NICHES

Nature's integration in cities' hydrologies, ecologies and societies

D3.3 Life cycle sustainability assessment of city-wide NBS

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1 Summary

This Life Cycle Sustainability Assessment of City-Wide Nature-Based Solutions (Deliverable 3.3) provides an examination of the environmental and socio-economic impacts of nature-based solutions in urban settings, focusing on the Metropolitan Area of Barcelona. The deliverable serves as an output of the NICHES project, offering guidelines to evaluate NBS through a spatially explicit life-cycle approach.

The assessment synthesizes insights from prior studies, combining methodologies like regionalized life cycle assessment, vulnerability mapping, and stakeholder engagement. The deliverable aims to deepen understanding of the metabolic impacts of NBS scenarios, including their trade-offs, synergies, and implications for urban vulnerabilities. By doing so, it highlights the systemic and interconnected effects of NBS on urban metabolisms, emphasizing the importance of localized assessments to capture both intended and unintended consequences.

By adopting a comprehensive approach that integrates ecosystem services, urban metabolism, and vulnerability analyses, the document provides a foundation for exploring and developing replicable methodologies across diverse urban contexts that assess the whole range of impacts associated with the implementation of urban NBS.

2 Introduction

Nature-based solutions (NBS) are being promoted as transformative approaches for addressing complex urban challenges (Bush & Doyon, 2019). From mitigating the effects of climate change and enhancing water security to fostering social development, NBS present opportunities for achieving sustainability while simultaneously delivering multiple co-benefits (Albert et al., 2020). By providing ecosystem services, NBS contribute to urban transformations that align with planetary well-being—ensuring the health and integrity of ecosystems to support the development of both human and non-human species. However, the multifaceted and context-sensitive characteristics of NBS demands a nuanced understanding of their impacts, trade-offs, and synergies, particularly in dynamic urban settings (Rödl & Arlati, 2022; Cohen-Shacham et al., 2016).

The increasing recognition of urban areas as core actors in sustainability transitions highlights the importance of integrating NBS into urban planning and policy. Urban sustainability, frequently framed as the long-term viability of the processes of urban subsystems, demands solutions that address social and environmental dimensions without compromising ecological carrying capacities. Metabolic perspectives (i.e., the sum of processes that an urban system needs to maintain itself by importing, producing and exporting materials, while also emitting waste), have been instrumental in conceptualizing this vision, emphasizing resource efficiency, waste reduction, and the maintenance of ecosystem services as essential to long-term urban resilience (Langemeyer et al., 2020). In this regard, NBS emerge as critical tools for enhancing the sustainability of urban systems by optimizing resource use, improving quality of life, and mitigating adverse environmental impacts (Dumitru et al., 2020).

Despite their potential, the implementation of NBS in urban environments reveals inherent complexities and challenges. These include unintended consequences, such as the trade-offs between resource efficiency and the energy demands of certain NBS installations, or the emission of allergens and biogenic compounds associated with specific vegetation choices (Pereira et al., 2023). Camacho-Caballero et al. (2024) found that the expansion of urban agriculture can help reduce vulnerabilities related to the lack of local food production and recreational spaces. However, it can also contribute to increased biodiversity loss due to the use of fertilizers. Moreover, while NBS offer localized benefits—such as reduced urban heat island effects, enhanced air quality, and water filtration—their broader impacts on urban metabolisms and the interrelations among social and environmental subsystems often remain underexplored (Rödl & Arlati, 2022; Langemeyer et al., 2020).

Understanding the systemic and interconnected impacts of these solutions requires robust frameworks that can capture not only their immediate benefits but also the unintended feedback loops that may influence their long-term effectiveness (Jezzini et al., 2023). Traditional evaluation approaches have tended to focus mostly on positive net impacts of NBS, often overlooking broader implications for urban sustainability and the potential for trade-offs among environmental and social outcomes. To bridge these gaps, a more comprehensive and integrative assessment methodology is needed, one that accounts for the complexities of urban metabolisms (Elliot et al., 2022).

This deliverable, as part of Task 3.3, seeks to address this knowledge gap by conducting an in-depth assessment of the environmental impacts of NBS scenarios in the Barcelona Metropolitan Area. Building on prior tasks and utilizing a spatially explicit life-cycle approach, the study aims to examine the metabolic consequences of mitigating NBS impacts across a range of physical metrics, including nutrient recovery, water reuse, energy and resource demand, and social, and environmental indicators.

To achieve this objective, the deliverable focuses on synthesizing insights from existing research that has examined the environmental and social dimensions of NBS in Barcelona. First, it explores the methodological approach developed by Mendoza et al. (2023) for assessing the environmental impacts of peri-urban agriculture in a spatially explicit way. Next, the research by Toboso et al. (2023) is presented. This study evaluates the potential impacts of NBS, and other strategies applied to building rooftops, using a localized, spatially explicit, and participatory approach. Following, we analyze the proposal by Camacho-Caballero et al. (2024), who presents a comprehensive framework that integrates ecosystem services and urban metabolism analyses with spatially explicit vulnerability assessments to evaluate the impacts of NBS on urban vulnerabilities. Finally, and based on the studies reviewed, we propose a methodology and a list of indicators to consider when evaluating the impacts and sustainability of urban NBS.

3 NBS in the Metropolitan Area of Barcelona and its metabolic impacts

Barcelona is one of the most densely populated urban areas in Europe, with a small fraction of green areas, but a rich variety of agricultural lands. The Metropolitan Area of

Barcelona AMB — the case study area employed in this deliverable (see **Fig. 1**) — comprises the municipality of Barcelona and other 35 surrounding municipalities with a total population of 3.3 million people (IDESCAT, 2020). The AMB, characterized by high compactness and population density (Baró et al., 2014), faces exacerbated vulnerabilities by climate change impacts (AMB, 2018). For this matter, the AMB plans to enhance resilience by creating green spaces, including urban and peri-urban agriculture, as part of the Urban Master Plan (PDU). This plan prioritizes ecosystem service provisioning and aims to protect agricultural land for local food production while preserving the natural system (Barcelona Regional and AMB-PDU, 2023).

