UNIVERSIDADE ESTADUAL PAULISTA
“JÚLIO DE MESQUITA FILHO”
Instituto de Biociências
Campus do Litoral Paulista

CARLOS HENRIQUE DE ANDRADE

MAPPING PRIORITY AREAS FOR MANGROVE CONSERVATION AND RESTORATION USING ECOSYSTEM SERVICE-BASED SPATIAL PLANNING

São Vicente

2026

UNIVERSIDADE ESTADUAL PAULISTA
“JÚLIO DE MESQUITA FILHO”
Instituto de Biociências
Campus do Litoral Paulista

CARLOS HENRIQUE DE ANDRADE

Mapping Priority Areas for Mangrove Conservation and Restoration Using Ecosystem Service-Based Spatial Planning

Dissertation submitted to São Paulo State University (UNESP), Institute of Biosciences, São Paulo Coastal Campus, in partial fulfillment of the requirements for the degree of Master of Science.

Area of Concentration: Biodiversity

Advisor: Profª. Drª. Débora Martins de Freitas

São Vicente

2026

D282m

de Andrade, Carlos Henrique
Mapping Priority Areas for Mangrove Conservation and Restoration Using Ecosystem Service-Based Spatial Planning / Carlos Henrique de Andrade. -- São Vicente, 2026
34 p. : il., tabs., fotos, mapas

Dissertação (mestrado) - Universidade Estadual Paulista (UNESP), Instituto de Biociências, São Vicente
Orientadora: Débora Martins de Freitas

1. Mangrove. 2. Strategic prioritization. 3. Ecosystem services. 4. Marxan. 5. Coastal wetlands. I. Título.

Sistema de geração automática de fichas catalográficas da Unesp. Dados fornecidos pelo autor(a).

ATA DA DEFESA PÚBLICA DA DISSERTAÇÃO DE MESTRADO DE CARLOS HENRIQUE DE ANDRADE, DISCENTE DO PROGRAMA DE PÓS-GRADUAÇÃO EM BIODIVERSIDADE DE AMBIENTES COSTEIROS, DO INSTITUTO DE BIOCIÊNCIAS - CÂMPUS DO LITORAL PAULISTA.

Aos 07 de agosto de 2026, às 14h, por meio de Videoconferência, realizou-se a defesa de DISSERTAÇÃO DE MESTRADO de CARLOS HENRIQUE DE ANDRADE, intitulada "Mapping priority areas for mangrove conservation and restoration using ecosystem servicebased spatial planning". A Comissão Examinadora foi constituída pelos seguintes membros: Profa. Dra. DÉBORA MARTINS DE FREITAS (Orientador(a) - Participação Virtual) do(a) Departamento de Ciências Biológicas e Ambientais / UNESP / Câmpus do Litoral Paulista - IBCLP, Profa. Dra. MARÍLIA CUNHA LIGNON (Participação Virtual) do(a) Departamento de Recursos Pesqueiros e Aquicultura / UNESP / Câmpus de Registro - FCAVR, Prof. Dr. HERMANO MELO QUEIROZ (Participação Virtual) do(a) FFLCH / USP/São Paulo (SP), Após a exposição pelo mestrando e arguição pelos membros da Comissão Examinadora que participaram do ato, de forma presencial e/ou virtual, o discente recebeu o conceito final: Aprovado . Nada mais havendo, foi lavrada a presente ata, que após lida e aprovada, foi assinada pelo(a) Presidente(a) da Comissão Examinadora.

gov.br Documento assinado digitalmente
DEBORA MARTINS DE FREITAS
Data: 07/08/2026 17:22:06-0300
Verifique em https://validar.iti.gov.br

Profa. Dra. DÉBORA MARTINS DE FREITAS

ACKNOWLEDGEMENTS

I would like to thank Professor Dr. Débora Martins de Freitas for her supervision, guidance, and continuous support throughout this research. I am also grateful for the opportunities, knowledge, and encouragement she provided during my academic training.

I sincerely thank Dr. Micheli Duarte de Paula Costa and Professor Dr. Hugh Possingham for their support and valuable contributions to this project. I appreciate the time they dedicated to sharing their knowledge and assisting in the development of this research.

Finally, I thank my family for their constant support and encouragement throughout my academic journey.

This research was funded by the São Paulo Research Foundation (FAPESP), grant number 2024/05654-3. The author also acknowledges the Coordination for the Improvement of Higher Education Personnel (CAPES) for financial support during the final stage of the master's program, through the Social Demand Program (DS), process number 88887.272860/2026-00.

ABSTRACT

Mangrove ecosystems are found along tropical and subtropical coastlines, providing essential environmental, social, and economic services, including shoreline protection, biodiversity conservation, and carbon storage. Despite their importance, mangroves are increasingly threatened by urban expansion, industrial development, and pollution, particularly in the Baixada Santista Metropolitan Region (São Paulo, Brazil), which hosts some of the state's most extensive mangrove forests. We used a spatial planning tool, Marxan, to identify priority areas for mangrove conservation and restoration based on the provision of key ecosystem services. Two target-based scenarios were evaluated: (1) a 30% conservation target applied across all three ecosystem services simultaneously (carbon stocks, coastal protection, and fisheries), and (2) a 30% target applied individually to each ecosystem service. Priority areas were identified using spatial data on carbon stocks, artisanal fishing activity, and coastal protection. Our results revealed clear spatial differences between conservation and restoration priorities. While restoration priorities were concentrated in a relatively small and consistent set of areas, conservation priorities were more spatially distributed, indicating that conservation targets can be achieved through multiple alternative spatial configurations across the region. In addition, no single municipality simultaneously maximized priorities for all three ecosystem services, reinforcing the need for multi-objective spatial planning rather than a single-service focus. These findings provide a robust basis for mangrove management by aligning conservation and restoration efforts with climate mitigation, biodiversity conservation, and coastal management objectives.

Keywords: mangrove; strategic prioritization; ecosystem services; Marxan; coastal wetlands.

Note: This dissertation includes results presented in the manuscript *Mapping priority areas for mangrove conservation and restoration through ecosystem service-based spatial planning*, which has been submitted to the Journal of Environmental Management and is currently under peer review (Manuscript Number: JEMA-D-26-07071).

SUMMARY

1. INTRODUCTION 2

2. MATERIALS AND METHODS 4

   2.1 STUDY REGION 4

   2.2 SPATIAL PRIORITIZATION APPROACH 6

   2.3 ESTIMATING ECOSYSTEM SERVICES 9

   2.4 SENSITIVITY ANALYSIS 11

3. RESULTS 12

4. DISCUSSION 16

5. CONCLUSION 20

6. REFERENCES 21

7. APPENDICES 26

   APPENDIX A 26

1. INTRODUCTION

Mangroves are vital ecosystems widely acknowledged for their capacity to deliver a wide range of environmental, social, and economic benefits (Dahdouh-Guebas *et al*., 2021). Distributed along tropical and subtropical coastlines, these ecosystems play a crucial role in coastal protection by acting as natural barriers against erosion and by improving water quality (Asari *et al*., 2021; Sultana *et al*., 2023). Their importance has become increasingly evident in the context of sea-level rise and the intensification of extreme weather events (Hülsen *et al*., 2025; Menéndez *et al*., 2020). In addition, mangroves support rich biodiversity, providing refuge and breeding grounds for numerous species and sustaining global fish populations, which makes them essential for biodiversity conservation and local fisheries (Friess *et al*., 2020).

Mangrove forests also show remarkable potential for climate change mitigation. They are among the most efficient ecosystems for carbon storage, holding up to 40 times more carbon per hectare than many terrestrial forests, and thus play a key role in reducing greenhouse gas emissions (Macreadie *et al*., 2021; McLeod *et al*., 2011). Despite their importance, mangroves are increasingly threatened by human activities, including urban expansion, industrial development, and pollution (Hagger *et al*., 2022; Moschetto *et al*., 2021).

In Brazil, mangroves are legally protected as Permanent Preservation Areas (Brazil, 2012), and recent years have seen growing integration of conservation policies with restoration and incentive-based mechanisms, including Payment for Ecosystem Services schemes (Brazil, 2021). These initiatives reflect a transition toward more proactive and multifunctional coastal management approaches. However, ensuring the effectiveness of these policies requires spatially explicit information to guide where conservation and restoration actions can deliver the greatest combined ecological and socio-economic benefits.

Coastal regions are critical priorities for conservation because they are subject to multiple and overlapping pressures, including industrial-scale fishing, climate change, and cumulative impacts from land-based activities (Magris *et al*., 2021). In this context, well-designed Payment for Ecosystem Services programs can play a key role in promoting conservation and restoration, particularly when they prioritize biodiversity, support the delivery of multiple ecosystem services, and account for the needs of diverse stakeholders (Bullock *et al*., 2011). The ongoing degradation of ecosystem services, including those provided by mangroves, highlights the urgent need to invest in natural capital and to integrate ecosystem values into economic and spatial planning. Both the conservation of existing ecosystems and the restoration of degraded areas are essential to halt biodiversity loss and ensure the long-term provision of ecosystem services (Barbosa *et al*., 2019).

Although ecosystem restoration can be critical in areas where degradation has already occurred, recovery processes are often slow and sometimes incomplete. Recent economic valuation studies suggest that, in many cases, the financial benefits of restoration may exceed its costs, particularly when we account for multiple ecosystem services (Bullock *et al*., 2011), but this is not always the case. Returns can vary substantially depending on ecosystem type, restoration strategy, and socio-ecological context. Spatial mismatches between restoration sites and benefit areas, ecological uncertainties, and delayed service recovery may limit the realization of expected outcomes (Costa *et al*., 2024; Rowland *et al*., 2024). In some cases, especially when ecosystem services take decades to recover or when restoration fails to re-establish key ecological functions, the return on investment may be lower than anticipated or even negative. These limitations reinforce the need to prioritize the protection of remaining intact ecosystems, while focusing on long-term monitoring, and carefully targeting restoration investments to maximize their effectiveness and cost-efficiency.

