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Assessing Nature-based solutions in the face of urban vulnerabilities: A multi-criteria decision approach

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ABSTRACT

Nature-based solutions (NBS) are increasingly employed to address urban challenges. Typically, NBS planning emphasizes environmental impacts and ecosystem services, often overlooking their role in addressing vulnerabilities. Our objective is to develop a framework assessing the extent to which NBS alter urban vulnerabilities. For this, we relate ecosystem service and urban metabolism analyses to spatially explicit vulnerabilities. The framework relies on multi-criteria decision analysis to integrate diverse impacts. It follows a stepwise approach including the development of land-use scenarios, selection of vulnerabilities and indicators, normalization and aggregation of indicators, and stakeholder weighting. We apply the framework to the Metropolitan Area of Barcelona to assess the impacts of increasing (peri-)urban agriculture in terms of critical vulnerabilities: heat, lack of recreational space, biodiversity loss, and lack of local food. Results show that agricultural expansion decreased the vulnerability of lack of local food, increased the vulnerability of biodiversity loss, and increased the heat vulnerability in terms of night temperatures for sensitive areas. Results reveal diverse spatial outcomes and trade-offs in urban vulnerabilities due to shifts in (peri-)urban agriculture. The framework innovatively evaluates NBS impacts by linking multiple evaluation methods through spatially explicit vulnerabilities, fostering the strategic planning of NBS at the urban metropolitan scale.

1. Introduction

Nature-based solutions (NBS) are being increasingly advocated to bolster urban resilience and sustainability (Cohen-Shacham et al., 2019). NBS are understood as "actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits" (United Nations, 2022). NBS, such as urban and peri-urban forests, green roofs and walls, pervious pavements, and urban agriculture, exemplify a multifunctional, solution-oriented approach to enhancing urban sustainability (Dorst et al., 2019). In particular, urban agriculture serves as a key illustration of NBS, and it will be a focal point throughout this study. Typically, planning NBS involves analyzing different alternatives and their projected outcomes in terms of the direct and indirect contributions to human well-being, or ecosystem service (ES) provision (Raymond et al., 2017). However, there is often insufficient attention given to how NBS address specific vulnerabilities in spatially heterogeneous urban landscapes (Langemeyer et al., 2020) (see). Considering such an aspect could enhance the evaluation of NBS by broadening the perspectives included in its assessment, contributing to a more comprehensive evaluation of NBS (Dumitru et al., 2020).

Abbreviations: NBS, Nature-based solutions; ES, ecosystem service; UM, urban metabolism; AMB, Metropolitan Area of Barcelona; PDU, urban master plan of the Metropolitan Area of Barcelona; UA, urban agriculture; S0, urban agriculture scenario "Current"; S1, urban agriculture scenario "Trending"; S2, urban agriculture scenario "Alternative"; S3, urban agriculture scenario "Potential".

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Vulnerability can be broadly defined as the susceptibility to harm (Cutter, 2016) of both social and ecological systems. Urban vulnerabilities are spatially heterogeneous and encompass two key dimensions: exposure and sensitivity. Exposure relates to the proximity of systems to hazards, while sensitivity describes the extent to which a system is impacted by hazards (Thiault et al., 2018). For instance, vulnerability analyses provide insights into the extent and patterns of people's exposure to climate-related risks and the inequalities in coping with these impacts (Baró et al., 2021). Yet, despite important advances toward a differentiated understanding of urban vulnerabilities (Herreros-Cantis & McPhearson, 2021), NBS planning is still widely based on the assessment of net ES.

The ES framework highlights the various ways in which humans can benefit from natural ecosystems (Fisher et al., 2009). NBS can bring these benefits and co-benefits in environmental, social, and economic terms (Cohen-Shacham et al., 2019). However, ES are spatially explicit (Herreros-Cantis & McPhearson, 2021) and the location of NBS determines its distribution. Depending on the ES type, its provision and beneficiaries may differ (Basnou et al., 2020) (e.g., food can be transported, temperature regulation cannot). This creates urban areas with ES deficits (Langemeyer et al., 2020), commonly referred to as areas with ES demands. These spatial (mis)matches need to be considered when planning NBS (Basnou et al., 2020) since the distribution of ES across various scales and groups is crucial from a socio-environmental perspective, not least under equity considerations (Langemeyer & Connolly, 2020).

Compared to ES, the environmental impacts of NBS have received less attention. Environmental impacts are generally analyzed through urban metabolism (UM) approaches, understood as the sum of processes that an urban system needs to maintain itself by importing, producing and exporting materials, while also emitting waste (Kennedy et al., 2007). UM offers essential evaluation techniques for sustainable city planning (Perrotti & Stremke, 2020). Under this perspective, NBS can be examined to understand their impacts on energy consumption/reduction, water consumption and greenhouse gas emissions. For instance, urban agriculture can contribute to nutrient discharges from fertilizer use, leading to eutrophication, and potentially impacting biodiversity (Firbank et al., 2007). Similar to the ES perspective, UM focuses on analyzing net impacts within a system by assessing the balance between inputs and outputs. Considering such impacts in a geographically explicit manner has been deemed necessary for a more differentiated understanding of NBS (Mendoza Beltran et al., 2022).