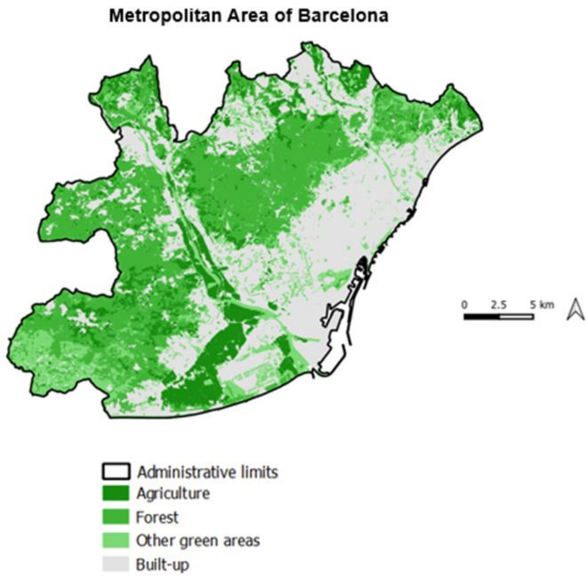

Figure 1. Metropolitan Area of *Barcelona* with land use maps

3.1 Environmental impacts of peri-urban agriculture

The methodological approach developed by Mendoza et al. (2023) provides an innovative framework for assessing the environmental impacts of NBS, as developed in the case study of peri-urban and urban agriculture (UA) in the AMB. This framework is built on the principles of regionalized Life Cycle Assessment (LCA), a methodology that accounts for spatial variability in agricultural practices, local biophysical conditions, and management techniques, thereby offering a more nuanced and context-specific understanding of environmental impacts. Unlike traditional LCA methods that often generalize across broad regions, the regionalized LCA employed by Mendoza et al. enables a finer resolution of assessment, ensuring that the characteristics and conditions of the AMB influencing NBS are accurately represented.

UA, as discussed in the paper, plays a pivotal role in enhancing local food security and sustainability by reducing the dependence on distant food sources and mitigating transboundary environmental impacts. However, this potential is accompanied by the generation of local environmental impacts. Mendoza et al. emphasizes the importance of integrating high-resolution inventory data into the LCA framework to capture the direct and indirect local environmental effects of peri-UA (see **Fig. 2**). This includes the spatially explicit mapping of inputs such as fertilizers, manure, and water, as well as outputs like emissions of nitrogen compounds and phosphorus runoff.

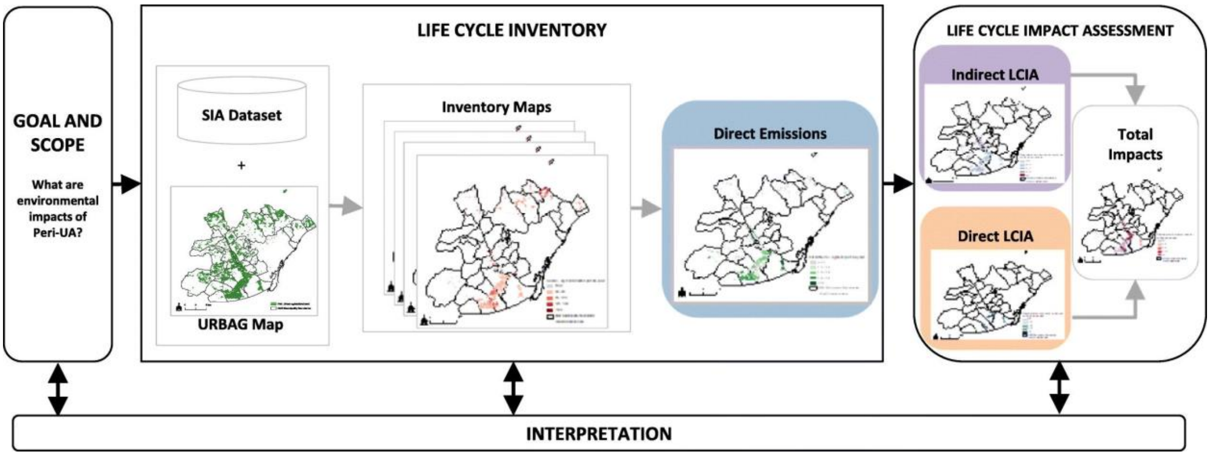

Figure 2. Graphical abstract of the research carried out by Mendoza et al. (2023). Source: Mendoza et al. (2023)

One of the key contributions of this approach is the emphasis on regionalization of eutrophication impacts. By tailoring characterization factors to the specific conditions of the Llobregat and Besòs river basins, the study highlights the critical role that localized assessments play in accurately estimating the impacts of nutrient pollution on freshwater and marine ecosystems. This regionalized approach reveals that conventional characterization factors may either underestimate or overestimate impacts, underscoring the necessity of using geographically precise data for effective sustainability assessments.

Furthermore, the findings of Mendoza et al. underscore the complex interplay between land use, management practices, and environmental outcomes. The study shows that land uses such as vegetable cultivation and greenhouse agriculture are associated with the highest environmental impacts due to the intensive use of NPK fertilizers (see **Fig. 3**). In contrast, other land uses, such as fruit orchards, are more affected by direct emissions from on-site nutrient management. This variability emphasizes the importance of tailoring mitigation strategies to specific land use types and management practices to optimize environmental outcomes.

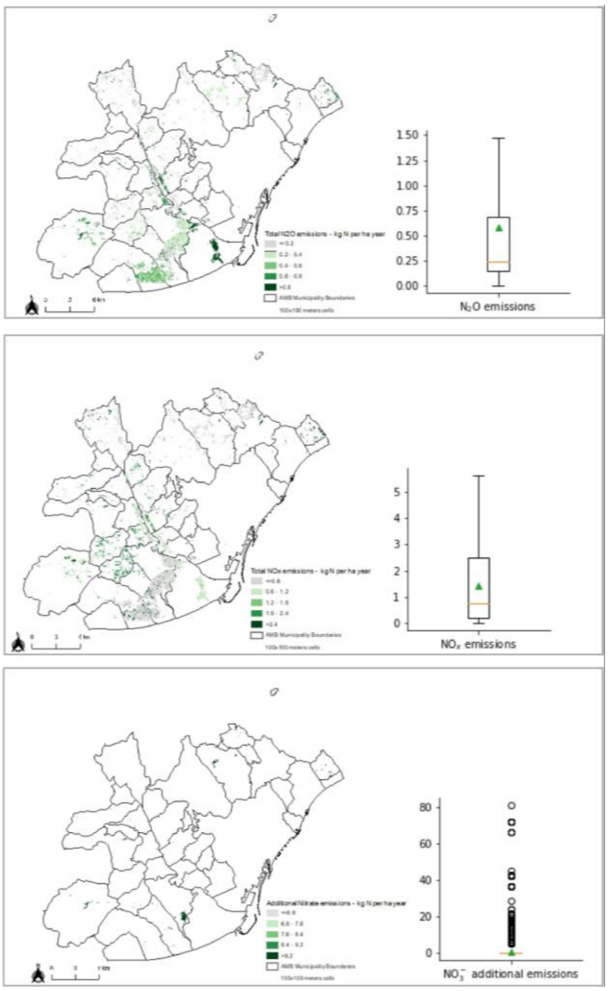

Figure 3. Maps and boxplots for total N emissions for peri-urban agriculture production in the Metropolitan Area of Barcelona (AMB) in the three different scenarios employed for the study. Source: Mendoza et al. (2023)

Moreover, the research identifies significant variability in environmental impacts across different plots within the AMB, driven by variations in management practices, crop types, and irrigation methods. This variability illustrates the necessity for high-resolution data collection and the application of site-specific management strategies to enhance the environmental performance of peri-UA. The study further suggests that replacing imported mineral fertilizers with locally sourced nutrient inputs, such as digested manure or municipal compost, could substantially reduce the environmental footprint of peri-UA by promoting circularity and self-sufficiency.