Considering the critical role mangroves play in delivering ecosystem services, there is an urgent need for targeted efforts to conserve and restore these ecosystems. Spatial conservation planning has emerged globally as the main approach for strategically allocating conservation and restoration actions based on the distribution of targets and the costs of those actions (Kukkala & Moilanen, 2013). While Brazilian environmental management has historically relied on regulatory instruments and protected areas to support biodiversity conservation, recent initiatives, including Payment for Ecosystem Services, have expanded opportunities for more proactive conservation planning. However, there remains considerable potential to strengthen these efforts through spatial prioritization frameworks that help allocate limited resources more efficiently across conservation and restoration actions. Previous studies have collectively shown that spatial trade-offs exist across ecosystem services (Adame *et al*., 2015; Atkinson *et al*., 2016; Araya-López *et al*., 2025), supply and demand of ecosystem services matter (Lin *et al*., 2022), and that feasibility and cost must be accounted for (Adame *et al*., 2015). However, few studies have applied spatially explicit, multi-objective frameworks at sub-national scales that compare how different service-based targets influence spatial priorities. Our study addresses this gap by developing and applying a service-oriented spatial prioritization framework for mangrove ecosystems in Southeastern Brazil, contrasting unified and service-specific objectives for both conservation and restoration. In doing so, it provides critical insights for embedding ecosystem services delivery into local and regional planning systems, where management goals must be balanced with limited resources and implementation constraints.

In this study, we identify priority areas for mangrove conservation and restoration under two distinct target-based scenarios. In the first scenario, we applied a 30% target guided by the combined contribution of the three ecosystem services assessed in this study. In the second scenario, we applied the same 30% target separately to each ecosystem service (i.e., carbon stock, coastal protection, and fisheries support. This dual-scenario approach offers strategic insights for designing cost-effective and service-oriented conservation strategies.

2. MATERIALS AND METHODS

2.1 STUDY REGION

The study region is focused on the Baixada Santista Metropolitan Region (São Paulo, Brazil; **Figure 1**), which hosts the second-largest concentration of mangroves along São Paulo's coastline (Projeto MapBiomas, 2024). This coastal area comprises nine municipalities: São Vicente, Santos, Guarujá, Cubatão, Peruíbe, Bertioga, Praia Grande, Mongaguá, and Itanhaém. Although mangroves occupy only 0.1% of the total area of the state of São Paulo (Nalon *et al*., 2022), their ecological importance underscores the need to identify priority areas for their conservation and restoration. These ecosystems are increasingly threatened by human pressures, including the operations of the Port of Santos, nearby industrial activities, and the expansion of informal settlements, many built on stilts ('palafitas') in ecologically sensitive areas (Moschetto *et al*., 2021; Schaffer-Novelli *et al*., 2003).

This tropical coastal region, where mangroves intersect with remnants of the Atlantic Forest, faces particularly acute pressures in the municipalities of Santos and São Vicente. Together, these two municipalities account for approximately 31% of São Paulo's total mangrove cover and 59% of the mangroves in the Baixada Santista (Sampaio, 2011). Rapid and often unregulated urban expansion has resulted in the establishment of informal settlements, where more than 75% of the resident population lives within the estuarine watershed, many in precarious housing conditions (Sampaio *et al*., 2016).

Although 68% of the state's mangroves fall within Permanent Preservation Areas (Nalon *et al*., 2022), the concentration of human activities and infrastructure continues to drive fragmentation and habitat degradation. Particularly significant is the pressure from expanding port operations, land filling, and informal occupation, as seen in the Dique da Vila Gilda, which is the largest stilt housing complex in Brazil and located within the mangrove fringes of Santos (Moschetto *et al*., 2021). These dynamics highlight the complex interplay between social vulnerability and ecological risk, reinforcing the need for spatial planning approaches that address both environmental conservation and socio-economic realities in the region.

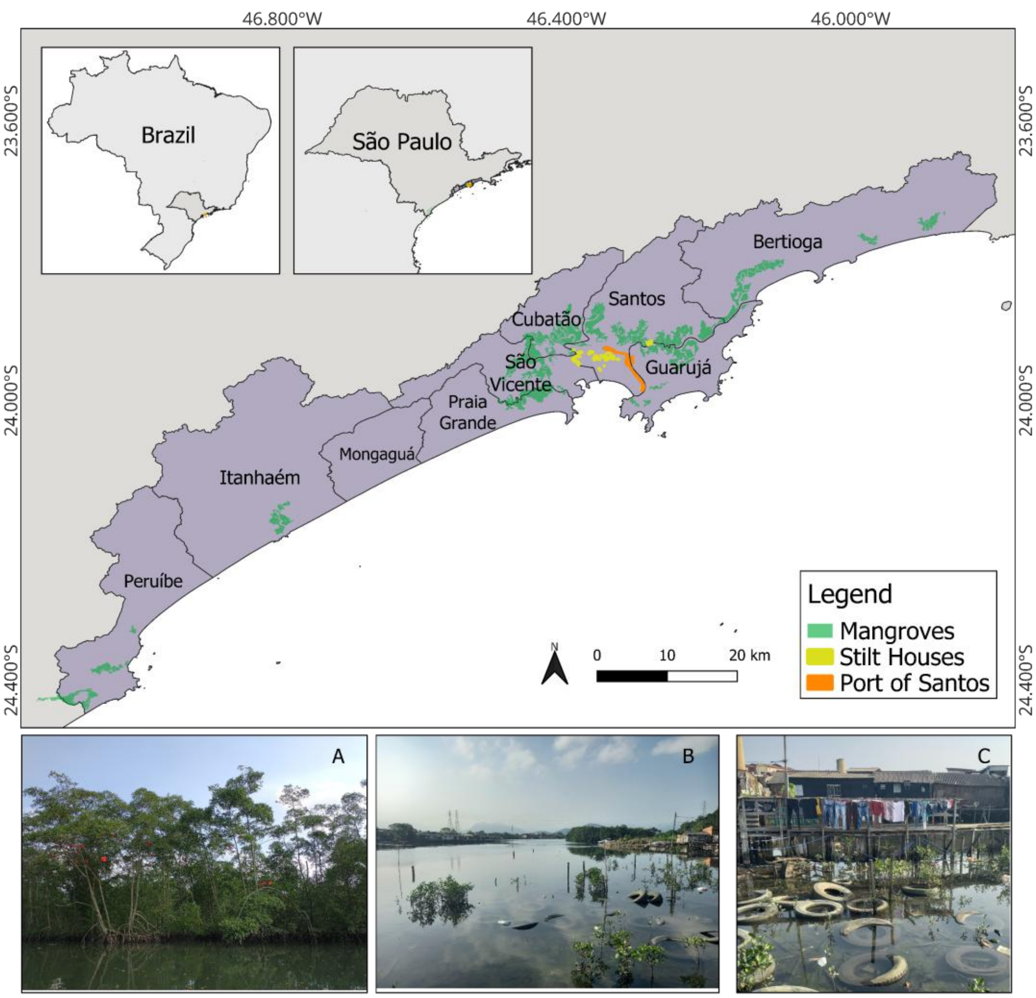

Figure 1. Map of the study area with the mangrove areas in the region (A) and stilt houses (= palafitas) associated with mangroves (B, C). Sources of spatial data: mangrove distribution (MapBiomas Project, 2024), stilt houses and port area (IBGE, 2022). Photos source: Débora Martins de Freitas.

2.2 SPATIAL PRIORITIZATION APPROACH

We used the decision support tool Marxan (v.2.43) to identify spatial solutions for implementing two different management actions: 1) mangrove conservation and 2) mangrove restoration in the study region (**Figure 2**). Marxan uses a simulated annealing algorithm to identify alternative solutions that meet a set of quantitative targets for minimum cost (Ball *et al*., 2009).

To prioritise actions in Marxan we first created planning units for the entire Baixada Santista metropolitan region, comprising hexagonal units of 8 hectares each, totaling 28,752 planning units. In addition, for each planning unit in both objectives, we calculated the management cost and the potential ecosystem service provided by mangroves. Each planning unit was also assigned to a unique identifier, status, and value, indicating areas designated for conservation (i.e., existing mangrove locations) and restoration (i.e., former mangrove areas converted to a different land use, as identified in De Andrade *et al*., 2025). The municipality of Mongaguá was excluded from the prioritization due to its current lack of mangrove cover (Prefeitura Municipal de Mongaguá, 2016).

For the conservation objective, we aimed to protect existing mangroves, while also maintaining their ecosystem service provision and resilience to ongoing environmental pressures. In contrast, the restoration is focused on areas where mangroves have been historically lost due to land use conversion in order to recover their ecological functions (including carbon stock and coastal protection). Protection costs were represented by the area of mangroves (in hectares) within each planning unit. Restoration opportunities were identified using historical land cover data (Projeto Mapbiomas 2024) and were informed by cost estimates, with an average investment of USD 3,000 per hectare (Bayraktarov *et al*., 2016). Although this value provides a useful benchmark, it may not accurately reflect the costs of mangrove restoration in the Baixada Santista region. However, the lack of documented large-scale restoration projects locally limits the development of more precise regional estimates. By incorporating both scenarios, our prioritization analysis produced spatially explicit priorities that optimize ecological benefits while considering the economic feasibility of conservation and restoration strategies.