Given the significance of spatial analysis in comprehending both ES and UM, adopting a vulnerability approach provides an advanced perspective for studying NBS impacts because of its spatially explicit characteristics. Vulnerability analyses have a well-established tradition in the disaster and risk literature (Liang & Xie, 2022), yet they have not been widely integrated into NBS planning, with few exceptions such as the case of Lehmann et al. (2023). Instead, ES demand approaches are trending (Pan et al., 2021). For example, ES demand has identified areas with insufficient green spaces that could benefit from green interventions to enhance heat and recreational conditions (Meerow & Newell, 2017). However, broader vulnerability considerations in NBS research are limited, as ES demand approaches often overlook potential changes arising from NBS implementation. A more comprehensive vulnerability assessment should thus consider changes in urban exposure and sensitivity due to NBS interventions, providing a novel understanding of NBS impacts. For UM, spatial analyses have become more widespread and are deemed necessary for enhancing land-use planning (Bahers et al., 2022). However, the spatial metabolic effects of NBS have been overlooked (Chrysoulakis et al., 2021). According to Otero Peña et al. (2022), UM has yet to consider urban vulnerabilities, which offer opportunities for enhancing resource efficiency in urban environments.

Furthermore, a spatially explicit integration between ES, UM and urban vulnerabilities can support the planning of NBS in urban environments. This involves considering both intended and unintended NBS impacts simultaneously (Dumitru et al., 2020), as well as their (dis)joint effects on urban vulnerabilities, as vulnerabilities may increase or decrease similarly or oppositely (Zuniga-Teran et al., 2020). These impacts can be related to land-use changes resulting from NBS implementations (Fernandes & Guiomar, 2018). The relevance of this aspect becomes apparent as the integration of NBS evaluation with urban policies remains partial (Pan et al., 2021).

Stakeholder involvement can boost the effectiveness of such an evaluation scheme. Stakeholder engagement aids in addressing the complexity of planning NBS by considering diverse urban perspectives (Nesshöver et al., 2017). Such collaborative approaches can foster urban resilience and sustainability, while also promoting acceptance of NBS (Mees et al., 2015). Because of these traits, stakeholder engagement is encouraged for NBS planning (Zingraff-Hamed et al., 2020). Stakeholders have been involved in NBS assessments to evaluate feasibility and estimate the provision and ranking of ES (Langemeyer et al., 2020; Venter et al., 2021). Consequently, involving stakeholders provides an opportunity for enhancing NBS assessments through urban vulnerabilities.

The objective of our study is to develop a stepwise, multi-criteria and integrated assessment framework capable of evaluating how and to what (Barcelona Metropolitan Area - AMB, 2018; Barcelona Regional and AMB-PDU, 2023; IDESCAT, 2020; IPCC, 2012; Kato-Huerta & Geneletti, 2023; Langemeyer & Gómez-Baggethun, 2017; Little, 2010; Mussinelli et al., 2021; Schneiderbauer et al., 2017; United Nations, 2022) NBS change urban vulnerabilities. This framework will anticipate and evaluate potential intended and unintended consequences arising from NBS implementation resulting in varying degrees of exposure to risks, an aspect that ES and UM assessments fail to contemplate and that can enhance the planning of NBS in urban environments. We hence propose to link the ES and UM analyses to spatially explicit vulnerabilities (see Fig. 1) for assessing NBS scenarios representing various land-use configurations while considering stakeholders' inputs. To demonstrate the effectiveness of our approach, we apply it to the case study of (peri-) urban agriculture in the Metropolitan Area of Barcelona (AMB, for its acronym in Catalan). Urban agriculture is a nature-based solution that plays a significant role in shaping the various land-use scenarios outlined in the Urban Master Plan of the AMB, providing valuable insights into the future development of the area.