While the study by Mendoza et al. (2023) primarily focuses on nutrient flows and eutrophication impacts, it is important to acknowledge that peri-urban agriculture (UA) can influence other categories of environmental impacts as well. For instance, UA practices may affect greenhouse gas (GHG) emissions through energy use in irrigation, machinery operation, and the production of agricultural inputs. Additionally, land use changes associated with UA can have implications for biodiversity, soil health, and water consumption. Future research could explore these dimensions to provide a more comprehensive assessment of the environmental trade-offs and synergies associated with UA. Integrating such analyses into the regionalized LCA framework would further enhance its applicability for holistic sustainability planning in urban and peri-urban contexts.

3.2 Potential impacts of NBS and other solutions in building rooftops

The study by Toboso et al. (2023) offers a detailed and multifaceted examination of the potential for implementing NBS through green roof mosaics in Cerdanyola, a small city within the AMB. This research integrates spatial analysis, urban metabolism evaluation, and impact assessments to explore the feasibility and implications of different roof mosaic scenarios across varied urban morphologies. The study not only underscores the critical role that urban form plays in the effectiveness of NBS but also provides actionable insights into sustainable urban planning and resource self-sufficiency.

One of the core contributions of Toboso et al.'s work is its integration of food, energy, and water (FEW) production systems on rooftops, which are examined in the context of Cerdanyola's diverse urban fabrics. The study recognizes that urban rooftops represent untapped potential for local resource production, a perspective that aligns with the broader sustainability agenda of enhancing urban self-sufficiency. By categorizing the urban morphology into distinct forms—housing estates, originary fabrics, and single-family housing areas (see **Fig. 4**)—the study provides an analysis of how urban form influences the viability and performance of green roof mosaics.

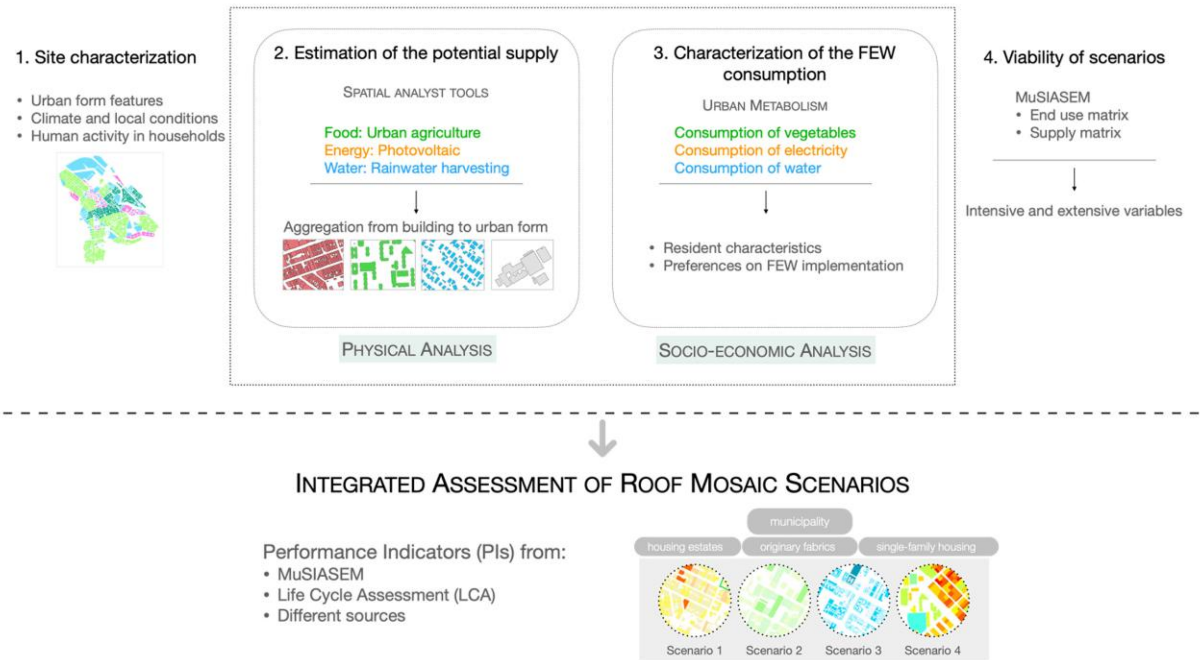

Figure 4. Diagram of the main steps of the applied methodology by Toboso-Chavero et al.. FEW: food-energy-water; MuSIASEM: Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism. Source: Toboso-Chavero et al. (2023)

A significant finding of the research is the impact of urban morphology on the distribution and effectiveness of NBS. Single-family housing areas, characterized by larger roof surfaces and greater open spaces, exhibited the highest potential for achieving self-sufficiency in energy and water production (see **Fig. 5**). In contrast, housing estates, with their extensive and flatter roofs, showed greater potential for rooftop farming, though their compact nature posed limitations for expansive green infrastructure. Originary fabrics (i.e., historic centers and sub-urban extensions) demonstrated a moderate potential for integrating NBS, with variations influenced by the heterogeneity of building types and rooftop characteristics.