Following the approach of Adame *et al*. (2015) and Araya-Lopez *et al*. (2025), we developed two target-based prioritization scenarios, drawing on the targets established under the Kunming–Montreal Global Biodiversity Framework. Specifically, the adoption of a 30% targ*et al*igns with Target 2, which calls for the effective restoration of at least 30% of degraded ecosystems by 2030, and with the 30×30 conservation goal (Target 3), which aims to ensure that at least 30% of terrestrial, inland water, coastal, and marine areas are effectively conserved by 2030. Using a 30% target therefore enhances the policy relevance of our prioritization framework by aligning it with internationally recognized biodiversity commitments. Within the Marxan framework, this target requires the selection of a set of planning units that collectively represents at least 30% of the total amount of each conservation feature or ecosystem service while minimizing the objective function. Consequently, planning units not selected in the optimal solution represent the remaining proportion of the landscape that is not required to achieve the specified target under the modeled scenario, rather than areas without ecological value or management importance. In the first scenario, we applied the same 30% target for all three ecosystem services (i.e., carbon storage, coastal protection, and fisheries enhancement) to identify priority areas that maximize the combined delivery of benefits while minimizing the cost of all actions. This scenario reflects a proportional target relative to the total potential supply of services across all planning units. In the second scenario, the 30% target was applied independently to each ecosystem service, with separate Marxan runs conducted for carbon stock, fisheries, and coastal protection, thereby enabling the identification of service-specific spatial priorities and trade-offs.

For each objective and target-based scenario, we set the parameters according to Marxan best practice (Ardron *et al*., 2013). For all scenarios, we set the boundary length modifier (BLM; parameter that controls the degree of connectivity between planning units) equal to 1. The parameter species penalty factor, which determines the penalty applied when a given ecosystem service fails to meet its conservation or restoration target, was set to 1 across all ecosystem services thus ensuring the targets are met. All scenarios were run with 100 repetitions and 1,000,000 iterations.

We assessed our results using two key outputs: the best solution, which represents the set of planning units that meets the defined targets at the lowest cost, and the selection frequency, which indicates how often each planning unit was selected amongst 100 good solutions. Together, these outputs provide a basis for identifying high-priority areas for conservation and restoration, which were identified by selecting planning units with a selection frequency greater than 70%. All spatial solutions were evaluated across the study region and the nine municipalities. The spatial analyses were conducted using QGIS version 3.38.2 under the SIRGAS 2000 coordinate reference system. All data analyses and graphing, including the Pearson correlation test, were performed using Microsoft Excel.

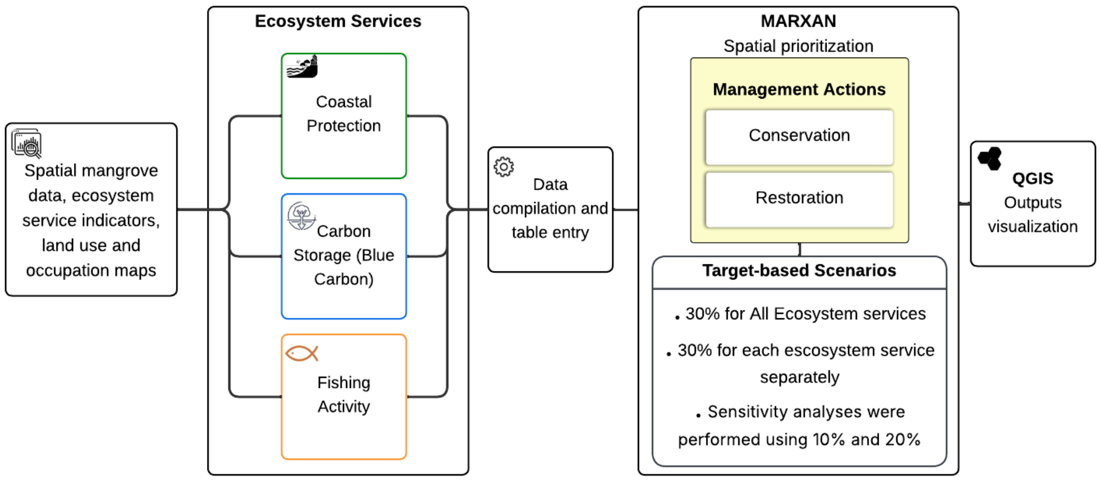

Figure 2. Diagram illustrating the steps involved in the mangrove conservation and restoration prioritization process implemented in this study.

Table 1. Overview of the main topics addressed in this study and their definitions.

Topic	Description
Management Actions	Conservation of existing mangroves in the study area. Restoration of lost mangroves (i.e., locations where mangroves previously occurred).
Ecosystem Services	Ecosystem services provided by mangroves considered in this study: consisting of carbon stock, fisheries, and coastal protection.
Scenarios	Scenarios applying a 30% target to all ecosystem services combined, and a 30% target to each service separately.
Management Cost	Cost of mangrove restoration (USD 3,000 per hectare) and conservation cost (i.e., calculated based on mangrove area in hectares) were estimated for planning unit.
Output	Best solution and selection frequency of planning units for the defined targets across 100 MARXAN runs.

Table 2. Marxan workflow used in this study from start to finish.

Step	Process	Description
1	Prepare the base map	Study area divided into 28,752 hexagonal Planning Units (PUs).
2	Assign a unique PU ID	Each hexagon receives a unique identification code (PU ID).
3	Build the Marxan input tables	Information is organized into four main input tables: Planning Unit table (PU ID and cost); Species table (targets defined for each ecosystem service); PU–Species table (ecosystem-service values assigned to each PU); and Boundary table (shared boundaries between neighboring PUs). The PU ID links each spatial hexagon to its corresponding information across the tables.
4	Define management eligibility before Marxan optimization	Conservation run: only conservation-eligible PUs can be selected. Restoration run: only restoration-eligible PUs can be selected. Important: Marxan does not determine whether a PU is for conservation or restoration; eligibility is defined beforehand.
5	Define scenarios for each run	Combined-service scenario: 30% target for Blue carbon + Coastal protection + Fisheries. Single-service scenarios: 30% target for each service separately.
6	Marxan optimization	Marxan is run separately for each management action: once for Conservation and once for Restoration. In each run, Marxan uses simulated annealing to iteratively search for an optimal set of eligible PUs. It selects and modifies PUs, evaluates each solution, checks ecosystem-service targets, and considers cost and boundary length. This process is repeated iteratively to improve the solution.
7	Generate Marxan outputs	Best solution and selection frequency across runs.
8	Classify selection frequency	Low → Intermediate → High frequency.
9	Produce final outputs	Conservation Priority Maps and Restoration Priority Maps.

2.3 ESTIMATING ECOSYSTEM SERVICES

Carbon stock was estimated using the InVEST Coastal Blue Carbon model. The model was parameterized for the Baixada Santista Metropolitan Region using aboveground and belowground carbon stock values reported in the literature for mangrove ecosystems in nearby and ecologically comparable regions (Rovai *et al*., 2021; Rovai *et al*., 2022). Model outputs included estimates of carbon sequestration, accumulation, emissions, and total carbon stock over time. For the purposes of this study, we used the spatial distribution of estimated carbon stock values for the year 2021, representing the most recent year with observed data available for the region (De Andrade *et al*., 2025). These values were then used to estimate the carbon stock for each planning unit.

Spatially explicit estimates of total ecosystem carbon stocks in mangrove areas were obtained from De Andrade *et al*. (2025), who mapped the blue carbon dynamics for the Baixada Santista region. We used this carbon stock layer as a conservative proxy for the climate regulation potential of mangroves on the basis that they represent the underlying blue carbon asset and the magnitude of potential emissions that could be avoided through conservation of existing mangroves. We acknowledge that this choice emphasises avoided emissions from conservation rather than additional removals from restoration and, as such, may underestimate the full mitigation potential of restored mangroves. This trade-off could be addressed in future work by re-running the prioritization using sequestration rates once more robust temporal data become available. We aggregated the carbon stocks values to the planning-unit level by calculating the mean value within each unit.

Coastal protection was represented using the number of properties potentially shielded by mangroves as a proxy for exposure reduction. We first obtained the spatial distribution of mangrove forests from MapBiomas (Projeto Mapbiomas, 2024), whose land cover products are validated using a nationwide stratified random sample interpreted through visual inspection of multi-temporal Landsat imagery by independent analysts. From this layer, we created a 1 km buffer around all mangrove polygons to approximate the coastal zone where mangroves are likely to contribute to wave attenuation and shoreline protection. Property location data were then sourced from the Brazilian Institute of Geography and Statistics (IBGE, 2022) and spatially overlaid with the buffered mangrove area. For each planning unit, we counted the number of properties within the buffer and used this count as an index of coastal protection, assuming that a higher number of properties within the mangrove protection zone reflects greater potential benefits provided by these ecosystems.

Fisheries ecosystem services were quantified using artisanal fishing data obtained from Petrobras's Monitoring Project for Fishing Activity (PMAP), which provides information on fish landings at the municipal level for the study area (Petrobras, 2023). We used a multi-year average from 2017 to 2019 of total artisanal landings, expressed as total landed catch in tonnes, as a proxy for fisheries provision. In the analyzed fisheries report, landing data were reported either by municipality or by species, but not as a combined municipality-by-species dataset. Therefore, total fishery landings by municipality were used as a proxy for the fishery provisioning service provided by mangrove ecosystems. Although this approach includes species with varying degrees of ecological association with mangroves, it represents the best available information to characterize the regional importance of fisheries. Furthermore, because most fisheries in the Baixada Santista operate within an estuarine–coastal system strongly influenced by mangrove ecosystems, municipal fishery landings provide a reasonable proxy for the fisheries provisioning service, despite not all landed species being directly dependent on mangrove habitats. Municipal landing values were spatially allocated to planning units based on municipal boundaries and adjusted according to the mangrove area within each municipality.