2. Nature-based solutions vulnerability framework

2.1. Conceptual approach

This study approaches urban environments as socio-ecological systems: a dynamic and interconnected network of biophysical and social elements that interact across multiple scales and affect the flow and use of critical natural, socio-economic, and cultural resources (Redman et al., 2004). Within these systems, NBS are designed to address both biophysical and social factors and their interrelationships (Tzoulas et al., 2021). The location, design and overall presence of NBS provide a variety of impacts that can change urban vulnerabilities in both intended and unintended ways (Pereira et al., 2023). Urban vulnerabilities can thus be enhanced or reduced by NBS (Herreros-Cantis & McPhearson, 2021). This study is based on the premise that NBS effects can result from changes in ES supply (e.g., altering temperature regulation through green areas) or from a change in UM (e.g., shifts in urban energy demands due to cooling building requirements). These two effects are often interlinked (e.g., expanding green spaces typically reduces temperatures, lowering the city's cooling energy demand) (Shao & Kim, 2022), causing changes in both the UM of energy and the ES supply of thermal regulation. Our suggestion is to comprehensively evaluate these effects, understanding how they influence urban exposures from a spatially explicit perspective. Then, relating these to sensitive urban areas, like places with low-income populations living in buildings with poor energy performance. In essence, we aim to develop a method that

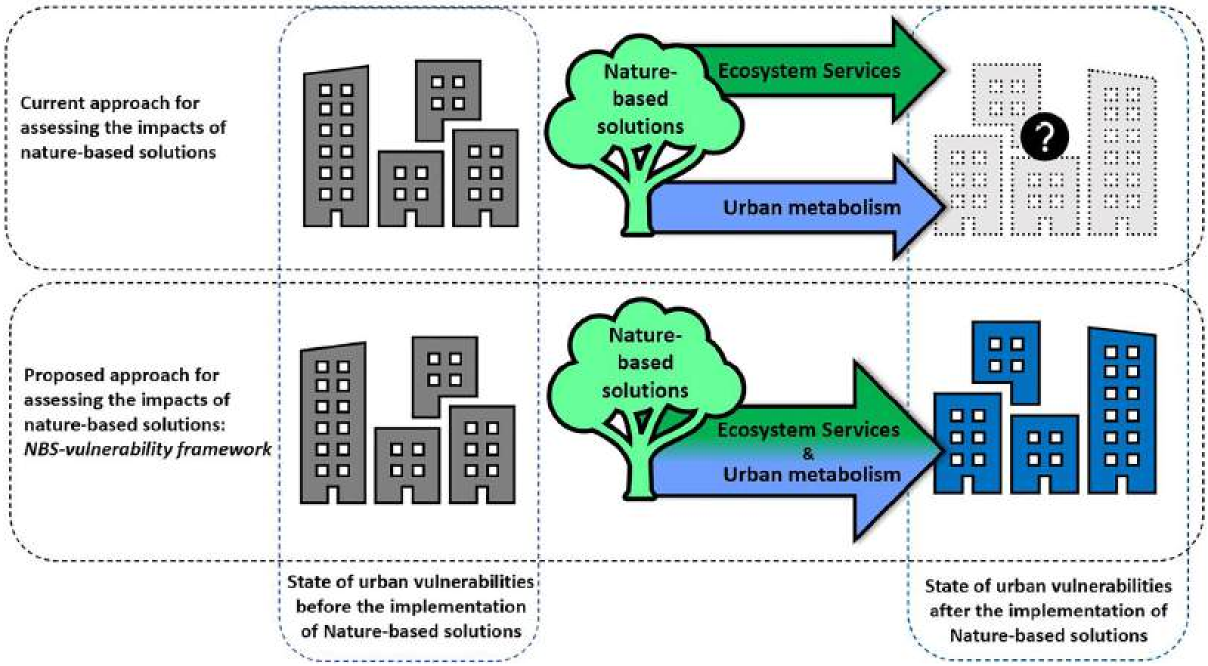

Fig. 1. Graphical representation of the current approach for assessing the impacts of nature-based solutions (NBS) in urban environments versus the NBS-vulnerability framework. Arrows represent NBS impacts in urban environments. The current approach focuses on assessing impacts either via ecosystem services 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.

