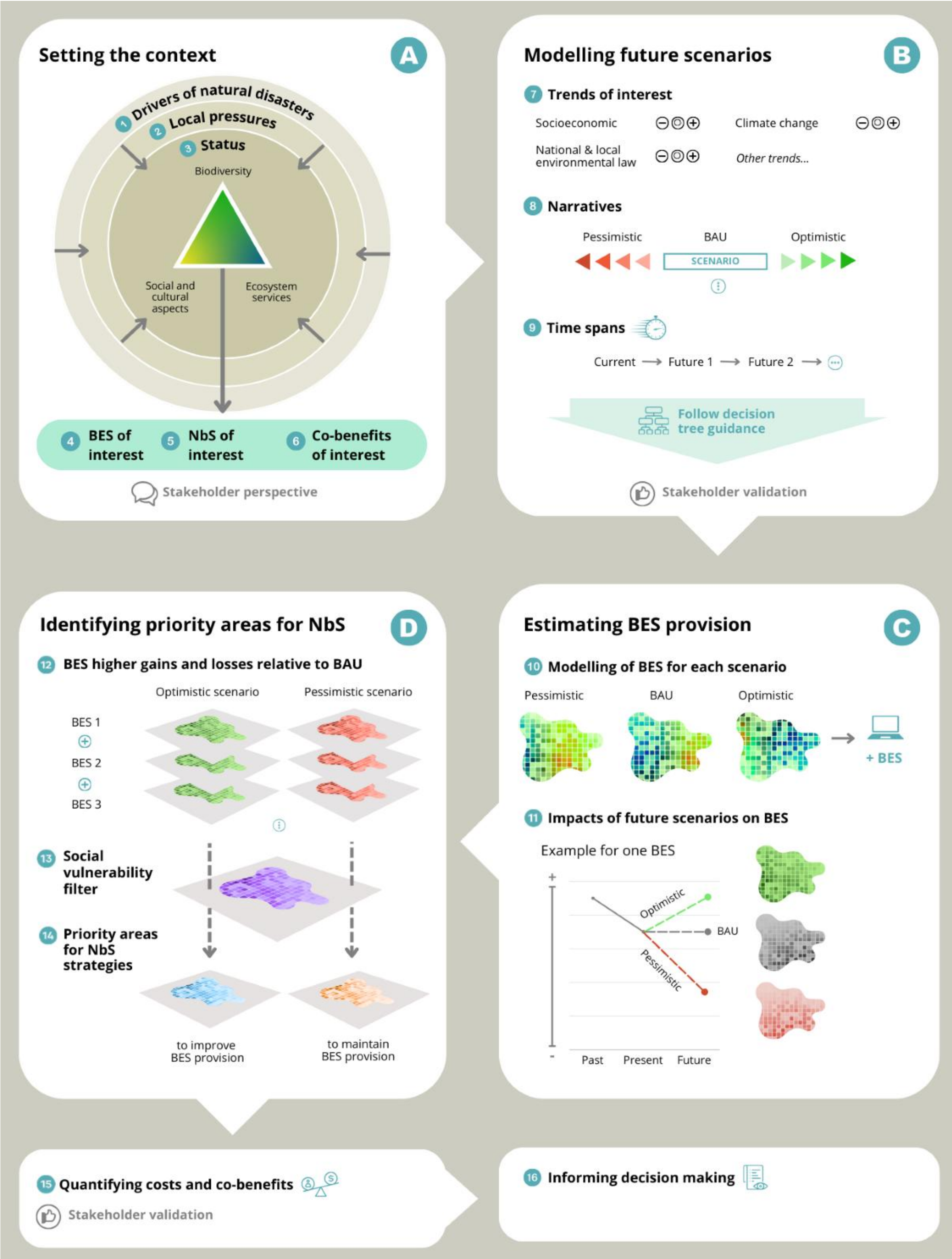

Figure 1. Graphic representation of the operational framework for managing environmental disaster risks.

Table 1. Description of each step of the operational framework.

Stage	Step	Description
A. Setting the Context	1. Drivers of environmental disasters	Identify natural or anthropogenic (human-induced) factors that directly or indirectly cause a change in nature and, in this case, lead to natural disasters.
	2. Local pressures	Identify the consequences of the driving forces, which in turn affect the status of the environment.
	3. Status	As a result of local pressures, the status of nature describes the environmental conditions from different perspectives. Identify the status of: * **Biodiversity**: addresses the impacts of local pressures on the intrinsic value of biodiversity. * **Ecosystem Services:** addresses the impacts of local pressures on the utilitarian benefits of nature for people. * **Social and cultural aspects:** addresses the impacts of local pressures on social, spiritual and other non-material benefits for people living in harmony with nature.
	4. Biodiversity and Ecosystem Services (BES) of interest	Choose the ecosystem services that will be estimated within the study area to identify priority areas of implementation of Nature-based Solutions (NbS).
	5. NbS of interest	Select the NbS to be implemented in the study area to improve and/or maintain the provision of the targeted BES.
	6. Co-benefits of interest	Choose additional benefits or positive outcomes that result from implementing NbS (beyond the primary objectives) estimated within the study area after the NbS implementation simulation.
B. Modelling Future Scenarios	7. Trends of interest	Identify trends of interest, including variations in socioeconomic factors, climate, compliance with environmental laws, among others. These trends may be positive, negative, or neutral.
	8. Narratives	Based on the identified trends, develop narrative descriptions of potential future scenarios. These scenarios should encompass combinations of trends to depict optimistic, neutral (business-as-usual; BAU), and pessimistic environmental pathways.
	9. Time spans	Determine the time spans for the scenarios, considering the current and future periods.
C. Estimating BES provision	10. Modelling of BES for each scenario	Based on the scenario narratives, build land cover and/or climate scenarios for each time span. Then, estimate the BES of interest for each scenario.
	11. Impacts of future scenarios on BES	Assess the impact of future scenarios on BES by comparing BES provision between alternative scenarios (optimistic and pessimistic pathways) and the business-as-usual scenario. Compare scenarios within the same time span.
D. Identifying priority areas for NbS	12. BES higher gains and losses relative to BAU	Normalize and combine the spatially explicit outputs from the impacts of future scenarios on each BES (step 11). Then, identify areas where changes in BES provision were higher by examining the aggregated scores (i.e., considering all evaluated BES).
	13. Social vulnerability filter	Evaluate social vulnerability indicators in the study region to identify areas more vulnerable to natural disasters and environmental degradation. This involves assessing socio-economic factors influencing a community's ability to prepare for, cope with, and recover from such events.
	14. Priority areas for implementing NbS strategies	Overlay the spatially explicit outputs of BES gain and losses (step 12) with spatially explicit social vulnerability indicators (step13).
Extra steps	15. Quantifying costs and co-benefits	Once priority areas for NbS implementation are defined, estimate their costs and co-benefits (if applicable).
	16. Informing decision-making	The results obtained from applying this framework can provide valuable insights for decision-makers at local, regional, and national levels. These insights can inform the design and implementation of NbS to mitigate natural disasters. A communication plan should be developed to facilitate disseminating the results and engaging different stakeholders.