2.4 SENSITIVITY ANALYSIS

After defining the initial scenarios, we re-ran the Marxan analyses using reduced targets of 10% and 20% for each ecosystem service. For each target level, selection frequency outputs were generated to evaluate potential shifts in spatial priorities. Reduced targets of 20% and 10% were selected to represent progressively less ambitious conservation and restoration objectives that may reflect resource-constrained management contexts. This allowed us to evaluate whether the spatial priorities identified under the 30% target remained robust when lower implementation targets were considered. The resulting frequency maps were examined in QGIS to visually assess differences in priority areas across targets. To quantitatively assess the spatial similarities among targets, we applied Pearson correlation tests to the selection frequency results using the Pearson formula in Microsoft Excel. This analysis was conducted separately for the conservation and restoration management actions, allowing us to compare how spatial priorities are sensitive to changes in the targets used in this study.

3. RESULTS

In the scenario where a 30% target was applied across all ecosystem services, we identified a total of 3,506 ha of mangroves as priority areas for conservation (39% of the total available for selection) and 5,773 ha as priority areas for restoration (62% of the total available for selection). Among the municipalities, Santos emerged as the top priority for conservation by area, encompassing the largest area of selected planning units (1,248 ha). In contrast, Bertioga led in restoration opportunities by area when all ecosystem services were considered (1,487 ha).

When considering individual ecosystem services, conservation priorities for coastal protection, were highest in São Vicente (97 ha), while restoration priorities were highest in Praia Grande (316 ha). São Vicente also stood out for its importance in the conservation of blue carbon stocks, with 97 ha identified as priority for conservation, while Santos had the highest restoration potential for this service (1,231 ha). For fisheries support, the top spatial priorities for conservation were identified in Santos (1,222 ha), Guarujá (721 ha), and Bertioga (493 ha), while for restoration, the leading municipalities were Bertioga (1,487 ha), São Vicente (993 ha), and Praia Grande (632 ha), highlighting their strategic relevance for sustaining artisanal fishing activities.

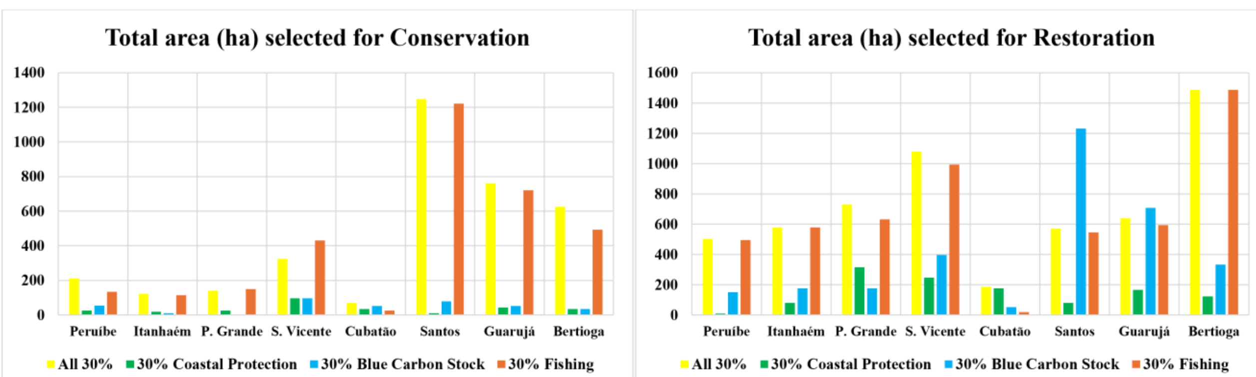

Figure 3. Total area (ha) of planning units selected under each prioritization scenario for each municipality, separately for the conservation (C) and restoration (R) management actions.

The selection frequency results for the 30% target for all ecosystem services scenario highlight marked differences between the spatial outcomes for conservation and restoration (**Figure 4**). 99% of the selected planning units showed high selection frequency, being chosen in more than 70% of the 100 Marxan runs, with high-frequency units clustering mainly in Bertioga (167 PUs) and São Vicente (110 PUs). This indicates that a relatively small, spatially concentrated set of areas is consistently required to meet restoration targets. By contrast, for conservation, only 0.3% of planning units were selected in ≥70% of runs, while 99% fell within intermediate frequencies (20–50%), with a strong concentration of planning units in Santos (806 PUs) and Guarujá (233 PUs). These patterns suggest that conservation objectives can be achieved through many alternative spatial configurations, whereas restoration success depends on a much narrower set of high-priority sites.

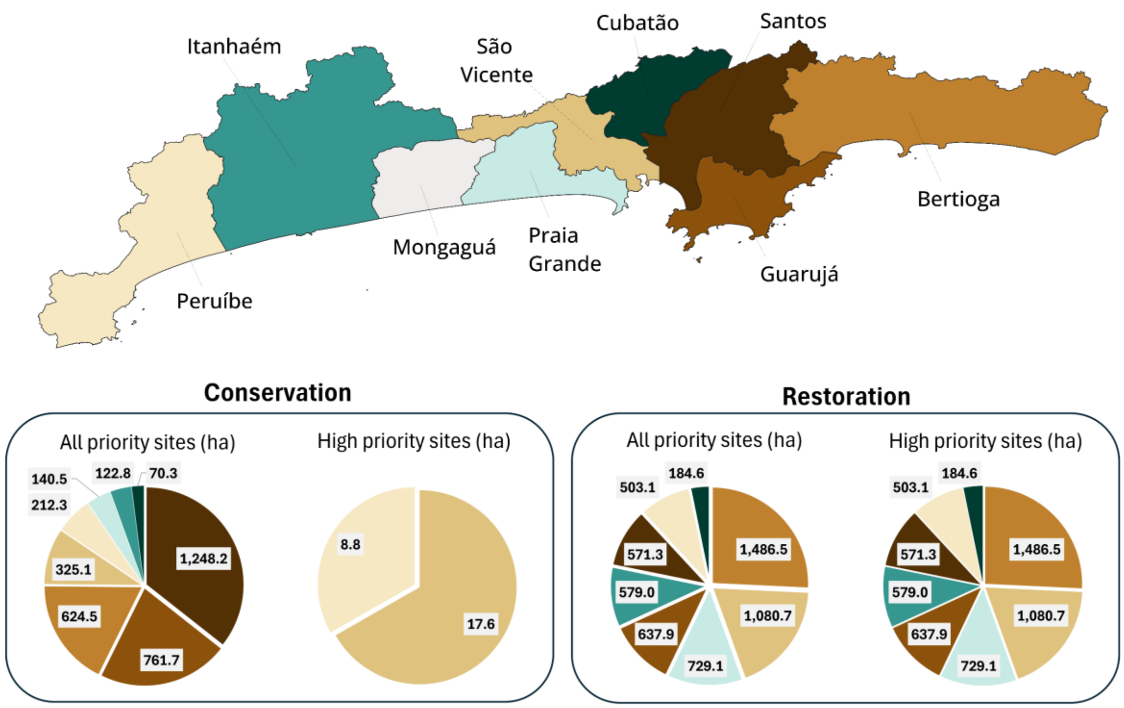

Figure 4. Area (ha) selected in the best solution for restoration and conservation in each municipality under the 30% target scenario for all ecosystem services. Results are shown separately for all planning units in the best solution (all priority sites) and for high-frequency units (high priority sites), which represent the subset of best solution units selected in more than 70% of Marxan runs based on selection frequency. The different colors represent each municipality.