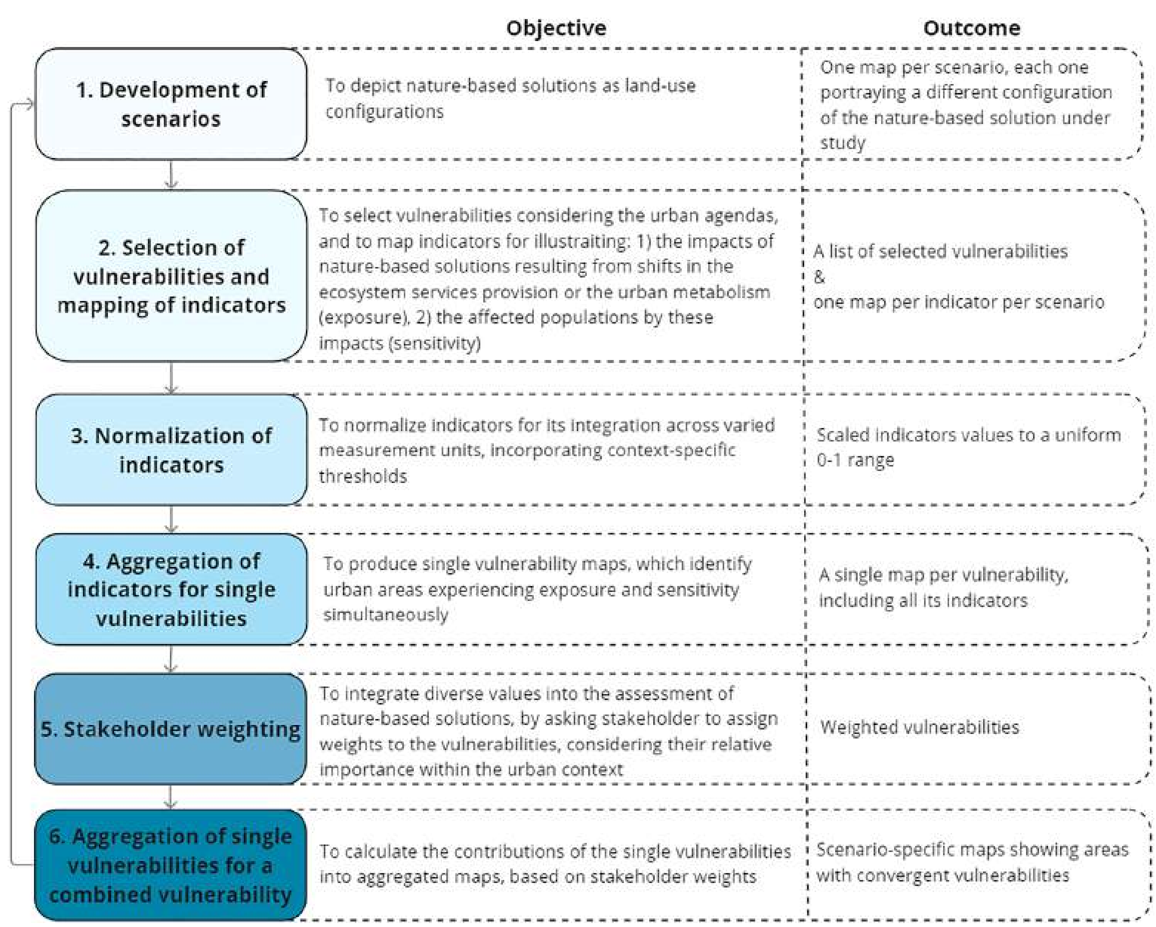

Fig. 2. Stepwise approach of the Nature-based solutions vulnerability framework, along with the objective of each step and its expected outcomes.

determines how the direct and indirect effects of NBS transform urban vulnerabilities.

To do so, we propose linking NBS impacts to spatially explicit changes in the exposures to hazards while considering sensitivities as a static variable. Furthermore, we understand that changes in vulnerabilities cause both joint and disjoint effects (Zuniga-Teran et al., 2020), which need to be assessed simultaneously to capture the synergies or tradeoffs incurred by NBS. Joint effects happen when NBS impact several vulnerabilities similarly: vulnerabilities either increase or decrease jointly. For instance, green areas have reduced vulnerabilities to air pollution and urban heat islands (Meerow & Newell, 2017). Conversely, disjoint urban vulnerabilities are those in conflict with one another, leading to trade-offs (i.e., increasing one vulnerability while decreasing another). For example, urban agriculture offers recreational opportunities (Langemeyer et al., 2021) reducing the vulnerability of lacking recreational spaces, but may negatively impact ecological vulnerability if non-organic fertilizers are used (Potter & LeBuhn, 2015). To operationalize the joint and disjoint effects on vulnerability, multi-criteria decision analysis (MCDA) premises are considered.

MCDA is a useful tool for developing holistic assessments of urban NBS (Venter et al., 2021), as it enables the integration of quantitative and qualitative data, discordant information, and stakeholders' considerations into decision-making processes, and allows the comparison of various alternatives by weighting different evaluation criteria (Marttunen et al., 2017). Relying on MCDA's capacity to compare different alternative scenarios and accommodate the diverse perspectives within urban environments, we propose a stepwise approach to examine the multidimensional impacts of NBS on vulnerabilities.

2.2. Stepwise approach of the Nature-based solutions vulnerability framework

The framework integrates urban ES and UM assessments to spatially explicit vulnerabilities into a structured approach consisting of several key steps, as shown in Fig. 2.