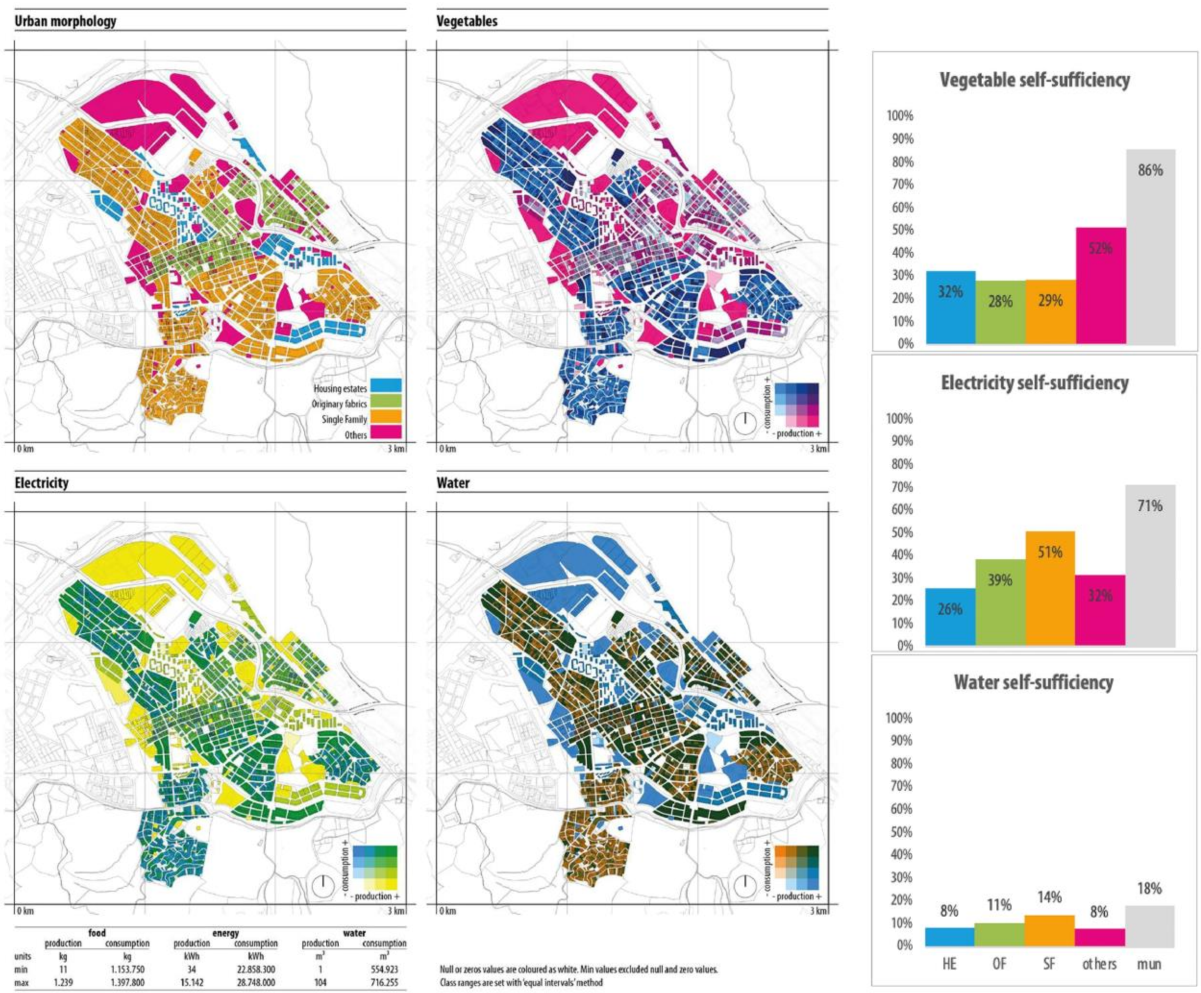

Figure 5. Fig. 2. Food, energy, and water consumption vs. production on rooftops. The first map identifies the three urban forms, e.g., housing estates, originary fabrics and single-family housing areas, as well as the others category. The rest of the maps represents the consumption vs. production of food, energy and water. The bar charts show the resource self-sufficiency by urban form and the total of the municipality. HE: housing estates; OF: originary fabrics; SF: single-family housing areas; others: public and private facilities and industrial parks; mun: municipality. Source: Toboso-Chavero et al. (2023)

Toboso et al. further emphasize the necessity of context-specific NBS implementation, showing that the feasibility of green roofs is not only a function of physical space but also of socio-economic factors, resident preferences, and consumption patterns. For instance, survey data indicated varying levels of acceptance for different solution types, with photovoltaic panels being the most preferred and rooftop farming the least, due to perceived challenges in maintenance and coordination among residents. This highlights the importance of aligning NBS strategies with the preferences and capabilities of urban communities to ensure long-term success.

In terms of environmental performance, the study demonstrates that implementing green roofs can reduce the reliance on externally produced resources, such as vegetable and electricity, thereby lowering the environmental footprint of urban areas. Scenarios combining photovoltaic panels with rainwater harvesting emerged as the most effective in achieving energy self-sufficiency, particularly in single-family housing areas. Meanwhile, rooftop farming scenarios, though less favored by residents, contributed significantly to food self-sufficiency and the creation of green spaces, which are critical for urban heat mitigation and biodiversity enhancement.

The insights from Toboso et al.'s study support the ongoing task of evaluating NBS in the AMB, particularly in terms of understanding how urban morphology influences the performance and scalability of these solutions. Their study provides a robust framework for replicating similar evaluations in other urban contexts different from the AMB.

3.3 Integrated assessment of NBS impacts through a vulnerability perspective

Camacho-Caballero et al. (2024) present a framework that integrates ecosystem services (ES) and urban metabolism (UM) analyses with spatially explicit vulnerability assessments to evaluate the impacts of NBS on urban vulnerabilities. This approach extends beyond traditional NBS evaluations by addressing how these interventions influence urban vulnerabilities (see **fig. 6**) such as heat exposure, lack of recreational space, biodiversity loss, and food security. The study offers a multidimensional perspective on how NBS can alter urban vulnerabilities through both intended and unintended consequences, providing critical insights for sustainable urban planning.