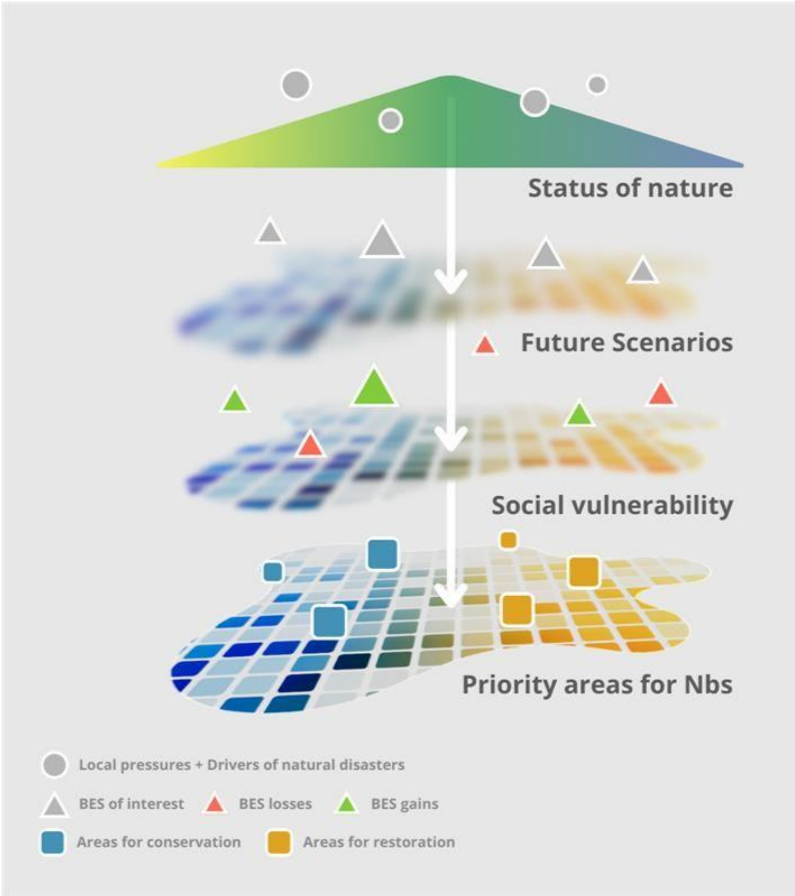

Figure 2. Graphic representation of the conceptual framework for managing environmental disaster risks.

Framework application

Stage A - Setting the Context

To identify the key drivers of environmental disasters, local pressures, and the state of nature in the Rio de Janeiro case study (Steps A1–3), we relied on the Climate Change Adaptation Plan for Rio de Janeiro (SEA/INEA 2018). This plan serves as a key policy document guiding government decision-making and outlining adaptation measures for the state. It integrates climate change projections and their sectoral impacts—including flooding, heat, water resources, and coastal dynamics—while incorporating local stakeholder perspectives. Additionally, we assessed ecosystem conditions by analyzing historical land-use patterns using a high-resolution (30-meter) annual land-use dataset (MapBiomas 2023a, Souza et al. 2020). This allowed us to track long-term environmental changes and identify key pressures on natural systems. Based on this analysis, we identified the primary drivers of environmental disasters and local pressures as: (i) the loss of native vegetation due to land-use changes driven by deforestation trends linked to urbanization, agricultural expansion, and environmental policies; and (ii) the increasing impacts of climate change, particularly extreme climatic events.

As a heavily urbanized coastal region, Rio de Janeiro faces major environmental disasters, including floods, urban heat waves, and coastal erosion and flooding. Therefore, we identified flood-risk reduction, thermal comfort, and coastal protection as the most critical ecosystem services for the region (Step A4). Given the study area's context—characterized by large protected areas surrounded by severely degraded lands—and their well-documented potential to mitigate disaster risks, we selected the conservation and restoration of native vegetation as key NbS to be implemented (Step A5). Considering their relevance in addressing both the biodiversity and climate crises, we selected biodiversity conservation and carbon sequestration as key co-benefits to be accounted for in the implementation of these NbS (Step A6).

We further validated the decisions made in Stage A through feedback from preliminary presentations to stakeholders from the State's Environmental Institute (Instituto Estadual do Ambiente – INEA) and discussions at scientific forums of international and local relevance. These included the World Biodiversity Forum (Davos, Switzerland, 2024) and regional events focused on enhancing Rio de Janeiro's environmental resilience.

Stage B - Modelling future scenarios

Building on the drivers and pressures identified in Stage A, we developed a current land-use scenario (2020) and three future land-use scenarios (BAU, optimistic, and pessimistic) to project potential changes by 2050. These scenarios account for trends in urban expansion, agricultural use, and environmental law compliance (Steps B7–9) (Figure 3). For all land-use analyses, we relied on the annual land-use series from MapBiomas at 30-meter resolution (MapBiomas 2023a, Souza et al. 2020). Under current conditions, 32% of Rio de Janeiro is covered by native vegetation, primarily concentrated within protected areas in the central mountainous region. Meanwhile, pasturelands dominate ~43% of the state's land area, and densely urbanized areas account for ~5%, mostly concentrated in the metropolitan region of the capital.

To design the future land-use maps (Step B8), we incorporated urban expansion across all three scenarios, recognizing the urbanized nature of Rio de Janeiro. However, the extent of urban expansion varied according to each scenario. We integrated urban expansion prediction maps into our optimistic, BAU, and pessimistic scenarios, aligning them with the Shared Socioeconomic Pathways (SSPs) framework from the IPCC (2019). Specifically, we used the projections from Chen et al. (2020), corresponding to: i) SSP1 (optimistic scenario) – low population growth and strong climate action, leading to more sustainable land use; ii) SSP2

(BAU scenario) – moderate population growth with intermediate challenges for climate change mitigation and adaptation; iii) SSP3 (pessimistic scenario) – high population growth and weak climate policies, leading to uncontrolled urban expansion and environmental degradation.

In the business-as-usual scenario, we assumed that native vegetation cover would continue following current land-use trends. By analyzing historical trends in the study area, we identified an ~1% increase in native vegetation cover over the past decade (2010–2020). Extrapolating this trend, we projected a potential ~3% increase in native vegetation cover by 2050, reaching ~35% of the state's total area. To predict where forest restoration would likely occur, we used three key variables: i) Proximity to regenerated forests – we considered secondary vegetation mapped by MapBiomas (2023b), prioritizing areas near forests that naturally regenerated between 2011 and 2020, assuming a higher likelihood of continued restoration; ii) Land price – we incorporated land value data (d'Albertas et al. 2024), assuming that lower-cost lands are more feasible for restoration efforts; iii) Pasture quality – we assessed pasture degradation levels using MapBiomas (2023c), prioritizing restoration in degraded pastures where natural recovery is more likely.

The optimistic scenario assumes that native vegetation gain will result primarily from law compliance, integrating national regulations with local commitments to forest conservation and restoration. We set the restoration goal for this scenario based on the official target from Rio de Janeiro's "Future Forests Program" (Programa Floresta do Futuro), which aims to restore 440,000 hectares by 2050 (Decree No 49.438). Achieving this goal would increase native vegetation cover from ~30% to ~40% of the state's total area. To determine which areas would be restored, we incorporated the requirements of the national Native Vegetation Protection Law (NVPL; Law N° 12.651/2012), which regulates land use in Brazil. The NVPL mandates that rural landowners in the Atlantic Forest must protect or restore at least 20% of their property as Legal Reserves (LR) and restore riparian zones and other sensitive areas classified as Areas of Permanent Protection (APPs) (Brancalion et al. 2016). We used official spatial databases of LR and APPs (available at www.car.gov.br and www.inea.rj.gov.br) to simulate the restoration of these areas across all private lands in the state. We also restored pastures within strict protection and sustainable use protected areas. However, restoration within environment protection areas was limited to zones designated for biodiversity conservation, as defined by INEA database (www.inea.rj.gov.br).

In the pessimistic scenario, we simulated vegetation loss by assuming that non-protected vegetation—i.e., areas not safeguarded by the NVPL or designated protected areas—would be lost by 2050. In practice, we considered that surplus vegetation (i.e., native vegetation located on private lands outside LR and APPs) would be converted into pasture. Additionally, we accounted for vegetation loss within protected areas of sustainable use, specifically in zones legally designated for agricultural activities according to INEA. Thus, the three future land-use scenarios exhibit substantial differences compared to current conditions. In the business-as-usual scenario, native vegetation increases by approximately 3%, while urban areas expand by 2.4%, and coastal vegetation declines by 4%. The optimistic scenario shows a more significant gain in native vegetation, reaching a 10% increase, with urban areas expanding by 2.1% and coastal vegetation increasing by 5%. In contrast, the pessimistic scenario results in a 10% loss of native vegetation, a 2.6% increase in urban areas, and a reduction of 26% in coastal vegetation.