First, NBS scenarios are developed to represent various land-use configurations specific to the urban environment under study. Within the MCDA methodology, scenarios — or "alternatives" — are useful for exploring potential future states of the environment in situations marked by uncertainty (Marttunen et al., 2017). Our framework starts by developing potential configurations of NBS in the form of land-use-change maps, to later contrast how the vulnerabilities shift when compared to a reference scenario. These maps require an appropriate resolution to accommodate vulnerabilities with different spatial patterns. The next step involves identifying and selecting the social-ecological vulnerabilities affected by the NBS. Vulnerabilities are chosen based on urban challenges and agendas, allowing for tailormade NBS planning adapted to local necessities. We propose for each vulnerability to be evaluated by at least one exposure and one sensitivity indicator. Exposure indicators are calculated for each scenario, while sensitivity indicators are calculated once and remain static for all scenarios. Indicators need to be spatially explicit and their resolution compatible with the defined land-use scenarios. The product of this step is a map for each indicator, for each scenario.

The third stage involves normalizing absolute values of exposure and sensitivity indicators to create a unified scale, enabling integration across different measurement units. Thresholds are included to determine the magnitude of the NBS impacts based on the selected indicators. 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. For instance, the threshold for what is considered a heatwave can vary by region due to differing meteorological conditions (Kovats & Kristie, 2006). By the end of this stage, all indicator absolute values are transformed to a uniform scale ranging from 0 to 1. In the fourth step, the normalized exposure and sensitivity indicators of each vulnerability are aggregated to obtain single vulnerability maps, which identify urban areas experiencing exposure and sensitivity simultaneously. Aggregation is employed for representing multidimensional realities through single indexes (OECD & European Union, 2008). In our case, aggregation is necessary to sum the indicators per vulnerability, resulting in a single map.

In the fifth stage, stakeholders are asked to assign weights to the vulnerabilities, considering their relative importance within the urban context. Stakeholder engagement integrates diverse values to the evaluation of the vulnerabilities (Reed, 2008) and has previously been used for assessing NBS. For example, Langemeyer et al. (2020) conveyed stakeholders to rank different ES demands, identifying urban areas where green infrastructure benefits are most needed. Stakeholder-assigned weights are subsequently employed to calculate the contributions of vulnerabilities defined in step 4 into aggregated maps. The outcome consists of scenario-specific maps showing areas with convergent vulnerabilities.

3. Case study: urban agriculture in the Metropolitan Area of Barcelona

Urban and peri-urban agriculture (UA), an example of NBS, can address urban challenges by improving food security, regulating urban temperatures, promoting social cohesion and enhancing pollination (Wilhelm & Smith, 2018). Yet, the omission of its multifunctionality regarding ES supply, coupled with metabolic impacts, within the context of specific social-ecological vulnerabilities, is a recognized barrier to its promotion (Langemeyer et al., 2021).

Previous metabolism studies indicate UA's significant influence on the inter-related flows of food, water and energy in cities, resulting in impacts on the environment. For example, local crop production can reduce the energy required for transporting fresh produce (Zumkehr & Campbell, 2015), food losses due to long supply chains (Tonini et al., 2022) and water requirements by optimizing irrigation systems (Parada et al., 2021). Metabolism analyses highlight the potential for lowering environmental impacts through resource circularity, such as reusing waste nutrients like phosphorus as fertilizers (Rufí-Salís et al., 2020).

Yet, assessments including both ES and UM perspectives need to be jointly considered (Perrotti & Stremke, 2020). While some studies have assessed various UA impacts, including ecological and social functions (Padró et al., 2020), there is an opportunity to further enhance the understanding of UA impacts by examining how vulnerabilities are being altered. As we will show, vulnerability assessment supports the integration of ES and UM, providing a common ground for interpreting the impacts of UA within the spatially explicit context.

The AMB —our case study area (see Fig. 3) — 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 (Barcelona Metropolitan Area - AMB, 2018). For this matter, the AMB plans to enhance resilience by creating green spaces, including UA, as part of the Urban Master Plan (PDU). This plan prioritizes ES and aims to protect agricultural land for local food production while preserving the natural system (Barcelona Regional & AMB-PDU, 2023).

4. Methodology

4.1. Development of scenarios

We apply the NBS-vulnerability framework to evaluate how four scenarios with various degrees of UA address the vulnerabilities of the AMB. The scenarios were developed by the office of the PDU (Barcelona Regional & AMB-PDU, 2023) to foresee possible land-use changes in the region. The scenarios are *Current* (S0), which serves as the reference state, relying on the the URBAG land-use map land-use map (Mendoza