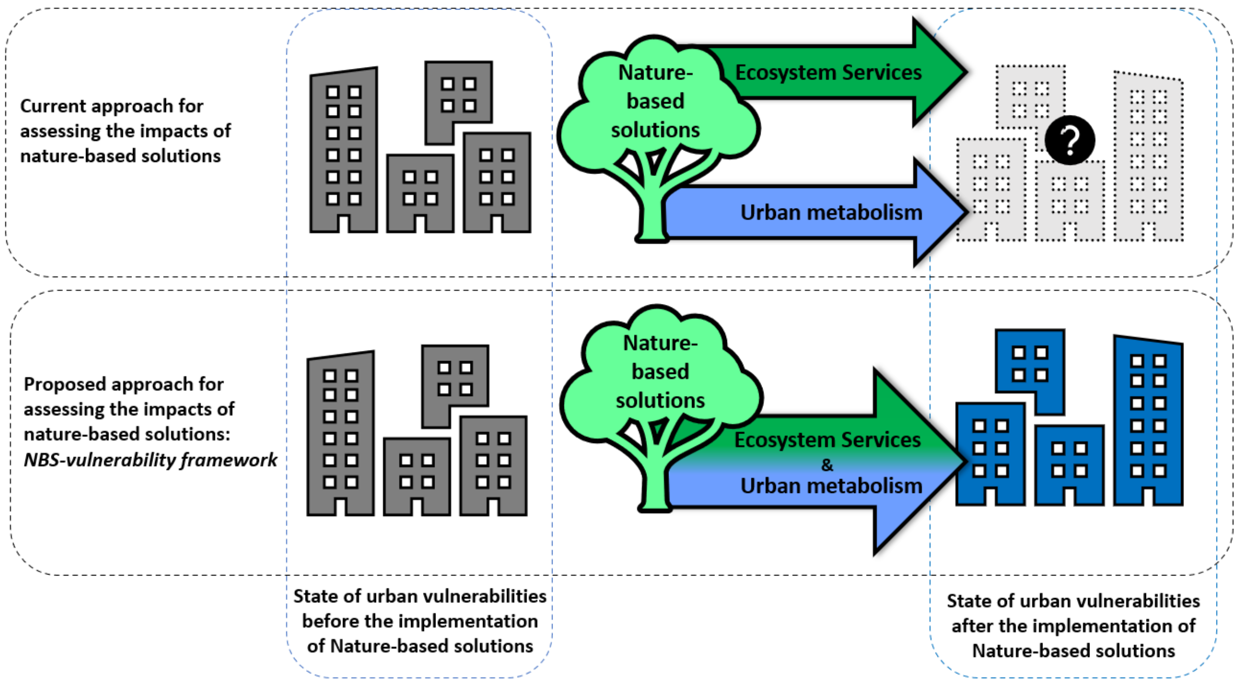

Figure 6. Graphical representation of the current approach for assessing the impacts of nature-based solutions (NBS) in urban environments versus the NBS-vulnerability framework proposed by Camacho-Caballero et al. (2024). Arrows represent NBS impacts in urban environments. The current approach focuses on assessing impacts either via ecosystem services or urban metabolism perspective, often overlooking their role in addressing vulnerabilities. The NBS-vulnerability framework suggests linking the ecosystem services and urban metabolism analyses to urban vulnerabilities, elucidating how NBS impacts can affect the latter. Source: Camacho-Caballero et al. (2024).

The framework developed by Camacho-Caballero et al. is distinguished by its emphasis on spatial specificity and the integration of diverse urban factors. Unlike previous studies that focus on net ES impacts, this framework uses a multi-criteria analysis approach to link NBS-driven changes in ES and UM to shifts in urban vulnerabilities. This is achieved by developing NBS scenarios that simulate various land-use configurations and assessing how these changes alter specific urban vulnerabilities indicators. The framework is applied in the

AMB to assess how peri-urban agriculture (UA), an example of NBS, influences urban vulnerabilities under different scenarios. By examining the spatial distribution of vulnerabilities and incorporating stakeholder input, the study provides a nuanced understanding of the trade-offs and synergies involved in NBS implementation.

A central principle of Camacho-Caballero et al.'s methodology is the differentiation between joint and disjoint effects of NBS on urban vulnerabilities. Joint effects occur when multiple vulnerabilities decrease or increase simultaneously due to an NBS intervention, while disjoint effects involve trade-offs where the reduction of one vulnerability may exacerbate another. For example, the study demonstrates how UA expansion can simultaneously reduce the vulnerability associated with lack of local food (see **fig. 7**) while increasing biodiversity loss (see **fig. 8**) due to intensified nutrient runoff. This highlights the complex interplay between ES provisioning, UM impacts, and urban vulnerability dynamics, demanding an integrated approach to NBS planning.

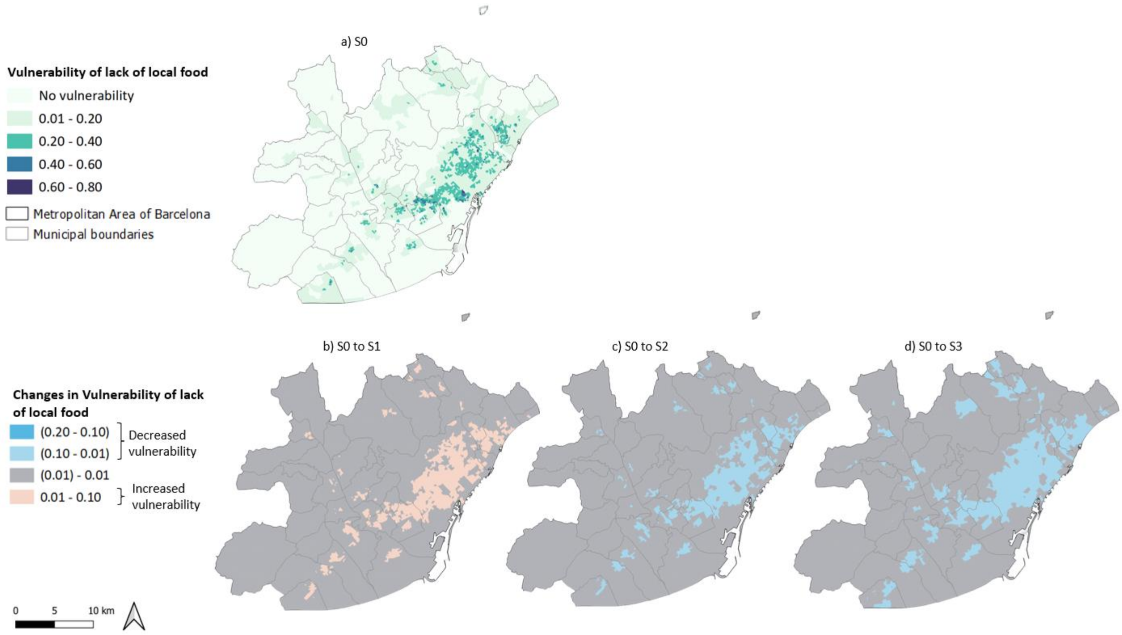

Figure 7. Spatial distribution of Vulnerability of lack of local food and changes across scenarios. Gray areas represent no vulnerability changes between scenarios.