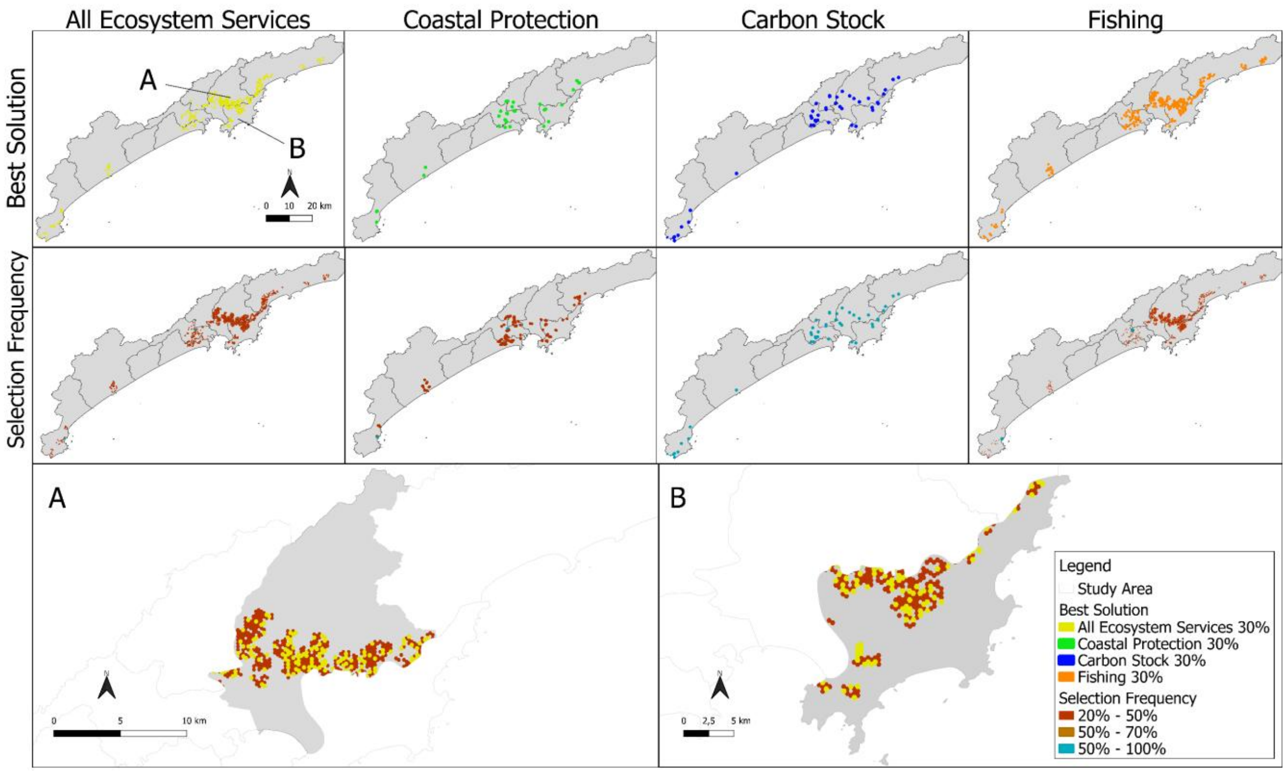

Figure 5. Spatial distribution of priority planning units for conservation under two scenarios: a 30% target for all ecosystem services and separate 30% targets applied to each service individually. The municipalities with the largest selected areas are highlighted: Santos (A) and Guarujá (B).

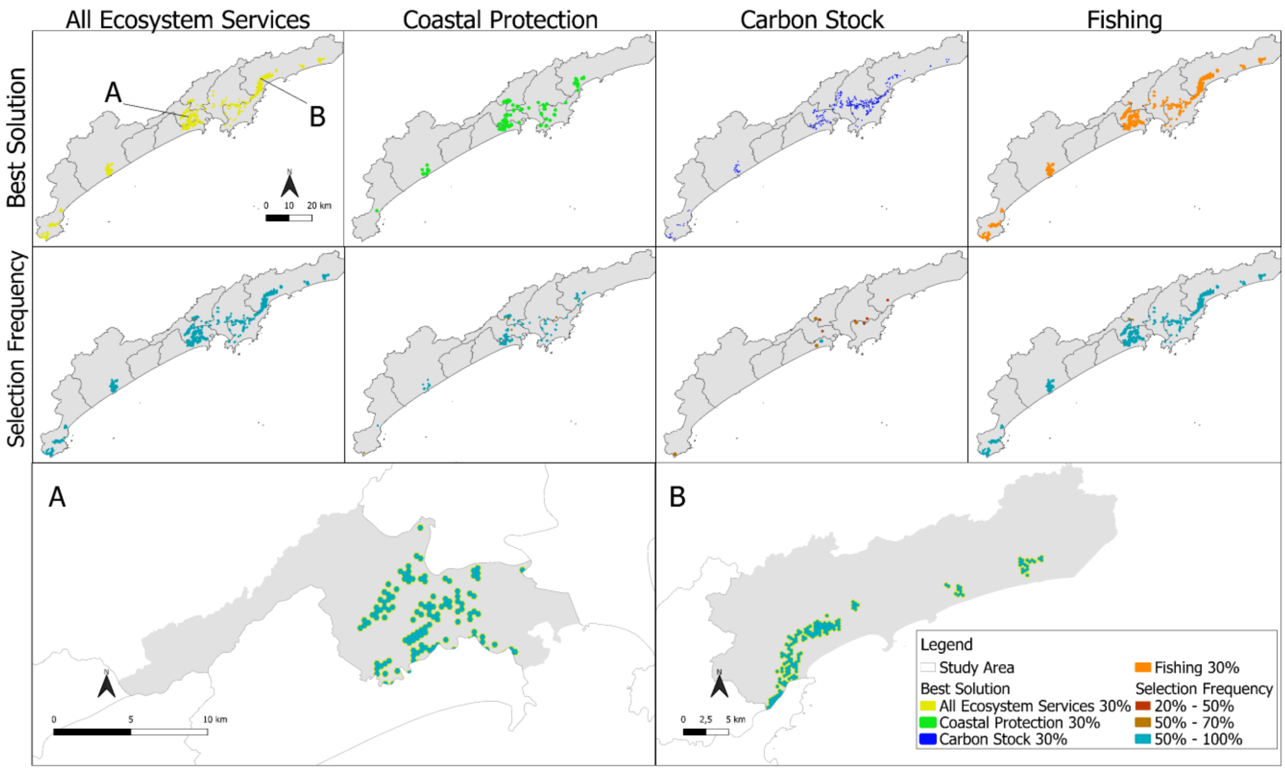

Figure 6. Spatial distribution of priority planning units (PUs) for restoration under two scenarios: a unified 30% target across all ecosystem services and separate 30% targets applied to each service individually. The municipalities with the largest selected areas are highlighted: São Vicente (A) and Bertioga (B).

Overall, spatial congruence between conservation and restoration priorities was moderate, with ~29% of planning units selected in both management actions for the 30% all services target. These overlapping areas were mainly concentrated in São Vicente and Bertioga, suggesting that they may represent particularly strategic locations for integrated management. For conservation, spatial congruence between the combined-target scenario and service-specific priorities was generally low. Overlap with the combined solution was 34% for fisheries, 27% for blue carbon, and 34% for coastal protection. Coastal protection priorities were concentrated in São Vicente, blue carbon priorities extended into São Vicente and Peruíbe, and fisheries priorities were distinct in Santos. These differences highlight municipalities which can provide cost-effective solutions for single ecosystem services.

For restoration, the overlap between single-service plan with the combined-service solution was much higher: 100% for fisheries and coastal protection, and 47% for blue carbon. Spatial differences were limited: blue carbon priorities extended into Santos, while coastal protection and fisheries priorities largely coincided with the combined scenario, indicating that most service-specific priorities align with the overall optimal restoration solution. No single municipality simultaneously maximized priorities for all three services, reinforcing the need for multi-objective planning rather than a single-service focus.

The Pearson correlation analysis of selection frequency across target scenarios (10%, 20%, and 30%) revealed distinct patterns for conservation and restoration objectives. For conservation, correlations were consistently high (ranging from 0.846 to 0.955), indicating strong similarity in spatial priorities across all target levels. This suggests that the planning units selected for conservation remain largely consistent whether the target is set at 10%, 20%, or 30%. In contrast, consistency in restoration priorities was more sensitive to changes in target levels. The 10% and 20% targets showed a strong correlation ($r = 0.940$), but the correlation between 10% and 30% targets was lower ($r = 0.595$), and that between 20%–30% comparison was moderate ($r = 0.650$). These results indicate that restoration spatial priorities shift more substantially as targets change, with higher targets bringing additional areas into the solution that were not consistently selected at lower targets. Overall, our results show that conservation planning can be relatively robust to the choice of target, whereas restoration planning is more sensitive to ambition levels and may require greater flexibility and stakeholder negotiation as targets increase.

4. DISCUSSION

The prioritization of mangrove conservation and restoration using ecosystem service-based spatial planning offers valuable insights for guiding decision-making in rapidly urbanizing coastal regions (Mazor *et al*., 2021). Our results show that areas with extensive mangrove cover and high ecological functionality tend to be consistently prioritized, particularly where multiple ecosystem services overlap. In this study, municipalities such as Santos and Bertioga exemplify regions that simultaneously support artisanal fisheries, coastal protection, and carbon stock (Petrobras, 2023; De Andrade *et al*., 2025). These multifunctional areas are strategically important and represent low-regret options for integrated conservation planning and align closely with regional climate and sustainability agendas.

Sites that combine high ecological value with intense human pressure, such as those with informal settlements, port infrastructure, or rapid land-use change, often emerge as dual priorities for both protecting remaining intact mangroves and restoring degraded zones. This dual role underscores the importance of integrated strategies that address both conservation goals and socio-environmental vulnerabilities (Moschetto *et al*., 2021; Sampaio *et al*., 2016). In such contexts, spatial prioritization does more than identify ecologically important areas; it also highlights locations where conservation and restoration can contribute to more equitable climate mitigation and adaptation policies. Conversely, areas with relatively intact and connected mangrove systems tended to be consistently prioritized across all ecosystem services, indicating strategic opportunities for cost-effective and long-term actions. These findings are consistent with broader international frameworks that emphasize ecosystem integrity and resilience before degradation becomes critical (Bayraktarov *et al*., 2016; Bullock *et al*., 2011).

The analysis also reveals that municipalities or regions with comparatively smaller mangrove extents can still deliver substantial ecosystem services. These findings reinforce that mangrove value is not solely determined by spatial coverage, but also by specific ecosystem services, such as sediment stabilization, wave attenuation, and support for local fisheries (Friess, 2016; Schaeffer-Novelli & Cintron-Molero, 2016; Friess *et al*., 2020; Costa *et al*., 2024). Protecting these concentrated, service-rich zones should therefore be a key element of integrated coastal zone management, particularly where local communities rely heavily on these benefits. In addition, the distribution of ecosystem services highlights the strategic importance of carbon-rich mangrove areas. Mangroves with high blue carbon stocks represent priority opportunities for climate mitigation, as their protection can contribute to carbon sequestration and emissions avoidance. Safeguarding these areas can therefore support conservation financing mechanisms, carbon offset initiatives, and policy frameworks aligned with global climate commitments such as the Paris Agreement (Beloto *et al*., 2023; Santos, 2015; McLeod *et al*., 2011; Dabalà *et al*., 2023). These areas not only serve local environmental goals but also provide measurable contributions to international nature-based solutions.