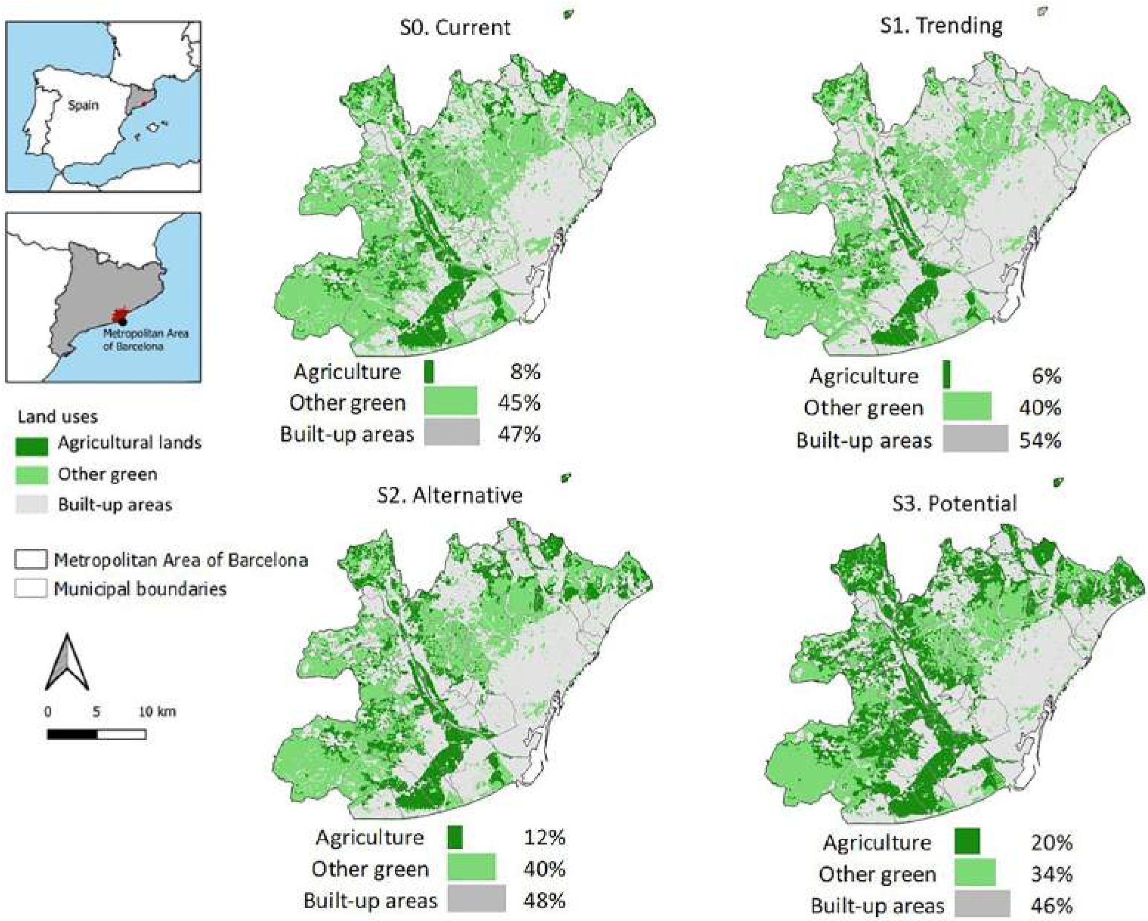

Fig. 3. Current land uses and proposed development scenarios for the Metropolitan Area of Barcelona with percentages of land used by agricultural lands, other green spaces and built-up areas.

Beltran et al., 2022); *Trending* (S1) representing a business-as-usual approach with urban expansion and a reduction of green areas. *Alternative* (S2) converting urban parks into agricultural areas, and *Potential* (S3), restoring agricultural lands to their 1956 state. Fig. 3 offers a scenario overview. For detailed descriptions, consult Padró et al. (2020).

We used QGIS 3.28.0-Firenze and ArcGIS 10.8.1 to produce and manage all maps and indicators. Scenarios and indicators were transformed into a 50×50 m grid that allowed us to (1) detail land-use changes across scenarios while considering the extension of the AMB, (2) aggregate various indicators, and (3) manage datasets within our data processing capabilities.

4.2. Selection of vulnerabilities and mapping of indicators

The second step in the NBS-vulnerability framework involves selecting the vulnerabilities and the spatially explicit exposure and sensitivity indicators that most appropriately define them. For this study, four vulnerabilities were selected based on AMB future objectives and policies (described in the next section): (1) vulnerability of lack of local food, (2) *Vulnerability to heat*, (3) vulnerability of lacking recreational space and (4) *Vulnerability of loss of biodiversity* (see Table 1). Each vulnerability is described by at least one exposure and one sensitivity indicator (see Appendix A). Indicators were chosen through a literature review and discussion among the interdisciplinary team of authors participating in the assessment. In some cases, the same sensitivity indicator (i.e. population density) is applied to various vulnerabilities because it is the most appropriate way of reflecting urban susceptibility. No double counting arises from these situations because exposure values are always different, and the multiplication of exposure and sensitivity values results in diverse vulnerability maps.

We converted indicators into a 50×50 m grid, allowing for the integration of different resolutions. Henceforth, we will refer to each of these grid cells as pixels.