Finally, while it is possible to incorporate climate change directly into scenario design—and we did so to some extent by using SSP trends for urban expansion, which account for climate change—we opted to integrate the impacts of extreme events more explicitly within the modelling approaches described in Stage C. In the supplementary material and decision tree, we provide additional recommendations for incorporating climate change into scenario development through alternative strategies. However, for our study case, we designed land-use change-focused scenarios while incorporating climate change in a more direct and targeted manner to evaluate the effectiveness of these scenarios as climate adaptation strategies. This approach allowed us to assess the role of specific climatic extreme events for each BES, using extreme rainfall for flood-risk reduction, extreme heat for thermal comfort, and extreme sea-level rise for coastal protection. By maintaining the same magnitude of extreme events across current and future scenarios, we were able to isolate and evaluate each scenario's contribution to disaster risk reduction in a consistent and comparable way.

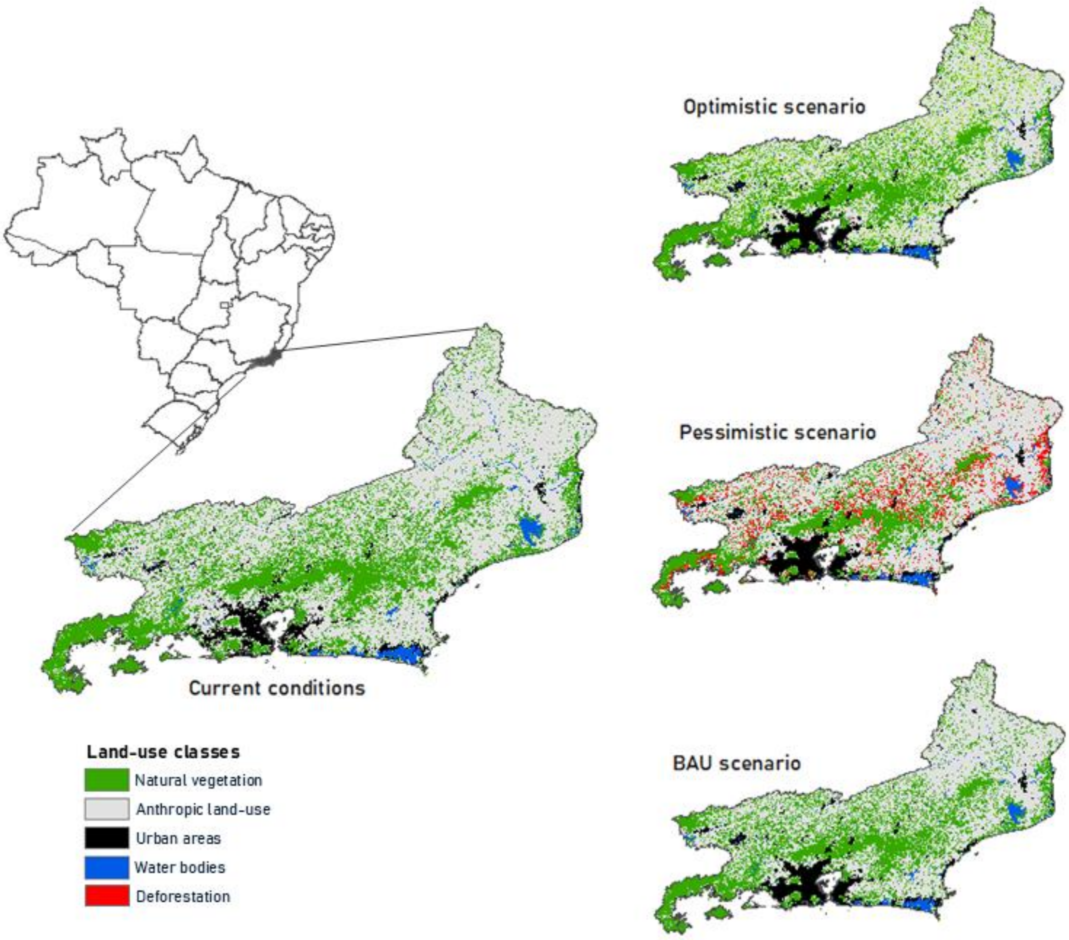

Figure 3. Scenarios developed for the Rio de Janeiro case study. Areas in green represent all types of native vegetation present in the study area (i.e. forests, mangrove, restinga sandbank vegetation and other non-forest formations) or areas that are restored with any of these native vegetation classes. Areas in grey represent anthropic land-uses, including pasture, agriculture, forest plantations and mosaic of uses, except for urban areas which are emphasized in black due to urban expansion in all scenarios. Areas in blue represent water bodies. Areas in red represent areas with degradation of any of the native vegetation classes.

Stage C - Estimating BES Provision

To evaluate the disaster risk management benefits of the BES identified in Stage A, we modeled the impact of each scenario on flood-risk reduction, thermal comfort, and coastal protection (Step C10) using the InVEST software suite (Integrated Valuation of Ecosystem Services and Tradeoffs; Natural Capital Project 2024). Each BES model was run independently four times, representing current conditions and three future scenarios (Step C10). We then assessed the impact of these scenarios (Step C11) by comparing changes in BES provision—measuring increases or decreases—relative to current conditions.

We used InVEST's Urban Flood Risk Mitigation Model to assess flood-risk reduction, following Manes et al. (2024). This model integrates land-use maps developed for each scenario, soil attributes (e.g., soil hydrologic group), and rainfall depth for a one-hour event (mm/h) to estimate flood risk. It evaluates the landscape's capacity to retain runoff and mitigate flooding, producing outputs of runoff retention capacity per pixel. To simulate extreme climatic events, we applied a rainfall depth of 50 mm/h across all scenarios, representing local extreme conditions for Rio de Janeiro (Manes et al. 2024). As expected, under current conditions, flood risks are highest in densely urbanized areas and significantly lower in regions with conserved vegetation (Figure 4). Compared to current conditions, flood control improved 1.4% under the BAU scenario and 5.9% under the optimistic scenario, while declining 9.7% under the pessimistic scenario (Figure 4).

We used InVEST’s Urban Cooling Model to assess heat mitigation and thermal comfort, following Silveira et al. (2024) and Carella (2023). This model estimates vegetation’s capacity to reduce temperatures based on shade, evapotranspiration, albedo, and proximity to cooling islands (e.g., large forest fragments), generating a heat mitigation potential index (see Supplementary Material for methodological details). The model's input data included land-use maps for each scenario, evapotranspiration data, and key biophysical parameters: i) A crop coefficient (Kc) for each land-use class, derived from the relationship between Kc and leaf area index (Kc-LAI) (Allen et al. 1998); ii) A shade ratio, representing the proportion of each land-use class covered by tree canopy at least 2 meters high, calculated using the 2019 Global Forest Canopy 1-60m Height Raster (30-m resolution) (Carella 2023); and iii) Albedo, the proportion of solar radiation reflected by each land-use class, based on Stewart and Oke (2012). We set the reference air temperature at 24ºC, based on a representative rural area in Rio de Janeiro state (climate-data.org), and accounted for an urban heat island effect of +5ºC, in line with INMET alerts on abnormal heat increases for the region. Compared to current conditions, the heat mitigation index increased 6.8% under the BAU scenario and 16.4% under the optimistic scenario, while decreasing 16.4% under the pessimistic scenario (Figure 4).