The service-specific scenarios usually produced priorities that were very different from the scenario that included all the services, with differences more pronounced for the action of conservation than for restoration. For conservation, spatial overlap between the combined solution and service-specific priorities was low, and selection frequency results showed that most planning units were selected at intermediate frequencies, indicating the existence of multiple alternative efficient spatial configurations capable of meeting conservation targets. In contrast, restoration priorities showed high congruence across services and were characterized by a set of planning units consistently selected across Marxan runs, particularly in Bertioga and São Vicente. Spatial overlap between conservation and restoration priorities was limited (~29%), reinforcing that these actions operate under different spatial logics within the study region and are unlikely to be efficiently addressed through a single, uniform intervention.

The municipalities most frequently selected as priorities, including Santos and São Vicente, highlight both feasibility and the need for coordinated action, as conservation and restoration objectives often span administrative boundaries. In Santos, interventions can be aligned with the Plano Municipal de Mudanças Climáticas (Prefeitura de Santos, 2022), while in São Vicente, the recently initiated Co-Planning for Climate Justice (COOP CLIMA) project, in partnership with universities, the municipal government, and civil society, aims to support the development of a municipal climate action plan. At the broader policy level, the priorities identified in this study can also contribute to the objectives of the ProManguezal (National Program for the Conservation and Sustainable Use of Mangroves), particularly by supporting the spatial identification of areas where mangrove conservation and restoration may provide important climate, ecological, and socio-economic benefits (Brazil, 2024). In addition, the identified priorities could inform the design or implementation of Payment for Environmental Services (PES) initiatives by helping to identify areas where conservation or restoration actions may generate multiple ecosystem-service benefits (São Paulo, 2022). Together, these initiatives provide existing institutional and policy frameworks through which Marxan-identified priorities could be integrated with local planning, governance, financial incentives, and community engagement, facilitating more coordinated implementation across scales (Secretaria Municipal de Desenvolvimento Urbano, 2016). In this context, the results can serve as a starting point for dialogue among municipalities, environmental agencies, local communities, and other stakeholders, supporting the identification of shared priorities and opportunities for coordinated action across administrative boundaries (**Table 3**).

Table 3. Potential contributions of the study's spatial prioritization results to existing climate, mangrove conservation, and environmental policy initiatives.

Policy / initiative	Scale	Potential use of this study's results
Plano de Ação Climática de Santos (PACS)	Municipal	The spatial priorities identified by Marxan can contribute specifically to Axis IV – Urban Resilience and Nature-Based Solutions (Prefeitura de Santos, 2022). The identification of priority areas for mangrove conservation and restoration can provide complementary spatial information to support nature-based solutions aimed at strengthening coastal resilience, while also considering the ecosystem services provided by mangroves.
COOP CLIMA – São Vicente	Municipal	The results can provide a spatial evidence base for participatory climate planning, helping identify areas where mangrove conservation and restoration may generate combined benefits for climate resilience, coastal protection, and fisheries.
ProManguezal – National Program for the Conservation and Sustainable Use of Mangroves	National policy with regional application	The study provides a regional-scale application that can contribute to the broader objectives of ProManguezal, by demonstrating how spatial prioritization can integrate multiple mangrove ecosystem services. The results are not intended to represent priorities for Brazil as a whole but may provide a methodological and regional example with potential relevance to national mangrove conservation and restoration strategies (Brazil, 2024).
State Policy and Program for Payment for Environmental Services (PEPSA/PPSA)	State of São Paulo	The priority maps can support the identification of areas where conservation or restoration actions may generate multiple ecosystem-service benefits, potentially helping to inform the spatial targeting of PES initiatives, subject to the specific eligibility and implementation criteria of each program (São Paulo, 2022).

Consistent with Araya-Lopez *et al*. (2025), we found that different ecosystem services highlight partially distinct priority areas, reinforcing the importance of multi-service planning. However, unlike previous studies at larger scales (Araya-Lopez *et al*., 2025; Fabbrizzi *et al*., 2023), our sub-national analysis reveals strong concentration of restoration opportunities in a small number of municipalities.

This study also has limitations related to the proxies and spatial datasets used to represent ecosystem services and mangrove dynamics. Coastal protection was approximated by the number of properties located near mangrove areas, which provides an indication of the potential benefits of mangroves for protecting human assets but does not explicitly account for structural and ecological characteristics of mangrove vegetation, such as tree density, species composition, vegetation structure, and other factors that influence wave attenuation and coastal protection. Similarly, the restoration scenario considered areas that had experienced mangrove loss over time as potentially suitable for restoration. However, this approach does not distinguish between areas with different levels of actual restoration feasibility or likelihood of natural or assisted recovery in practice, as these may depend on local hydrological conditions, land use, accessibility, degradation levels, and other site-specific factors. Blue carbon stocks were estimated using the InVEST Coastal Blue Carbon model and biophysical parameters derived from a regional study conducted in only part of the mangrove area of the Baixada Santista. Therefore, these values may not fully represent the spatial variability of carbon stocks across the entire region. Fisheries were represented using municipal-level artisanal fishery landings that were spatially redistributed among planning units, which provides a regional proxy but does not capture the precise spatial distribution of fishing activity or the ecological dependence of individual species on mangrove ecosystems. Consequently, the Marxan outputs should be interpreted as a strategic, regional-scale prioritization framework rather than precise site-level prescriptions or direct management recommendations for individual municipalities. Future studies should incorporate more detailed, municipality-specific datasets, including field-based measurements of carbon stocks, vegetation structure and species composition, hydrological and restoration feasibility assessments, and finer-scale fisheries data. Such improvements would allow for more accurate identification of priority areas and provide a stronger basis for site-specific conservation and restoration planning.

5. CONCLUSION

This study aimed to identify priority areas for mangrove restoration and conservation in the metropolitan region of Baixada Santista, using spatial prioritisation based on three ecosystem services (fisheries, blue carbon, and coastal protection). Our results revealed contrasting patterns between conservation and restoration priorities: restoration hotspots were spatially concentrated in a few municipalities such as Bertioga and São Vicente, whereas conservation priorities were more evenly dispersed. Multi-service hotspots were limited, and no single municipality simultaneously maximized priorities for all services, highlighting strong trade-offs between objectives. Importantly, our analysis demonstrates that focusing solely on mangrove area would overlook areas of high functional value; integrating multiple services provides a more nuanced and actionable understanding of priorities.

Our approach and results have direct relevance for local and regional management, providing spatially explicit guidance for municipal and state planning efforts. The outputs can support the implementation of legal and policy instruments, facilitating the identification of sites where restoration or conservation investments are likely to yield the greatest benefits. Future efforts should integrate socio-economic and governance data, as well as local stakeholder knowledge, to refine priorities and ensure feasibility. Additionally, the framework developed here can be replicated or scaled to other coastal regions globally, providing a robust approach for multi-service ecosystem management.

6. REFERENCES

Adame, M. F. (2015). Selecting cost-effective areas for restoration of ecosystem services. Conservation Biology, v. 29, n. 2, p. 493-502. DOI: 10.1111/cobi.12391

Araya-Lopez, R. *et al*. (2025). Prioritizing tidal marsh restoration in grazing lands. Journal of Environmental Management, v. 380, p. 124952.

Ardron, J. A.; Possingham, H. P.; Klein, C. J. (2008). Marxan good practices handbook. Pacific Marine Analysis and Research Association, Vancouver, v. 149.

Asari, N. *et al*. (2021) Mangrove as a natural barrier to environmental risks and coastal protection. In: Mangroves: ecology, biodiversity and management. Singapore: Springer Singapore. p. 305-322.

Atkinson, S. C. *et al*. (2016). Prioritising mangrove ecosystem services results in spatially variable management priorities. PLOS One, v. 11, n. 3, p. e0151992.

Ball, I. R.; Possingham, H.P.; Watts, M. (2009). Marxan and relatives: software for spatial conservation prioritisation. Spatial conservation prioritisation: Quantitative methods and computational tools, v. 14, p. 185-196.

Barbosa, A. *et al*. (2019). Cost-effective restoration and conservation planning in Green and Blue Infrastructure designs. A case study on the Intercontinental Biosphere Reserve of the Mediterranean: Andalusia (Spain)–Morocco. Science of the Total Environment, v. 652, p. 1463-1473. DOI: 10.1016/j.scitotenv.2018.10.416.

Bayraktarov, E. *et al*. (2016). The cost and feasibility of marine coastal restoration. Ecological Applications, v. 26, n. 4, p. 1055-1074. DOI: 10.1890/15-1077.

Beloto, N. *et al*. (2023). Blue carbon stock heterogeneity in Brazilian mangrove forests: A systematic review. Marine Pollution Bulletin, v. 197, p. 115694.

Brazil. (2002). Decreto nº 4.297, de 10 de julho de 2002 – Regulamenta o art. 9º, inciso II, da Lei nº 6.938/1981, estabelecendo critérios para o Zoneamento Ecológico-Econômico do Brasil (ZEE) e dá outras providências. Brasília, Brazil: Presidency of the Republic.

Brazil. (2012). Lei nº 12.651, de 25 de maio de 2012. Dispõe sobre a proteção da vegetação nativa. Diário Oficial da União.

Brazil. (2021). Lei No. 14,119, de 13 de janeiro de 2021 - Institui a Política Nacional de Pagamento por Serviços Ambientais (PNPSA) e altera as Leis nos 8.212/1991, 8.629/1993 e 6.015/1973. Brasília, Brazil: Presidency of the Republic.