4.2.1. Vulnerability of lack of local food

Urban expansion and land abandonment in the AMB caused a significant reduction in agricultural land, from 24,600 hectares in 1956 to 5400 hectares in 2009 (IERMB, 2016). To address this, the AMB aims to enhance food security via urban policies, including the protection of urban agricultural spaces (Barcelona Regional & AMB-PDU, 2023).

We define lack of local food as a region's ability to meet its residents' food demand, a vulnerability affected by UA's role in increasing and diversifying food production (Langemeyer et al., 2021). To assess this vulnerability, the exposure indicators are (a) diversity of crops, as diversity is linked to improved yield and disease management (He et al., 2019), (b) production of vegetables and (c) fruits in the AMB as a proxy for food supply assessment. The sensitivity indicator is the overall population density, representing areas with higher food demand (for detailed indicator descriptions, justification for its selection and calculations, see Appendix B, Section 1).

4.2.2. Vulnerability to heat

In general, vegetation regulates temperatures during heatwaves (Shao & Kim, 2022) by absorbing solar radiation, enabling transpiration, and providing shade. Regarding UA, irrigation offers daytime cooling through evapotranspiration (Kueppers et al., 2007). Given the future projection of more intense and frequent heat waves at the AMB (del Río et al., 2007), the AMB has recognized the *Vulnerability to heat* as an

Table 1
Vulnerabilities, indicators, average/sum of absolute indicator values before normalization, thresholds and weights from the assessment of urban agriculture in the Metropolitan Area of Barcelona.

Vulnerability	Indicator	Unit	Exposure/ Sensitivity	Average/sum of absolute indicator values before normalization					Threshold value for normalization	Weights for single vulnerability aggregation	Stakeholder weights for combined vulnerability
				S0.	S1.	S2.	S3.	Average/sum			
Vulnerability of lack of local food	Diversity of crops	Index	Exposure	0.018	0.015	0.022	0.036	Average	No threshold value	0.5	48 %
	Production of vegetables in the AMB	Ton	Exposure	39,148	34,369	49,014	64,984	Sum	No exposure ≥ 57,348 Ton of vegetables produced for the whole AMB per year	0.25	
	Production of fruits in the AMB	Ton	Exposure	9284	7767	12,138	23,104	Sum	No exposure ≥ 59,088 Ton of fruit produced for the whole AMB per year	0.25	
	Population density	Hab./Km^2	Sensitivity	5061	N/A	N/A	N/A	Average		1	
Vulnerability to heat	H eatwave day temperatures	°C	Exposure	29.05	29.07	29.04	29.02	Average	No exposure ≤ 32 °C	0.5	14 %
	H eatwave night temperatures	°C	Exposure	24.25	24.27	24.24	24.26	Average	No exposure ≤ 23 °C	0.5	
	Population density	Hab./Km^2	Sensitivity	5061	N/A	N/A	N/A	Average		0.5	
	Elderly population density	Hab./Km^2	Sensitivity	980	N/A	N/A	N/A	Average		0.5	
Vulnerability of lacking recreational space	Areas with accessibility to green spaces at less than 300 m, less than 1000 m and more than 1000m	Km^2	Exposure	54.7	65.1	55.7	53.6	Sum of Km^2 with accessibility to green spaces at more than 1000 m	No exposure ≤ 300 m	1	9 %
									High exposure ≥ 1000 m		
	Population density	Hab./Km^2	Sensitivity	5061	N/A	N/A	N/A	Average		1	
Vulnerability of loss of biodiversity	Phosphorous discharges from fertilizer use	Ton	Exposure	21	19	28	38	Sum	No exposure ≤ 363.43 Ton/ year for the whole region	1	29 %
	Functional diversity	Composed Index	Sensitivity	0.23	N/A	N/A	N/A	Average		0.5	
	Singular biodiversity	Composed Index	Sensitivity	0.35	N/A	N/A	N/A	Average		0.5	

urgent challenge to address (Barcelona Metropolitan Area - AMB, 2018).

To evaluate exposure to heat, we include two indicators: daytime temperatures (13h-16 h) and nighttime temperatures (21 h-7 h), as observed during a heatwave in the AMB (June 20th 2015 - July 25th 2015). Both indicators have been correlated with health problems (Heaviside et al., 2016). Sensitivity indicators are based on (a) overall population density and (b) elderly population density, both employed for assessing population at risk (for detailed indicator descriptions, justification for its selection and calculations, see Appendix B, Section 2).

4.2.3. *Vulnerability of lacking recreational space*

AMB's high compactness and limited green spaces (Baró et al., 2014) lead to a high demand for outdoor recreational areas, a valuable factor for residents' physical and mental well-being (Triguero-Mas et al., 2015). The AMB plans to improve NBS accessibility to fulfil this need (Barcelona Regional & AMB-PDU, 2023). Peri-urban farmland offers a wide range of recreation opportunities (Langemeyer et al., 2021), and can thus address the *Vulnerability of lacking recreational space*.