We used InVEST’s Coastal Vulnerability Model to assess coastal protection, following Arkema et al. (2013) and Manes et al. (2023). This model generates a comparative index along the coastline, identifying areas that are more protected versus those at higher risk of coastal erosion and flooding. The model incorporates six biophysical factors: wind speed, wave power, surge potential, relief, sea-level rise, and the coverage of natural habitats along the coastline. Each variable’s raw value is converted into five percentile rankings, from 1 (most protected) to 5 (most at risk), and their geometric mean is calculated for each point in a 30-meter resolution grid. We then interpolated these values to produce a raster of coastal risk along a 2 km-wide coastal strip. Sea-level rise was treated as an aggravating factor, assigned a high-risk rank (5) across the entire landscape. Natural habitats were ranked separately based on their protective capacity: forests, mangroves, and wooded sandbank vegetation were assigned the highest protection rank (1), while herbaceous sandbank vegetation, beaches, and other non-forest formations were given an intermediate rank (3). The final coastal vulnerability index was classified as low risk (1–2.33), intermediate risk (2.33–3.66), or high risk (3.66–5). Under current conditions, most of the coastline exhibited medium to high risk levels, with lower risk observed in coves and areas sheltered from wave effects (Figure 4). Compared to present conditions, the extent of high-risk areas increased less than 1% under both the BAU and optimistic scenarios but rose 3.3% under the pessimistic scenario, meaning that 5% of the coastline would fall into the highest risk category (Figure 4).

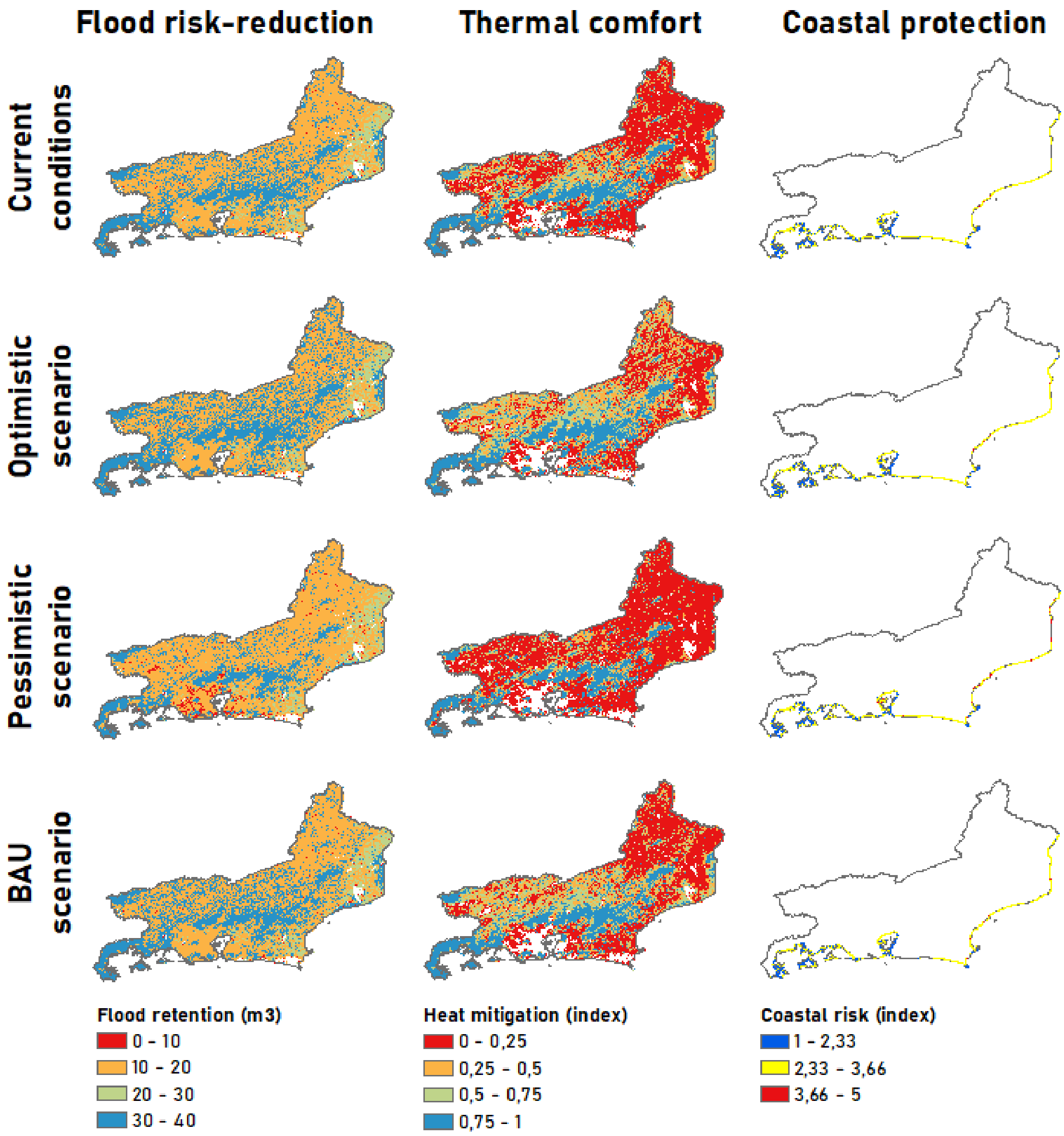

Figure 4. Estimating BES provision for flood-risk reduction, thermal comfort and coastal protection in each scenario. Warmer colours represent smaller provision of flood retention volume (in m^3) and heat mitigation (index), and lower coastal protection (higher risks), whereas cooler colours represent greater benefits for all BES. Coastal protection results are calculated and shown only for the shoreline and can be difficult to visualize in this scale.

Step D - Identifying Priority Areas for NbS

The comparisons between the BAU and alternative scenarios highlight regions where NbS could have the greatest impact on the provision of BES. To assess these differences, we analyzed each BES individually over the same timespans, identifying potential gains under the optimistic scenario and potential losses under the pessimistic scenario relative to current conditions. To enable direct comparisons, we standardized these differences on a scale from 0 to 1. We then aggregated the BES impacts and calculated the mean values between the potential changes across all three BES, identifying areas with the highest overall impact (both gains and losses) in each scenario (Step D12). This aggregated BES impact provided a comprehensive spatial assessment of where the NbS interventions could be most effective. To identify priority areas for NbS implementation, we integrated BES impact maps with a social vulnerability index, using the latter as a weighting factor (Step D13). The Municipal Vulnerability Index, specifically developed for the state of Rio de Janeiro, serves as a tool to guide climate adaptation policies, reduce inequalities, and improve the well-being of vulnerable populations (IVM; IOC/Fiocruz 2014).

The values obtained by combining the BES impact maps with the Municipal Vulnerability Index generate a ranked priority map of areas for NbS implementation (Step D14, Figure 5). All areas available for restoration or conservation are classified in priority tiers (e.g., top 10%, top 20%), guiding the strategic implementation of NbS across the landscape. In the case of Rio de Janeiro state, under the optimistic scenario, priority areas are those where restoration efforts would yield the highest gains in all three BES while benefiting the most socially vulnerable populations. Conversely, under the pessimistic scenario, priority areas are those where conservation actions would prevent the greatest losses of BES in regions with high social vulnerability.