Brazil. (2024). Decreto nº 12.045, de 5 de junho de 2024 - Institui o Programa Nacional de Conservação e Uso Sustentável dos Manguezais do Brasil – ProManguezal. Brasília, DF, 2024.

Bullock, J. M. *et al*. (2011). Restoration of ecosystem services and biodiversity: conflicts and opportunities. Trends in Ecology & Evolution, v. 26, n. 10, p. 541-549. DOI: 10.1016/j.tree.2011.06.011.

Costa, M.D.P. *et al*. (2024). Spatially explicit ecosystem accounts for coastal wetland restoration. Ecosystem Services, v. 65, 101574. DOI: https://doi.org/10.1016/j.ecoser.2023.101574.

Dabalà, A. *et al*. (2023). Priority areas to protect mangroves and maximise ecosystem services. Nature Communications, v. 14, n. 1, p. 5863. DOI: 10.1038/s41467-023-41333-3.

Dahdouh-Guebas, F. *et al*. (2021). Reconciling nature, people and policy in the mangrove social-ecological system through the adaptive cycle heuristic. Estuarine, Coastal and Shelf Science, v. 248, p. 106942.

Dai, Z. *et al*. (2023). Estimated mangrove carbon stocks and fluxes to inform MRV for REDD+ using a process-based model. Estuarine, Coastal and Shelf Science, v. 294, p. 108512.

De Andrade, C. H.; De Paula Costa, M. D.; De Freitas, D. M. (2025). Assessing the carbon sequestration potential by mangroves in a coastal metropolitan region. Regional Studies in Marine Science, p. 104478.

Ellison, A. M. *et al*. (2005). Loss of foundation species: consequences for the structure and dynamics of forested ecosystems. Frontiers in Ecology and Environment, v. 3, n. 9, p. 479-486. DOI: 10.1890/1540-9295(2005)3[479:LOFSFC]2.0.CO;2.

Fabbrizzi, Erika *et al*. (2023). The challenge of setting restoration targets for macroalgal forests under climate changes. Journal of environmental management, v. 326, p. 116834.

Friess, D. A. (2016). Mangrove forests. Current Biology, v. 26, n. 16, p. R746-R748.

Friess, D. A. *et al*. (2020). Ecosystem services and disservices of mangrove forests and salt marshes. Oceanography and Marine Biology: An Annual Review, 58, p. 107–142.
Gilman, E. L. *et al*. (2006). Adapting to Pacific Island mangrove responses to sea level rise and climate change. Climate Research, v. 32, n. 3, p. 161-176.
Hagger, V. *et al*. (2022). Drivers of global mangrove loss and gain in social-ecological systems. Nature Communications, v. 13, n. 1, p. 6373.
Hülsen, S. *et al*. (2025) Mangroves and their services are at risk from tropical cyclones and sea level rise under climate change. Communications Earth & Environment, v. 6, n. 1, p. 262.
IBGE. (2022). Census 2022. Available at: https://www.ibge.gov.br/en/statistics/social/labor/22836-2022-census-3.html. Accessed on: July 06, 2026.
ICMBIO. (2018). Instituto Chico Mendes de Conservação da Biodiversidade. Atlas of Mangroves in Brazil. 176 p.
Koch, E. W. *et al*. (2009). Non-linearity in ecosystem services: temporal and spatial variability in coastal protection. Frontiers in Ecology and the Environment, v. 7, n. 1, p. 29-37. DOI: 10.1890/080126.
Lin, Shiwei *et al*. (2022). Identifying priority areas for tidal wetland restoration by integrating ecosystem services supply and demand mismatches. Frontiers in Marine Science, v. 9, p. 1019619.
Macreadie, P. I. *et al*. (2021). Blue carbon as a natural climate solution. Nature Reviews Earth & Environment, v. 2, n. 12, p. 826-839.
Magris, R. A. *et al*. (2021). A blueprint for securing Brazil's marine biodiversity and supporting the achievement of global conservation goals. Diversity and Distributions, v. 27, n. 2, p. 198-215. DOI: 10.1111/ddi.13183.
Marxan. (2024). About Marxan - Conservation Solutions. Available at: . Accessed on: July 06, 2026.
Mazor, T. *et al*. (2021). Future-proofing conservation priorities for sea level rise in coastal urban ecosystems. Biological Conservation, v. 260, p. 109190.
Mcleod, E. *et al*. (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Frontiers in Ecology and the Environment, v. 9, n. 10, p. 552-560. DOI: 10.1890/110004.

Menéndez, P. *et al*. (2020). The Global Flood Protection Benefits of Mangroves. Scientific Reports, 10, 4404. https://doi.org/10.1038/s41598-020-61136-6

Moschetto, F. A. *et al*. (2021). Urban expansion, regeneration and socioenvironmental vulnerability in a mangrove ecosystem at the southeast coastal of São Paulo, Brazil. Ocean & Coastal Management, p. 105418. DOI: 10.1016/j.ocecoaman.2021.105418.

Nalon, M. A. *et al*. (2022). Inventário da cobertura vegetal nativa do Estado de São Paulo. São Paulo: SIMA/IPA. 238p.

Petrobras. (2023). Fishing Activity Monitoring Project (PMAP). Available at: https://comunicabaciadesantos.petrobras.com.br/projeto-de-monitoramento-da-atividade-pesqueira-pmap-. Accessed on: July 06, 2026.

Prefeitura de Santos. (2022). Plano de Ação Climática de Santos (PACS): Sumário executivo. Prefeitura Municipal de Santos.

Prefeitura Municipal de Mongaguá. (2016). Product 02 - Georeferencing of Attractions and Tourist Equipment. Integrated Sustainable Tourism Development Plan - (PDITS) - Mongaguá/SP.

Projeto Mapbiomas. (2024). Collection 9 (1985-2023) of the Annual Land Use and Land Cover Maps of Brazil.

Qgis [GIS software]. (2024). Version 3.38.2. QGIS Geographic Information System. Open Source Geospatial Foundation Project.

Rovai, A. S. *et al*. (2021). Ecosystem-level carbon stocks and sequestration rates in mangroves in the Cananéia-Iguape lagoon estuarine system, southeastern Brazil. Forest Ecology and Management, 479, 118553. https://doi.org/10.1016/j.foreco.2020.118553

Rovai, A. S. *et al*. (2022). Brazilian mangroves: blue carbon hotspots of national and global relevance to natural climate solutions. Frontiers in Forests and Global Change, v. 4, p. 217. https://doi.org/10.3389/ffgc.2021.787533

Rowland, Phebe I. *et al*. (2024). Restored and created tidal marshes recover ecosystem services over time. Environmental and Sustainability Indicators, v. 24, p. 100539. https://doi.org/10.1016/j.indic.2024.100539

Sampaio, A. F. P. (2010). Avaliação da correlação entre parâmetros de qualidade da água e socioeconômicos no complexo estuarino de Santos-São Vicente, através de modelagem numérica ambiental. Tese de Doutorado. Universidade de São Paulo.

Sampaio, A. F. P. *et al*. (2016). Sanitation and microbiological water quality in the watershed of Santos-São Vicente Estuary. Revista DAE, v. 64, n. 204, p. 64-72.

Santos. (2015). Decreto no 7.293 de 30 de novembro de 2015. Cria a Comissão Municipal de Adaptação à Mudança do Clima. Available at: https://www.santos.sp.gov.br/static/files_www/dec_729_de_30-11-2015.pdf. Access: July 06, 2026.

São Paulo. (2022). Decreto nº 66.549, de 7 de março de 2022. Disciplina a aplicação, no âmbito do Estado de São Paulo, da Lei federal nº 14.119, de 13 de janeiro de 2021, institui a Política Estadual de Pagamento por Serviços Ambientais – PEPSA, o Programa Estadual de Pagamento por Serviços Ambientais – PPSA e o Cadastro Estadual de Projetos de Pagamento por Serviços Ambientais, e dá providências correlatas.

Schaeffer-Novelli, Y. *et al*. (2003). Baixada Santista, Estado de São Paulo, Brasil: Instrumento Técnico Científico. BIOMA–Centro de Ensino e Informação sobre Zonas Úmidas Costeiras Tropicais com ênfase no ecossistema manguezal. Instituto Oceanográfico–USP, São Paulo, SP. SP. Ref. Rep. nº 08123.

Schaeffer-Novelli, Y.; Cintron-Molero, G. (2016). Small mangrove areas: managing for endurance. Frontiers in Marine Science, v. 3, p. 67.

Secretaria Municipal de Desenvolvimento Urbano. (2016). Estado da Arte: Plano Municipal de Mudança do Clima de Santos – PMMCS. Santos, Brasil: Comissão Municipal de Adaptação à Mudança do Clima. [Decretos nº 7.293/2015 and 7.379/2016].

Sultana, S. *et al*. (2023). Trapping effect of mangrove and saltmarsh habitats on geochemical elements: a case study in Ximen Island, Zhejiang, China. Journal of Soils and Sediments, v. 23, n. 6, p. 2327-2343. DOI: 10.1007/s11368-023-03503-0

7. APPENDICES

APPENDIX A - Spatial distribution maps of priority planning units for conservation and restoration targets of 10% and 20%.