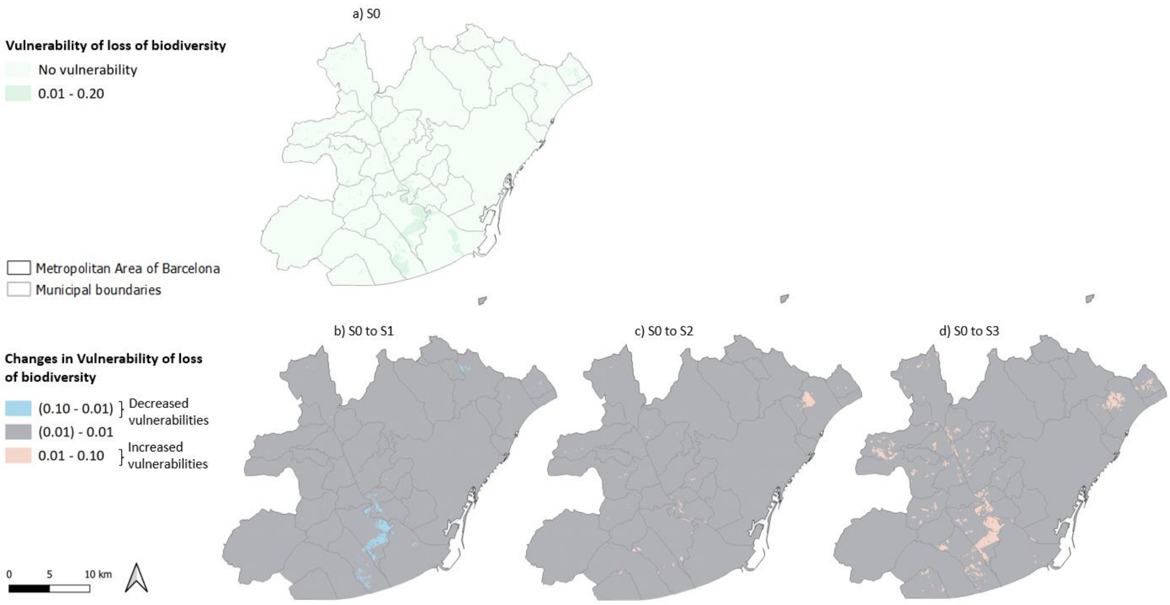

Figure 8. Spatial distribution of Vulnerability of loss of biodiversity and changes across scenarios. Gray areas represent no vulnerability changes between scenarios.

Camacho-Caballero et al.'s framework also demonstrates the importance of stakeholder engagement in NBS assessment. Through participatory workshops, stakeholders were involved in the selection and weighting of vulnerability criteria, ensuring that the assessment reflects local priorities and concerns. This collaborative approach enhances the relevance and applicability of the findings, providing a robust basis for decision-making in urban planning.

The application of this framework in the AMB reveals significant spatial variations in vulnerability reduction and exacerbation, emphasizing the role of local context in determining the effectiveness of NBS. For instance, areas with higher population density and limited green space experienced greater reductions in vulnerabilities related to recreational access when UA was expanded. Conversely, regions where UA replaced other green spaces saw increased vulnerability to heat and biodiversity loss. These findings illustrate the necessity of tailoring NBS strategies to specific urban morphologies and socio-ecological conditions.

4 NBS impacts on both spatially and non-spatially explicit vulnerabilities: the case of green roofs in Oslo

While the framework proposed by Camacho-Caballero et al. (2024) provides a valuable approach for assessing NBS impacts through ES, UM and vulnerability analyses, it overlooks a critical dimension: the potential impacts of NBS beyond the urban boundaries where they are implemented. This consideration is crucial, as urban NBS function at the intersection of local socio-ecological benefits and broader environmental trade-offs.

The studies presented earlier in this deliverable primarily focus on NBS impacts within urban settings. However, the following case study expands this perspective by examining how NBS influence Earth System Boundaries (ESBs) beyond city limits. ESBs are defined as "a set of safe and just Earth system boundaries for climate, the biosphere, fresh water, nutrients, and air pollution at global and subglobal scales" (Rockström et al., 2023). This section explores findings from an integrated NBS assessment in Oslo, where different green roof scenarios were analyzed using a vulnerability-based framework.

Building on the Camacho-Caballero et al. (2024) approach, the Oslo case study applied a spatially explicit multi-criteria analysis to evaluate how different levels of green roof implementation influence local-scale vulnerabilities. Additionally, this study introduced a novel dimension by assessing the global environmental impacts of NBS through the ESB framework. The research argues that surpassing an ESB threshold can be interpreted as a vulnerability, as it increases the susceptibility of social and ecological systems to harm. Within this framework, both local and broad-scale vulnerabilities are recognized as being influenced by NBS. Local-scale vulnerabilities refer to those experienced within the urban area where NBS are implemented, such as heat exposure and air pollution. In contrast, broad-scale vulnerabilities stem from impacts that extend beyond city boundaries (see Fig. 9).

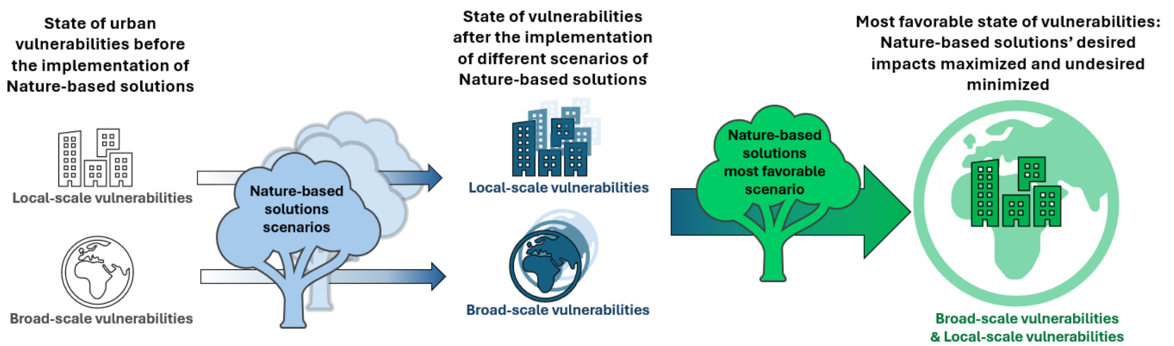

Figure 9. Graphical representation of the nature-based solutions (NBS) vulnerability framework. Arrows represent NBS impacts on vulnerabilities. The NBS-vulnerability framework proposes to consider the NBS' impacts on both local and broad-scale vulnerabilities.

Key local-scale vulnerabilities assessed in the Oslo case study included heat exposure (see Figure 10), heavy rainfall, air pollution, lack of pollinator habitats, and reduced opportunities for nature interaction. The findings indicate that increasing green roof coverage significantly reduces heat and stormwater vulnerabilities, particularly in high-density areas with limited green infrastructure.