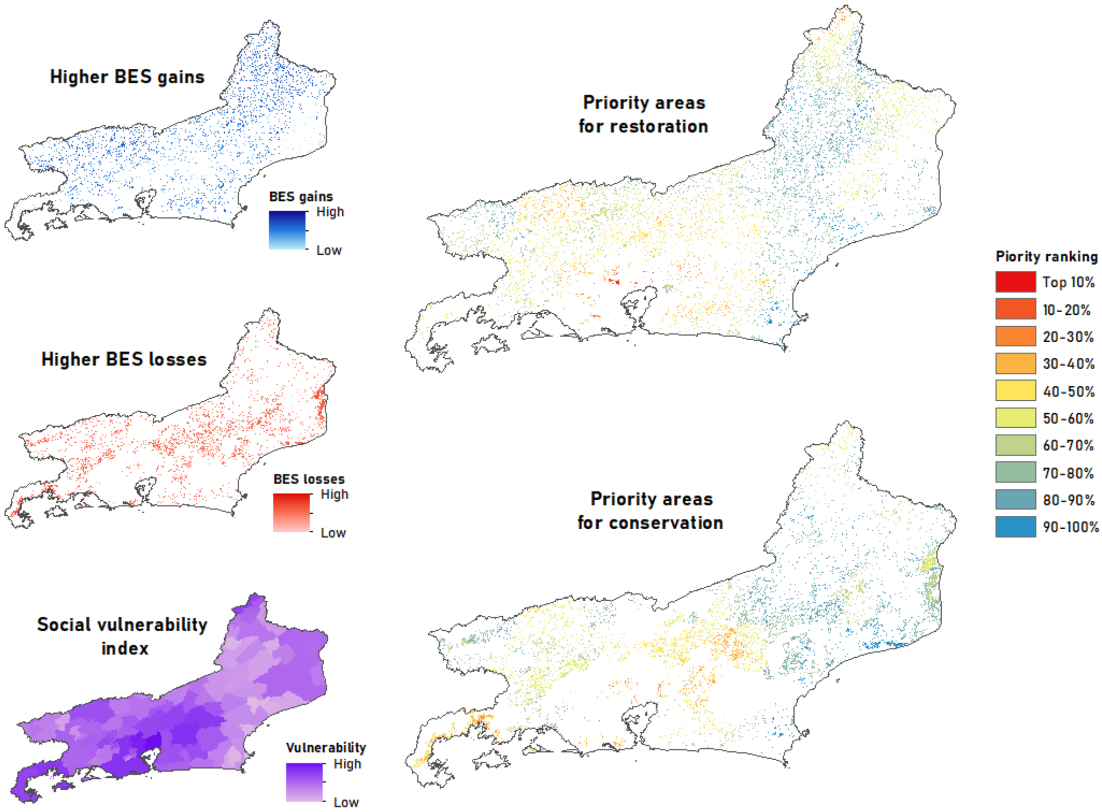

Figure 5. Identification of priority areas for restoration and conservation. Priority areas are identified by multiplying the higher BES gains (restoration) and BES losses (conservation) by the social vulnerability index. The priority areas map ranks all areas assessed for restoration and conservation in an order of priority, where warmer colours represent the top priorities (eg. red represents the top 10% most prioritized areas).

Costs and co-benefits

Once the priority areas were identified, we estimated the associated costs and co-benefits (Step D15). For the pessimistic scenario, we calculated the opportunity costs of conserving priority areas based on the bare land value in Brazilian Reais (R$), following d'Albertas et al. (2024). For the optimistic scenario, we calculated both opportunity costs (d'Albertas et al. 2024) and implementation costs for restoration in the priority areas. The implementation cost was based on official values set by the state of Rio de Janeiro for forest compensation, as defined by the Resolution SEA/INEA No. 630 of May 18, 2016 (Table S2).

We quantified the potential contributions of priority areas to climate mitigation and biodiversity conservation. We estimated carbon stock potential for restoration (optimistic scenario) and avoided carbon loss for conservation (pessimistic scenario), following Liévano-Lattore et al. (2025). To do so, we overlaid a spatial database of carbon stocks onto the priority area map and extracted the total amount of carbon (tons/ha) that could be sequestered or preserved across all restorable and conserved pixels. In the optimistic scenario, priority pixels were ranked from highest to lowest potential carbon sequestration. We then aggregated the total carbon sequestration potential as each additional 10% of priority pixels was restored, up to full restoration (100%). In the pessimistic scenario, we calculated the total above- and belowground carbon stocks in native vegetation (tons/ha) within the highest-priority conservation areas, progressively assessing the amount of carbon preserved as successive 10% increments of these areas were protected, up to full conservation (100%) (Figure S2).

To assess biodiversity co-benefits, we quantified potential habitat gains for thousands of species in the study area, following Strassburg et al. (2019, 2020). This analysis estimates the contribution of each restored pixel (optimistic scenario) or the avoided loss of each conserved pixel (pessimistic scenario) to increasing overall habitat availability within species' suitable distributions, based on Species Distribution Models (SDMs). We used a function based on the inverted species-area relationship, which considers the ratio between current and potential habitat availability because of changes in each pixel. This allowed us to estimate how much each priority pixel contributes to overall habitat availability for the species that inhabit it. The final output is a biodiversity index, representing the sum of the proportional habitat gains (from restoration) or avoided habitat losses (from conservation) across all species benefiting from each given pixel (Figure S2).

Informing decision making

The results will be presented and validated by stakeholders from the State's Environmental Institute (Instituto Estadual do Ambiente – INEA). This collaborative step ensures that the outcomes of the framework are aligned with local priorities and expertise. By engaging with INEA and other relevant stakeholders, we aim to refine and validate the results, ensuring that the findings can effectively support the planning and policy development processes for the state. This validation step will help ensure the practical applicability of the framework in guiding future environmental management strategies and the implementation of nature-based solutions in Rio de Janeiro (Step D16).

Discussion

The proposed framework serves as a strategic tool for identifying priority areas for NbS implementation, addressing the urgent societal need to manage environmental disaster risks in an increasingly uncertain climatic future. It functions as a roadmap for guiding NbS investments to maximize environmental, social, and economic benefits. Spatial prioritization strategies are essential for identifying the most effective pathways to sustainability, focusing on areas of greater vulnerability and communities with the most pressing needs to enhance outcomes and cost-effectiveness. However, its utility extends beyond identifying priority areas (Stage D). Each stage of the framework provides critical insights to support decision-making, including the socioecological characterization of relevant areas (Stage A), the development of scenario storylines tailored to the study regions (Stage B), and, most importantly, the modeling of key ecosystem services to pinpoint high-vulnerability areas for a more informed call to action (Stage C).

Our framework aligns with multiple global agendas, including the fight against climate change, the biodiversity crisis, and the pursuit of Sustainable Development Goals, all of which are fundamentally linked to biodiversity and ecosystem services. By prioritizing areas where NbS can maximize both ecological and social benefits, the framework directly supports international commitments such as the UN Decade of Restoration, which aims to halt and reverse ecosystem degradation worldwide. One of the most well-established NbS strategies is the restoration of native vegetation, increasingly recognized as a cost-effective solution for enhancing climate resilience, preserving biodiversity, and supporting sustainable livelihoods (Bustamante et al. 2019). The framework not only facilitates the integration of global conservation and climate mitigation efforts into local-to-regional decision-making but also provides a structured, science-based approach for directing restoration and conservation investments where they are most needed.

Applying the framework to the state of Rio de Janeiro provides valuable insights into the potential impacts of NbS on ecosystem services and climate adaptation. Our findings highlight that enforcing environmental legislation under the optimistic scenario could significantly enhance flood mitigation, delivering benefits up to four times greater than those observed in the BAU scenario. For urban cooling, the optimistic scenario could more than double heat mitigation benefits compared to BAU, even when accounting for anticipated urban expansion. In terms of coastal protection, while enforcing environmental legislation remains crucial, it may not be sufficient to counteract the effects of urban growth on coastal vulnerability. The ranking of priority areas ensures that NbS strategies are effectively targeted, optimizing both ecosystem service provision and social resilience—key elements for strengthening climate adaptation and promoting equitable environmental management.

By integrating BES impact and social vulnerability, the framework identifies priority areas that not only experience the highest BES impact but also encompass regions of greatest social vulnerability, ensuring that interventions are directed where BES are most needed. Additionally, incorporating cost estimates provides a financial framework to support decision-making, balancing ecological benefits with economic feasibility. The inclusion of co-benefits further reinforces the framework. The carbon stock potential for restoration and avoided carbon loss for conservation offer a comprehensive perspective on NbS' role in climate mitigation, while the biodiversity index provides a spatially explicit assessment of how NbS interventions can support biodiversity conservation at a broader landscape scale.

Although we used Rio de Janeiro as an illustrative case study to demonstrate the framework's application, we designed it as a flexible tool that can be adapted to different contexts and tailored to local needs (e.g., selecting alternative ecosystem services, scenarios, or NbS). Beyond customizing specific factors within the framework, additional modifications are also possible. While our framework application accounts for NbS implementation costs and co-benefits such as carbon sequestration and biodiversity conservation, these aspects could be more explicitly integrated into earlier stages if deemed relevant, for instance, during scenario development. Additionally, instead of relying on extreme climatic events, users could incorporate established climate change scenario storylines (e.g., IPCC scenarios) or directly embed climate change projections into land-use maps to construct future scenarios (e.g., Vale et al. 2021).