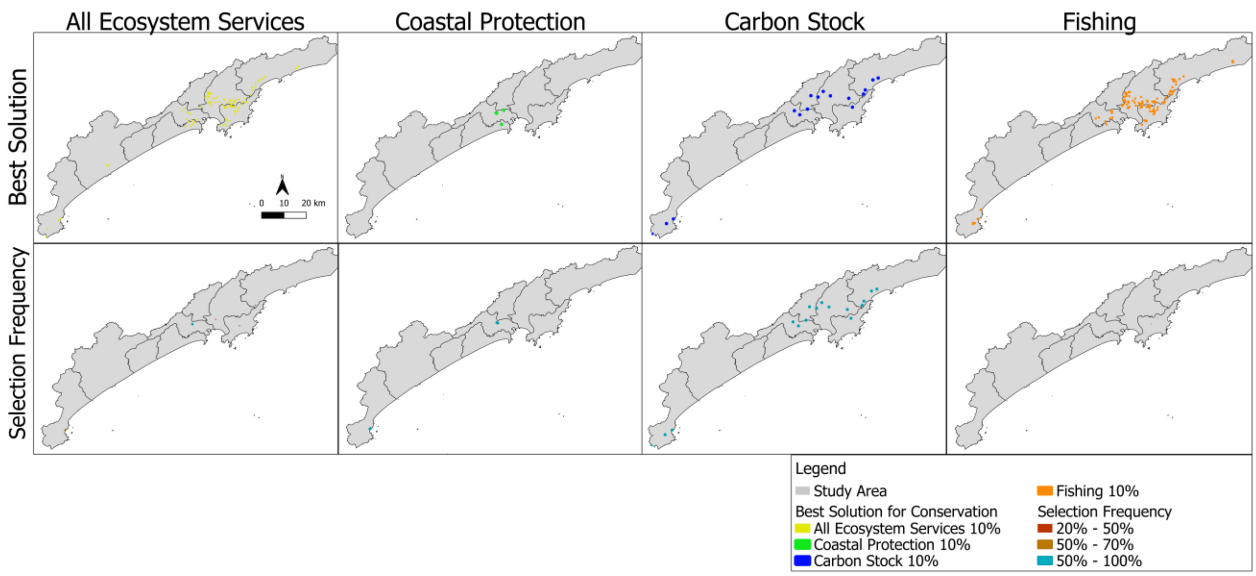

Figure 7. Spatial distribution of priority planning units (PUs) for conservation under two scenarios: a unified 10% target across all ecosystem services and separate 10% targets applied to each service individually.

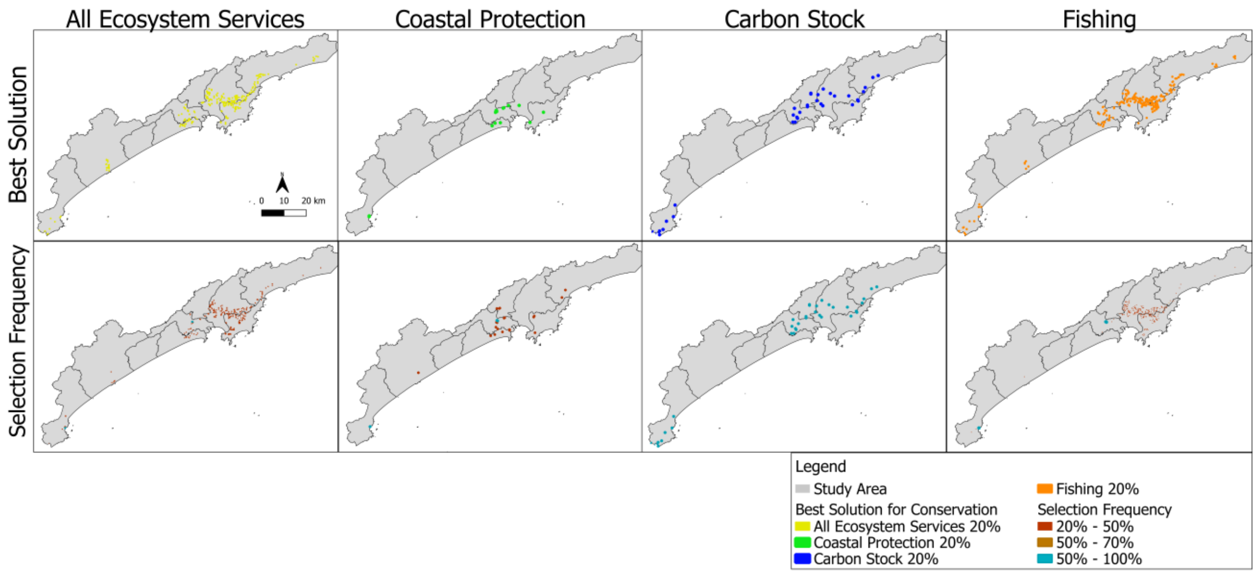

Figure 8. Spatial distribution of priority planning units (PUs) for conservation under two scenarios: a unified 20% target across all ecosystem services and separate 20% targets applied to each service individually.

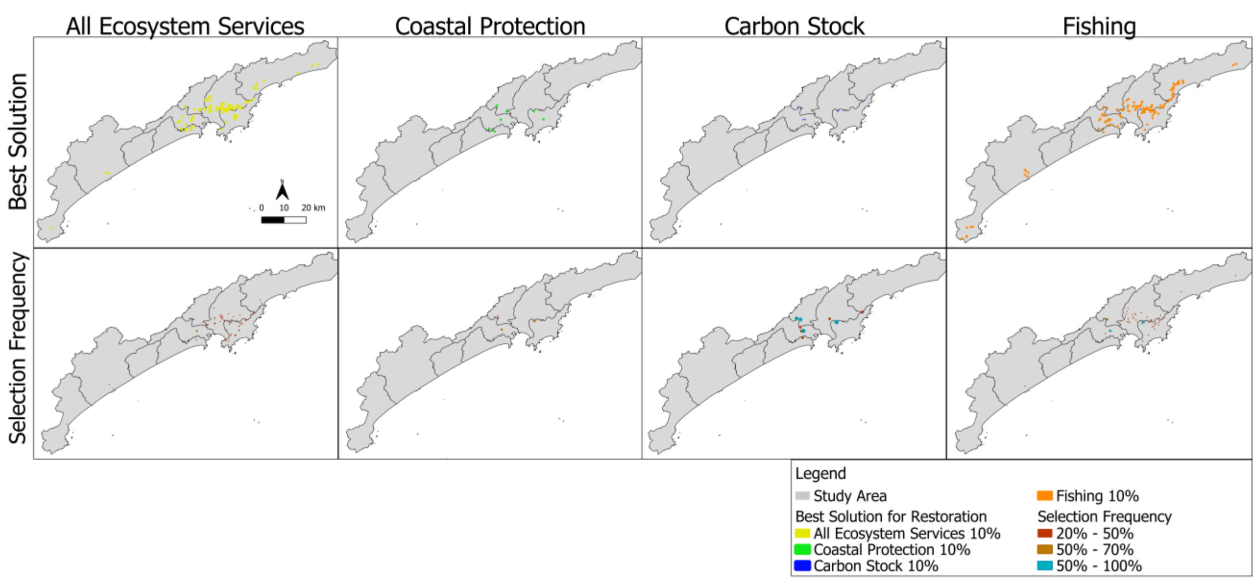

Figure 9. Spatial distribution of priority planning units (PUs) for restoration under two scenarios: a unified 10% target across all ecosystem services and separate 10% targets applied to each service individually.

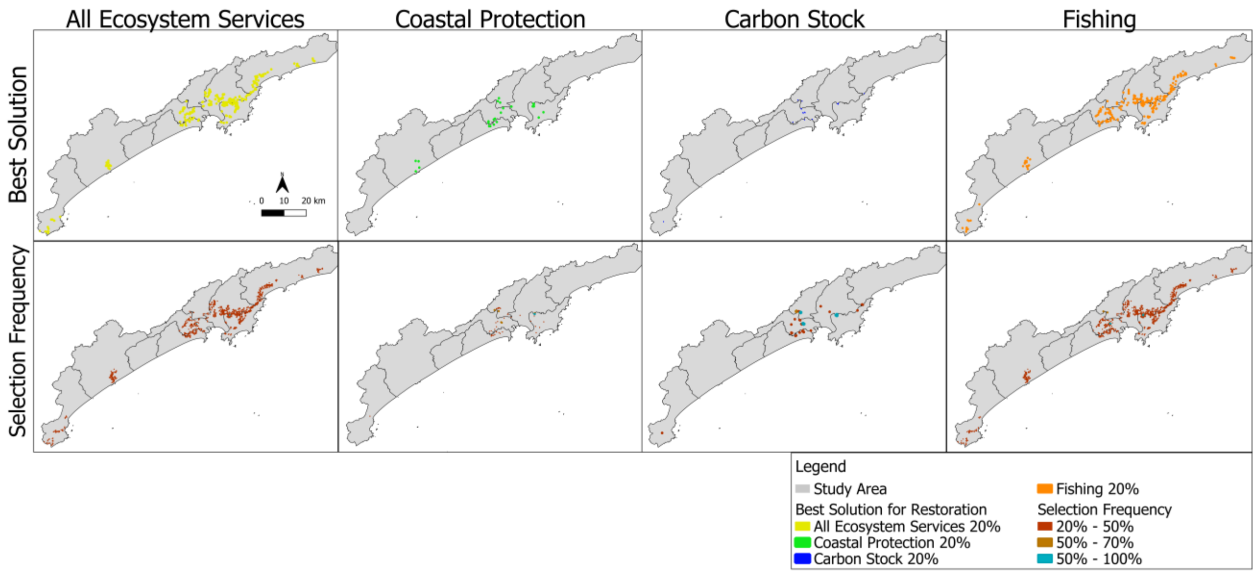

Figure 10. Spatial distribution of priority planning units (PUs) for restoration under two scenarios: a unified 20% target across all ecosystem services and separate 20% targets applied to each service individually.