To assess broad-scale vulnerabilities, a life cycle assessment (LCA) was conducted to evaluate the environmental impacts associated with the construction, installation, use, and disposal of 1m² of an extensive green roof over one year. Each LCA impact category was then linked to an ESB based on established connections in prior research. This approach revealed that, while green roofs provide local resilience benefits, their material production, maintenance, and disposal processes contribute to broader environmental pressures, including increased greenhouse gas emissions and nutrient pollution. Specifically, while green roof expansion were able to capture greenhouse gases in Oslo, their net implementation led to increases in climate-related emissions due to the life-cycle impacts of construction materials and fertilizers, mirroring similar concerns raised in Barcelona's sustainability discussions.

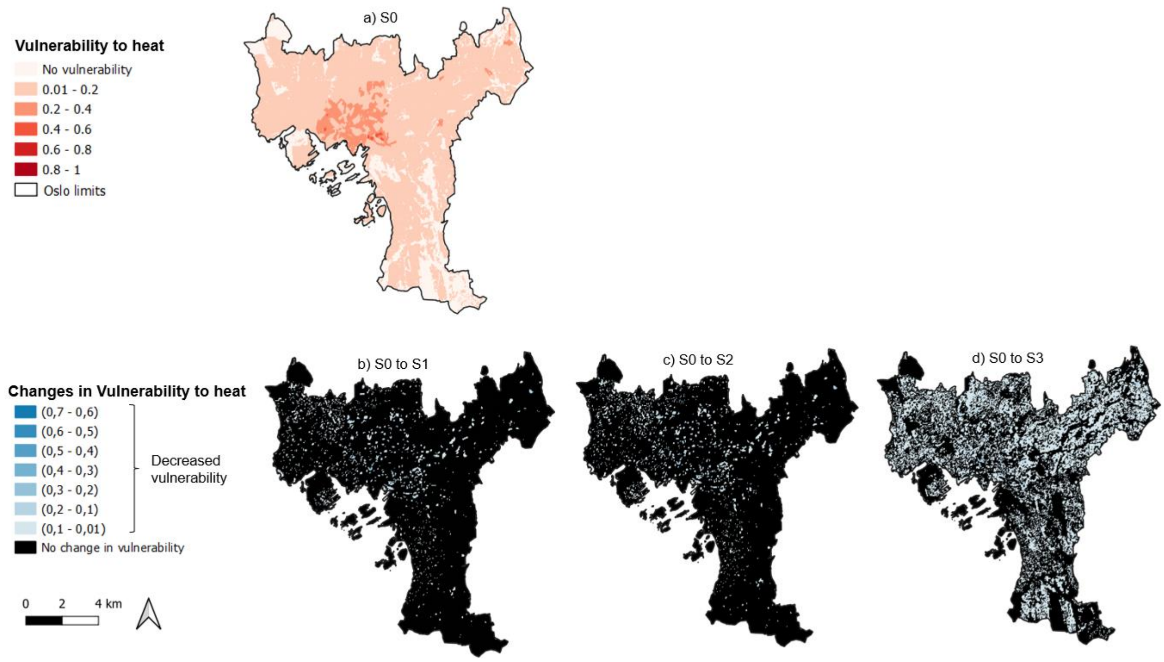

Figure 10. Spatial distribution of Vulnerability to heat and changes across scenarios. Black areas represent no vulnerability changes between scenarios.

The Oslo case study underscores the importance of considering how local and global impacts of NBS can create both synergies (i.e., positive impacts occurring simultaneously) and trade-offs (i.e., positive and negative impacts co-occurring). More importantly, it provides new insights into how to quantify and balance these effects to optimize NBS planning.

5 NICHES proposal: understanding NBS metabolic impacts through a vulnerability perspective

Based on the studies previously presented, NICHES proposes a framework that draws on the vulnerability framework developed by Camacho-Caballero et al. (2024) and its application on the case study of Oslo's green roofs to assess the socio-ecological impacts NBS on urban vulnerabilities. This approach integrates ES and UM analyses with spatially explicit vulnerability assessments to evaluate the extent to which NBS mitigate urban vulnerabilities, particularly those related to combined sewer overflow events and aquatic ecosystem degradation. The methodology is designed to be replicable across diverse urban contexts, offering insights into the social metabolic consequences of NBS while considering trade-offs and synergies.

Similar to Camacho-Caballero et al. (2024) and the Oslo case study, the framework is based on the conceptual framework that urban environments are treated as dynamic socio-ecological systems where NBS serve as interventions that influence vulnerabilities. The methodology links NBS implementation to changes in urban exposure and sensitivity to hazards, emphasizing spatial heterogeneity and stakeholder involvement in evaluating trade-offs.

5.1 NBS Scenarios and Land-Use Configurations

To capture the potential impacts of NBS on urban vulnerabilities, various spatially explicit NBS scenarios will be developed, reflecting different land-use configurations. These include:

- **Baseline scenario**: Current urban configuration with existing green and grey infrastructure.
- **NBS scenarios**: Configurations that incorporate new NBS (e.g., bioretention ponds, green roofs) with variations in scale and location of interventions.

Land-use change maps will be generated using GIS tools to spatially visualize how the implementation of NBS alters urban vulnerabilities across different locations. For each scenario, vulnerabilities are calculated. Then the baseline scenario is compared to each of the NBS scenarios to understand how much vulnerabilities have changed (i.e., increased/ decreased).

5.2 Selection and Measurement of Vulnerabilities

It is recommended to assess the state of the socio-ecological vulnerabilities listed in **Table 1,** each linked to relevant NBS impact criteria and potential indicators for calculation. As seen in the Oslo case study, vulnerabilities can arise both within and beyond the urban areas where NBS are implemented.

Table 1. List of suggested vulnerabilities and indicators for assessing urban NBS