Notably, while our framework is a valuable tool for guiding NbS investments, its applicability has certain limitations. One key challenge is data availability, as high-quality spatial data on BES, social vulnerability, and NbS costs may be lacking in some regions, requiring reliance on proxies or expert input. Additionally, policy and governance structures vary across contexts, influencing the feasibility of NbS implementation and necessitating alignment with local regulations. Stakeholder engagement is also critical but can be hindered by competing interests, resource constraints, or lack of awareness. Furthermore, the dynamic nature of climate and land-use changes introduces uncertainties, requiring adaptive management to ensure long-term relevance. Finally, implementation feasibility depends on financial, technical, and logistical factors that may limit NbS adoption in prioritized areas. Addressing these challenges requires integrating participatory approaches, securing financial mechanisms, and continuously updating spatial prioritization to reflect evolving socioecological conditions.

In an era of escalating climate challenges and environmental degradation, strategic approaches for Nature-based Solutions are essential to maximize their effectiveness and impact. Our framework offers a flexible, science-driven methodology to identify priority areas for NbS implementation, balancing ecological benefits, social equity, and economic feasibility. While challenges such as data limitations, governance complexities, and implementation constraints must be addressed, the framework provides a valuable roadmap for decision-makers seeking to optimize NbS investments. By integrating ecological, social, and financial considerations, it ensures that NbS strategies not only enhance resilience and sustainability but also align with global environmental commitments. Ultimately, by translating broad conservation and climate adaptation goals into actionable, localized solutions, this framework supports more effective, just, and impactful environmental decision-making.

References

Arkema, K. K., Guannel, G., Verutes, G., Wood, S. A., Guerry, A., Ruckelshaus, M., Kareiva, P., Lacayo, M., & Silver, J. M. (2013). Coastal habitats shield people and property from sea-level rise and storms. *Nature Climate Change, 3*(10), 913–918. https://doi.org/10.1038/nclimate1944

Brancalion, P. H., Garcia, L. C., Loyola, R., Rodrigues, R. R., Pillar, V. D., & Lewinsohn, T. M. (2016). A critical analysis of the Native Vegetation Protection Law of Brazil (2012): Updates and ongoing initiatives. *Natureza & Conservação, 14*(1), 1–15. https://doi.org/10.1016/j.ncon.2016.03.003

Bustamante, M. M. C., Silva, J. S., Scariot, A., Sampaio, A. B., Mascia, D. L., Garcia, E., Sano, E., Fernandes, G. W., Durigan, G., Roitman, I., Figueiredo, I., Rodrigues, R. R., Pillar, V. D., Oliveira, A. O., Malhado, A. C., Alencar, A., Vendramini, A., Padovezi, A., Carrascosa, H., ... Valle, R. (2019). Ecological restoration as a strategy for mitigating and adapting to climate change: Lessons and challenges from Brazil. *Mitigation and Adaptation Strategies for Global Change, 24*, 1249–1270. https://doi.org/10.1007/s11027-018-9837-5

Carella, C. (2023). *Estimating the benefits of urban green infrastructure in increasing resilience of schools against chronic and acute heat stresses using geospatial modelling: The case of Cali, Colombia* (Master's thesis). Imperial College London.

Chen, G., Li, X., Liu, X., Chen, Y., Liang, X., Leng, J., Xu, X., Liao, W., Qiu, Y., Wu, Q., & Huang, K. (2020). Global projections of future urban land expansion under shared socioeconomic pathways. *Nature Communications, 11*, 537. https://doi.org/10.1038/s41467-020-14386-x

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (Eds.). (2016). *Nature-based solutions to address global societal challenges*. IUCN.

d'Albertas, F., Rocha, D., Lacerda, E., Niemeyer, J., & Oliveira, L. G. (2024). *Spatial model of land value for the Brazilian territory with 1km resolution.*

Holifield, R. (2001). Defining environmental justice and environmental racism. *Urban Geography, 22*(1), 78–90. https://doi.org/10.2747/0272-3638.22.1.78

Instituto Brasileiro de Geografia e Estatística (IBGE). (2022). *Censo Brasileiro de 2022*.

Intergovernmental Panel on Climate Change (IPCC). (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation.* Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2019). *Summary for policymakers*. In *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.

Intergovernmental Panel on Climate Change (IPCC). (2021). *Summary for policymakers*. In *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the IPCC*. Cambridge University Press.

International Union for Conservation of Nature (IUCN). (2020). *Global standard for nature-based solutions: A user-friendly framework for the verification, design and scaling up of NbS*.

Jones, H. P., Hole, D. G., & Zavaleta, E. S. (2012). Harnessing nature to help people adapt to climate change. *Nature Climate Change, 2*, 504–509. https://doi.org/10.1038/nclimate1463

Lavorel, S., Colloff, M. J., Locatelli, B., Gorddard, R., Prober, S. M., Gabillet, M., Devaux, C., Laforgue, D., & Peyrache-Gadeau, V. (2019). Mustering the power of ecosystems for adaptation to climate change. *Environmental Science and Policy, 92*, 87–97. https://doi.org/10.1016/j.envsci.2018.11.010

Liévano-Latorre, O., et al. (2025). Addressing the urgent climate and biodiversity crisis through strategic ecosystem restoration in Brazil. *Biological Conservation, 302*, 110972. https://doi.org/10.1016/j.biocon.2025.110972

Manes, S., Vale, M. M., & Pires, A. P. F. (2022). Nature-based solutions promote climate change adaptation safeguarding ecosystem services. *Ecosystem Services, 55*, 101439. https://doi.org/10.1016/j.ecoser.2022.101439

Manes, S., Gama-Maia, D., Vaz, S., Pires, A. P. F., Tardin, R., Maricato, G., Bezerra, D. S., & Vale, M. M. (2023). Nature as a solution for shoreline protection against coastal risks associated with ongoing sea-level rise. *Ocean and Coastal Management, 235*, 106487. https://doi.org/10.1016/j.ocecoaman.2023.106487

Manes, S., Vale, M. M., & Pires, A. P. F. (2024). Nature-based solutions potential for flood risk reduction under extreme rainfall events. *Ambio, 53*, 1168–1181. https://doi.org/10.1007/s13280-024-02005-8

MapBiomas. (2023a). Collection 8 of the Annual Land Cover and Land Use Maps of Brazil (1985-2022). https://brasil.mapbiomas.org/colecoes-mapbiomas/

MapBiomas. (2023b). *Deforestation and Secondary Vegetation – Appendix Collection 8, Version 1*.

MapBiomas. (2023c). *Pasture - Appendix Collection 8, Version 1.*

Martins, J. H., Camanho, A. S., & Gaspar, M. B. (2012). A review of the application of driving forces, pressure, state, impact, and response framework to fisheries management. *Ocean and Coastal Management, 69*, 273–281.

Myhre, G., Alterskjær, K., Stjern, C., Hodnebrog, Ø., Marelle, L., Samset, B. H., Sillmann, J., Schaller, N., Fischer, E., Schulz, M., & Stohl, A. (2019). Frequency of extreme precipitation increases extensively with event rareness under global warming. *Scientific Reports, 9*, 1–10. https://doi.org/10.1038/s41598-019-52277-4

Natural Capital Project. (2024). *InVEST 0.0*. Stanford University. https://naturalcapitalproject.stanford.edu/software/invest

Niemeyer, J., Barros, F. S. M., Silva, D. S., Crouzeilles, R., & Vale, M. M. (2020). Planning forest restoration within private land holdings with conservation co-benefits at the landscape scale. *Science of The Total Environment, 717*, 135262. https://doi.org/10.1016/j.scitotenv.2019.135262

PBL (2018). *Report on the Workshop "Next Steps in Developing Nature Futures"*. PBL Netherlands Environmental Assessment Agency, The Hague.

Pörtner, H. O., Roberts, D. C., Adams, H., Adler, C., Aldunce, P., Ali, E., Begum, R. A., Betts, R., Kerr, R. B., Biesbroek, R., Birkmann, J., Bowen, K., Castellanos, E., Cissé, G., Constable, A., Cramer, W., Dodman, D., Eriksen, S. H., Fischlin, A., ... Ibrahim, Z. Z. (2022). *Summary for Policy Makers*. In *Climate change 2022: Impacts, adaptation and vulnerability*. IPCC, UN.

Prado, R. B., Overbeck, G. E., Graco-Roza, C., Moreira, R. A., Monteiro, M. M., & Duarte, G. T. (Orgs.). (2024). *Relatório Temático sobre Agricultura, Biodiversidade e Serviços Ecossistêmicos*. Plataforma Brasileira de Biodiversidade e Serviços Ecossistêmicos (BPBES). 1ª Ed. Campinas: Ed. dos Autores. https://doi.org/10.4322/978-65-01-21502-0

Reed, M. S. (2008). Stakeholder participation for environmental management: a literature review. *Biological Conservation, 141*(10), 2417-2431.

Rezende, C. L., Scarano, F. R., Assad, E. D., Joly, C. A., Metzger, J. P., Strassburg, B. B. N., Tabarelli, M., Fonseca, G. A., & Mittermeier, R. A. (2018). From hotspot to hopespot: An opportunity for the Brazilian Atlantic Forest. *Perspectives in Ecology and Conservation, 16*, 208-214. https://doi.org/10.1016/j.pecon.2018.10.002

SEA/INEA (2018). *Plano de Adaptação Climática do Estado do Rio de Janeiro*. Secretaria de Estado do Ambiente (SEA) e Instituto Estadual do Ambiente (INEA). Disponível em: http://centroclima.coppe.ufrj.br/images/documentos/Produto_11_PAERJ-Relat%C3%B3rio_Final.pdf

Silveira, C., Dias, A. T. C., Amaral, F. G., Gois, G., & Pistón, N. (2024). The importance of private gardens and their spatial composition and configuration to urban heat island mitigation. *Sustainable Cities and Society, 112*, 105589. https://doi.org/10.1016/j.scs.2024.105589

Strassburg, B. B. N., et al. (2019). Strategic approaches to restoring ecosystems can triple conservation gains and halve costs. *Nature Ecology & Evolution, 3*(1), 62–70. https://doi.org/10.1038/s41559-018-0743-8

Strassburg, B. B. N., Iribarrem, A., Beyer, H. L., Cordeiro, C. L., Crouzeilles, R., Jakovac, C. C., Braga Junqueira, A., Lacerda, E., Latawiec, A. E., Balmford, A., Brooks, T. M., Butchart, S. H. M., Chazdon, R. L., Erb, K. H., Brancalion, P., Buchanan, G., Cooper, D., Díaz, S., Donald, P. F., & Visconti, P. (2020). Global priority areas for ecosystem restoration. *Nature, 586*(7831), 724–729.

Souza, C. M., Shimbo, J., Rosa, M. R., et al. (2020). Reconstructing three decades of land use and land cover changes in Brazilian biomes with Landsat archive and Earth Engine. *Remote Sensing, 12*(2735). https://doi.org/10.3390/rs12172735

Tscherning, K., Helming, K., Krippner, B., Sieber, S., & Paloma, S. G. Y. (2012). Does research applying the DPSIR framework support decision making? *Land Use Policy, 29*(1), 102-110. https://doi.org/10.1016/j.landusepol.2011.05.009

Vale, M. M., Lima-Ribeiro, M. S., & Rocha, T. C. (2021). Global land-use and land-cover data: Historical, current and future scenarios. *Biodiversity Informatics, 16*, 28-38.

Supplementary Material

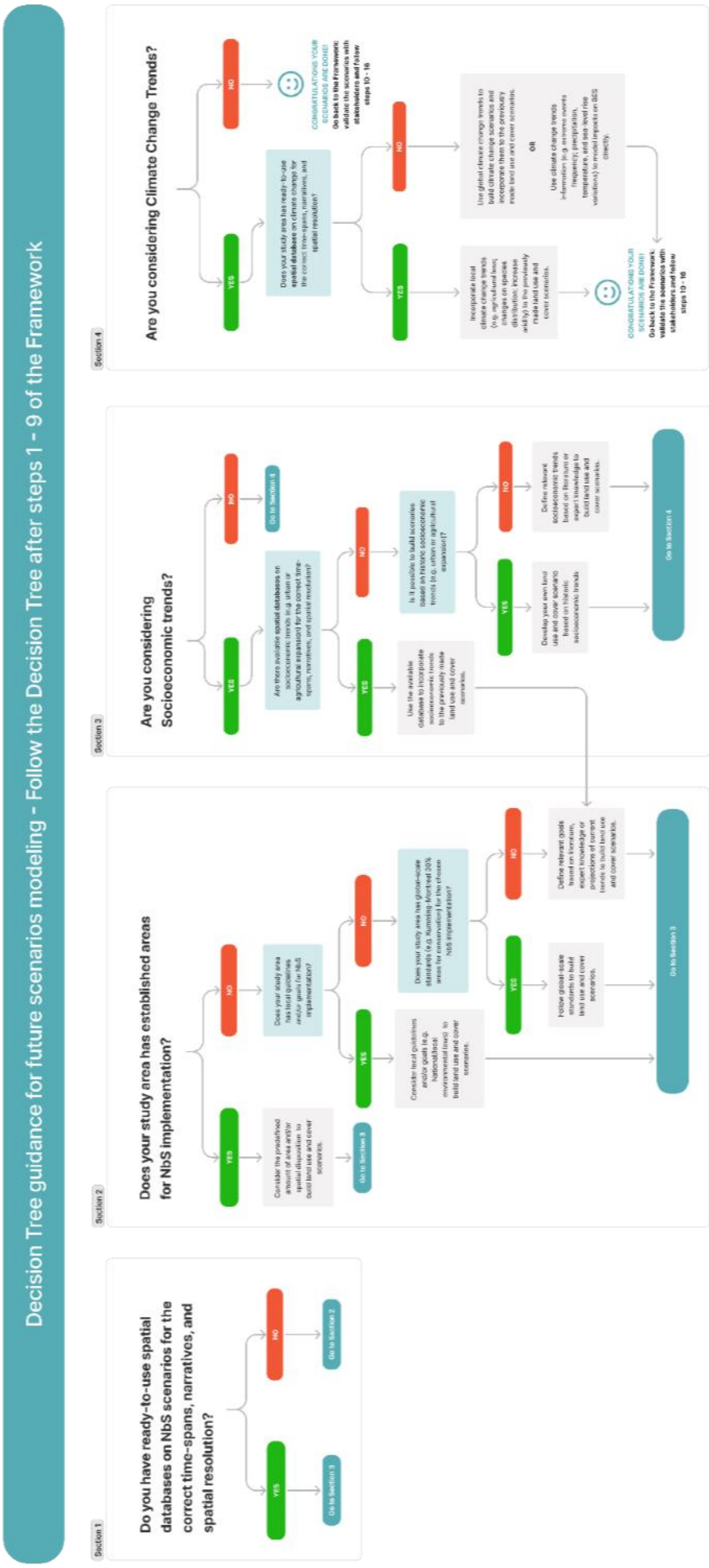

Figure S1. Decision tree.