Vulnerability	Indicator
Vulnerability to nutrient recovery	Efficiency in recovering nutrients (e.g., nitrogen, phosphorus) from urban wastewater or organic waste.
	Reduction in reliance on synthetic fertilizers due to local nutrient cycling.
	Nutrient runoff reduction from NBS (e.g., bioretention ponds, constructed wetlands).
	Ecological sensitivity of local water bodies to nutrient pollution (e.g., biodiversity presence)
	Presence of vulnerable aquatic ecosystems sensitive to nutrient enrichment (e.g., freshwater biodiversity, eutrophication zones).
Vulnerability to lack of water management	Volume of rainwater harvested through NBS
	Local water retention and infiltration rates through urban green infrastructure.
	Reduction in potable water use due to irrigation reuse or greywater systems.
	Water demand in neighborhoods
	Proximity of vulnerable populations (e.g., low-income areas) to water-efficient NBS installations.
	Dependency on local water sources for irrigation and daily needs in water-scarce areas.
Vulnerability to energy demands	Energy savings due to temperature regulation provided by NBS (e.g., cooling effects of green roofs, shade).
	Integration of renewable energy systems (e.g., solar panels on green roofs, biogas from organic waste).
	Reduction in energy consumption for cooling/heating due to the microclimatic effects of NBS.
	Energy consumption patterns in urban areas, particularly in high-density or low-income neighborhoods.
Vulnerability to resource demand	Changes in material inputs such as fertilizers, pesticides, and fossil fuels during the lifecycle of NBS
	Availability of local materials for NBS construction and maintenance
Vulnerability to accessibility to green spaces	Proximity of urban populations to green spaces or recreational areas created or enhanced by NBS.
	Demographic groups with limited access to green spaces (e.g., elderly, children, low-income residents).
	Total population density
Vulnerability to heat	Heatwave temperatures (day, night)
	Sensitivity of vulnerable populations to extreme heat (e.g., elderly, low-income households with poor building insulation).
Vulnerability to social cohesion	Proximity of urban populations to green spaces or recreational areas created or enhanced by NBS.
	Demographic diversity
Vulnerability to biodiversity conservation	Increase in habitat availability for native species and pollinators due to NBS
	Presence of rare or sensitive species in urban environments.
	Sensitivity of ecosystems to invasive species or habitat fragmentation due to urban development.

5.3 Data Collection and Indicator Normalization

Quantitative data should be gathered from various sources, including spatial data on land use, hydrological models, and socio-demographic datasets. All indicators will be normalized using a min-max scaling approach to allow for cross-comparison across different vulnerability types, while considering local threshold for its normalization. Threshold values will be established based on scientific literature, stakeholder input, and local policy targets. According to Camacho-Caballero et. al (2024), "Thresholds serve as cutoff values and are established based on scientific knowledge or urban objectives. Thresholds are context-specific, reflecting the urban environment where NBS are situated, enabling risk differentiation based on local conditions".

At this stage, all indicator values are normalized onto a consistent scale between 0 and 1. Subsequently, indicators for each vulnerability are combined to produce comprehensive vulnerability maps, highlighting urban zones where indicators intersect, in those cases where vulnerabilities are spatially explicit. When they are not, vulnerability will be assessed only by the change in the vulnerability values and not based on its location.

5.4 Stakeholder Engagement for Weighting Vulnerabilities

Stakeholders, including local authorities, urban planners, and community representatives, will participate in workshops to prioritize and weight vulnerabilities based on local needs and values. This ensures the assessment reflects local socio-ecological contexts and enhances the legitimacy and applicability of results. Weights assigned by stakeholders are then applied to determine the influence of vulnerabilities identified in the previous step on the creation of composite maps. The resulting outputs are scenario-specific maps that highlight regions with overlapping vulnerabilities.

5.5 Spatial Aggregation and Visualization of Results

By employing the weights assigned by stakeholders, the final step involves aggregating vulnerability maps for each scenario to produce combined vulnerability profiles. These maps will be visualized using GIS to illustrate areas of vulnerability reduction and exacerbation, guiding decision-makers in optimizing NBS placement (see fig. 11 as an example).

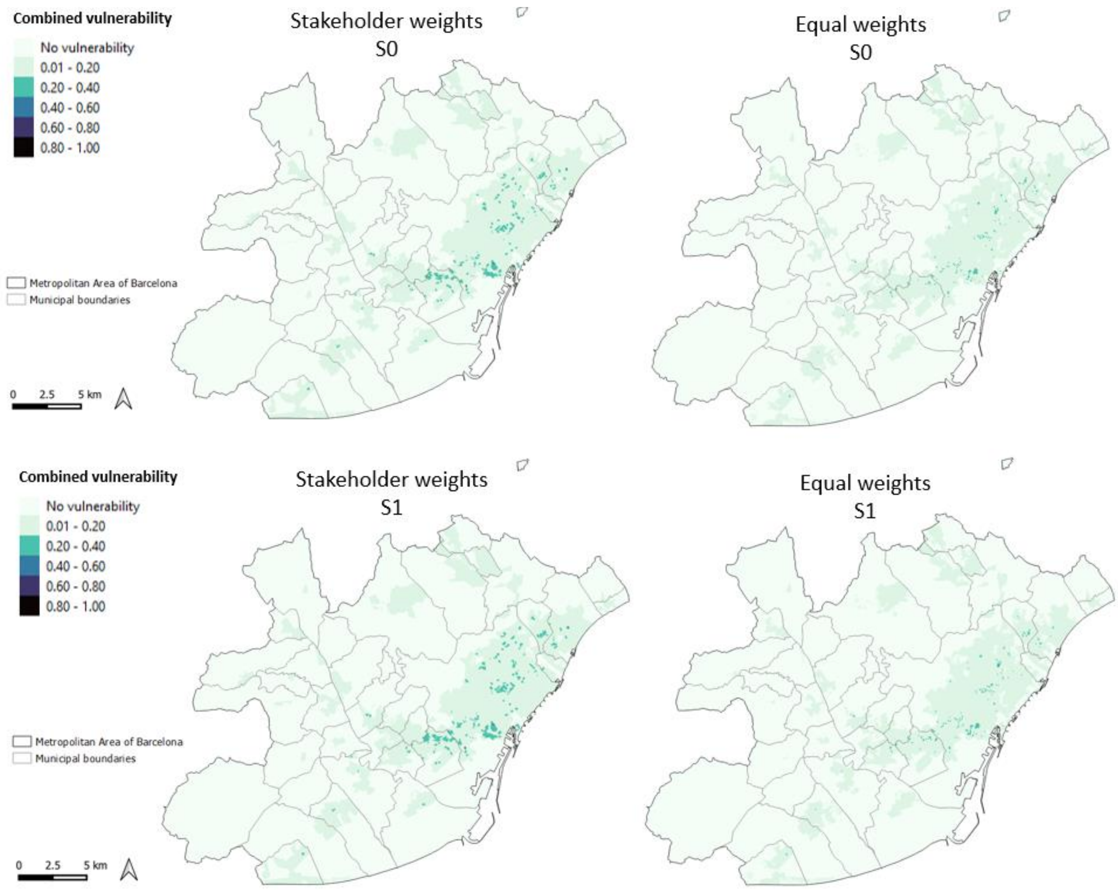

Figure 11. Example of the spatial distribution of combined vulnerabilities extracted from Camacho-Caballero et al. (2024). Maps display the spatial aggregation of all social-ecological vulnerabilities considered in the study (Lack of local food, heat, lack of recreational spaces and loss of biodiversity) for one of the urban agriculture scenarios employed for the study.

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