Table S1. Examples illustrating the implementation the operational framework

Stage	Step	Example
A. Setting the Context	1. Drivers of environmental disasters	Economic growth
		Population growth
		Agricultural policies
		Environmental policies
		Climate changes
		Land use changes
		Degradation
		Overexploitation of natural resources
		Species introduction
	2. Local pressures	Changes in precipitation patterns
		Changes in temperature patterns
		Sea level rise
		Defrost
		Deforestation
		Urban expansion
		Agricultural expansion
		Increase in water demand
		Degradation of coastal environments
		Harvesting of wild populations
		Water polution
		Soil polution
		Air polution
		Exotic species invasion
		Wildfires
	3. Status	
	Biodiversity	Biodiversity loss
		Native species loss
		Endemic species loss
		Native vegetation loss
		Threats to aquatic ecosystems
	Ecosystem Services	Erosion intensification
		Floods intensification
		Coastal hazards intensification
		Water provision decrease
		Water quality decrease
		Agriculture productivity decrease
	Social and cultural aspects	Loss of medicinal species
		Loss of recreational and/or religious spaces
		Spread of diseases
		Impacts on mental health
		Income reduction
		Impacts on infrastructure
	4. Biodiversity and Ecosystem Services (BES) of interest	Floods control
		Coastal protection
		Thermal comfort
		Landslide control
		Heatwave mitigation
	5. NbS of interest	Native vegetation conservation
		Native vegetation recovery
		Naturalization of urbanization, such as green bike paths, tree planting, and the creation of shaded and cooling places
		Water interventions, such as the installation of sustainable drainage systems, rain gardens, floodable parks, water treatment and irrigation through green filters and natural treatment, replacement of asphalt pavement with green areas in parking lots and other places
		Green infrastructure, such as the installation of green pathways for tricycles and pedestrians, implementation of pollinator systems, smart soils, vertical and horizontal green infrastructures (such as noise barriers, green facades, and roofs), pollutant filters, urban agriculture
	6. Co-benefits of interest	Extinction risk reduction
		Carbon sequestration
		Recreational spaces provision
		Social vulnerability reduction

B. Modelling Future Scenarios	7. Trends of interest	Variation in urban sprawl	
		Variation in agricultural expansion	
		IPCC - SSPs approach	
		Variation in precipitation patterns	
		Variation in temperature patterns	
		Variation in sea level patterns	
		IPCC - RCPs approach	
		Compliance with environmental law	
		Non-compliance with environmental law	
		Flexibilization of environmental laws	
		Implementation of stricter environmental laws	
	8. Narratives	Increase in vegetation restoration	
		Reduction in deforestation	
		Implementation of good agricultural practices	
		Implementation of stricter environmental laws	
		Total compliance with environmental law	
		Expansion of protected areas network	
		Reduction in the intensity of climate change	
		Implementation of Sustainable city policies	
		Implementation of Sponge city policies	
		Decrease in vegetation restoration	
		Increase in deforestation	
		Non-implementation of good agricultural practices	
		Flexibilization of environmental laws	
		Non-compliance with environmental law	
		Reduction of protected areas network	
		Increase in the intensity of climate change	
		Maintenance of historical pattern of land use	
		Maintenance of historical intensity of climate changes	
	9. Time spans	1950, 2000...	
		2020, 2022, 2024...	
		2050, 2100...	
D. Identifying priority areas for NbS	13. Social vulnerability filter	Number of people potentially affected by natural disasters (e.g. population density)	
		Distribution of socioeconomically vulnerable populations	
		Indexes of socioeconomic vulnerability	
		National/local indicators of social vulnerability (e.g. age, sex, ethnicity, education, income, poverty, unemployment, access to green and blue spaces, access to health services, social isolation, etc.)	
Extra steps	15. Quantifying costs and co-benefits	Opportunity cost of the land	
		Cost of vegetation restoration implementation	
		Cost of establishing new protected areas	
		Cost of green infrastructure implementation	

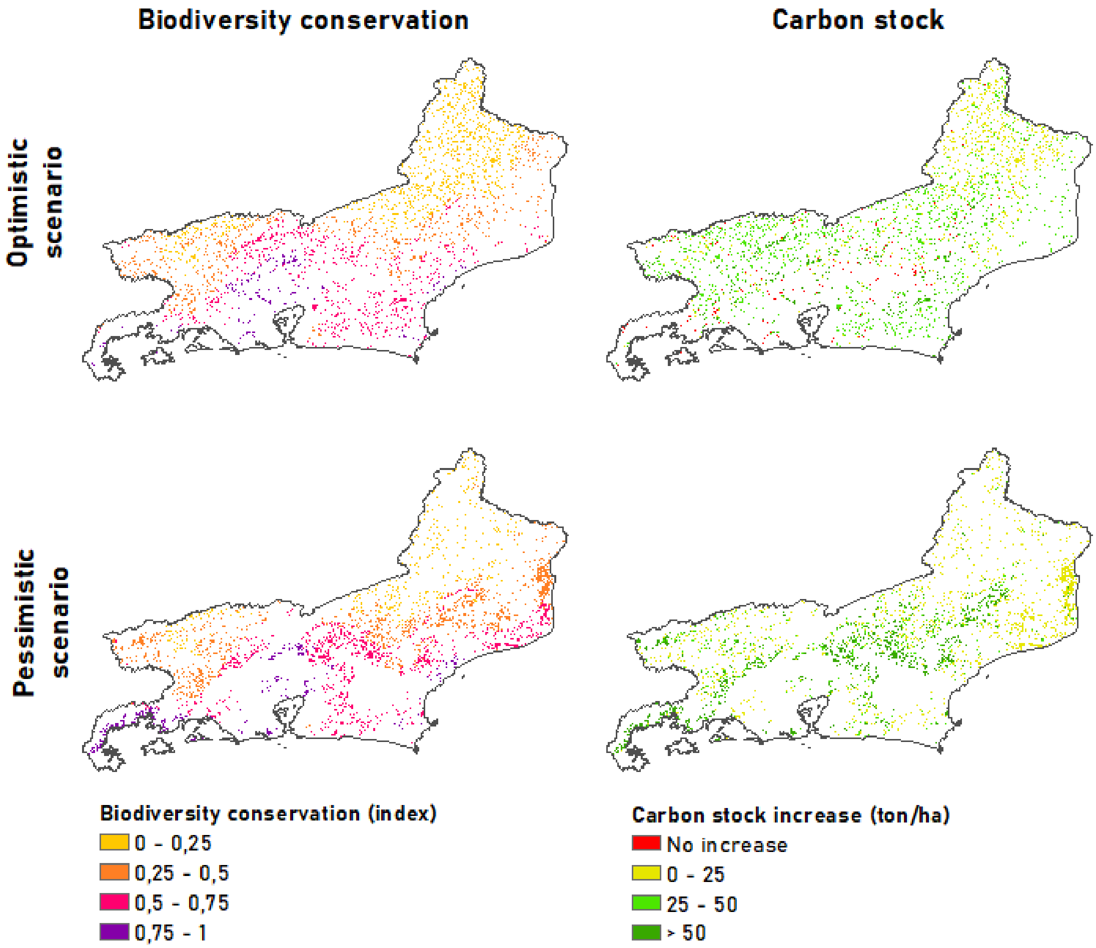

Figure S2. Quantification of co-benefits of the identified priority areas for biodiversity conservation and carbon stock increase. In the biodiversity conservation index, darker colours represent greater habitat gain benefits for species. In the carbon stock maps, darker greens represent higher carbon stock, measured in tons per hectares. Carbon stock values can reach up to 189 tons/ha.

Table S2. Total costs for NbS implementation (forest restoration and conservation) in Rio de Janeiro State in Brazilian Reais (R$).

Ranking of priority areas (%)	Total restoration costs (oportunity + implementation costs)	Conservation costs (oportunity costs)
10	814,525,291.43 - 1,852,836,887.76	667,609,077.84
20	1,556,652,266.26 - 3,421,022,890.90	1,137,846,275.51
30	2,249,774,201.03 - 4,795,134,621.13	1,516,886,506.07
40	2,783,830,392.13 - 6,010,133,836.58	1,865,249,015.24
50	3,285,810,423.80 - 7,309,339,185.51	2,254,433,488.56
60	3,759,114,691.12 - 8,489,941,320.28	2,658,852,312.84
70	4,211,333,210.94 - 9,483,046,156.51	3,040,533,647.55
80	4,666,833,909.28 - 10,512,293,205.31	3,398,130,954.35
90	5,112,962,634.08 - 11,393,744,551.95	3,756,535,422.28
100	5,498,062,299.73 - 12,128,955,252.17	4,113,716,950.15