To assess this vulnerability's exposure, the indicator selected was accessibility to green spaces at less than 300 m, less than 1000 m and more than 1000 m (Grunewald et al., 2017), while the sensitivity indicator consists of overall population density (for detailed indicator descriptions, justification for its selection and calculations, see Appendix B, Section 3).

4.2.4. *Vulnerability of loss of biodiversity*

The AMB's diverse urban environments foster a variety of species, while nearby forests provide a stable habitat for adapted species (Langemeyer & Gómez-Baggethun, 2017). The AMB plans to enhance biodiversity in parks and coastal regions (Barcelona Metropolitan Area - AMB, 2018). Despite its benefits, UA can negatively impact ecosystems if non-organic fertilizers are used (Potter & LeBuhn, 2015). To evaluate the *Vulnerability of loss of biodiversity*, the exposure indicator phosphorous discharges from fertilizer is used as a proxy for potential eutrophication affecting biodiversity conditions (Firbank et al., 2007). The sensitivity indicators include (a) functional biodiversity and (b) singular biodiversity, providing insights into the relationships between biodiversity and ecosystem functioning (Basnou et al., 2020) (for detailed indicator descriptions, justification for its selection and calculations, see

Appendix B, Section 4).

4.3. Normalization of indicators

The third step in the NBS-vulnerability framework is to normalize the exposure and the sensitivity indicators so that they can be compared on the same scale (see Appendix A). All indicators' absolute values were scaled to 0-1 using min-max normalization (see Appendix B, Section 5), where 0 indicates no exposure/sensitivity and 1 indicates the highest exposure/sensitivity.

First, min-max values for the exposure indicators are defined according to threshold values provided by the literature (Inèdit, 2022; Díaz et al., 2015; Royé, 2017; Stigsdotter et al., 2010; Vos et al., 2022; Bauwelinck et al., 2021; Grazuleviciene et al., 2014; Paquet et al., 2013; Reid et al., 2017; European Environmental Agency, 2020). Thresholds representing no exposure are included as minimum values, while those indicating high critical exposure are set as maximum values. For example, the no-exposure threshold for the *Heatwave Day temperatures* indicator is 32 ºC (Díaz et al., 2015) - below this temperature, the exposure to heat is deemed insignificant and consequently, there is no vulnerability. Likewise, the no-exposure threshold for the indicator *Phosphorous discharges from fertilizer use* is 363.43 tonnes/year for the AMB (European Environmental Agency, 2020). Below this value, the exposure is not deemed critical for biodiversity and therefore no *Vulnerability of loss of biodiversity* is given. The thresholds selected for this study are described in Table 1 (for detailed normalization calculations, see Appendix B).

Indicators *Phosphorous discharges from fertilizer use* and production of vegetables/fruits included extra steps in the normalization to provide a more accurate representation of the final value (e.g., production of vegetables was normalized to consider both pixel-level production and overall production in AMB). This is because certain impacts can only be accurately assessed at the AMB level. For instance, the production of vegetables threshold is based on the target amount of locally produced vegetables that AMB residents should consume, while *Heatwave day temperatures* rely on a fixed temperature that may or may not occur in many areas simultaneously.

4.4. Aggregation of indicators for single vulnerabilities

The next step is to aggregate the normalized indicators into a single exposure and a single sensitivity for each vulnerability (see equation in Appendix B, Section 6.1). For this, the relative weights of the indicators were equally distributed (see Table 1). Next, and for each of the vulnerabilities, the single exposure and single sensitivity were aggregated (see equation in Appendix B, Section 6.2). This allowed us to obtain a single vulnerability that effectively summarizes its exposures and sensitivities. Additionally, we have incorporated calculations of the sum of pixel values and their relative change between scenarios for each of the vulnerabilities to depict the magnitude of each vulnerability in the AMB and its behavior across scenarios.

4.5. Stakeholder weighting

Next, stakeholder participation is held to determine the weight of vulnerabilities towards calculating an overall score for each NBS scenario. We held a workshop on November 25th, 2022 (URBAG, 2022) , where stakeholders ranked relevant vulnerabilities for future UA planning in the AMB. Values from the ranking are displayed in Table 1. For details about this dynamic, please see Appendix B, Section 7. For photographs of the workshop, please see Appendix A, Figs. A.2–A.4.

4.6. Aggregation of single vulnerabilities for a combined vulnerability

Based on the weights established by stakeholders, the *single vulnerabilities* calculated in Step 5.4 were aggregated via a weighted sum (see Appendix A). By doing this, we produced a *Combined vulnerability* including all indicators from all vulnerabilities (see equation in Appendix B, Section 8). This final aggregation was repeated using equal weights to understand the robustness of our analysis and whether vulnerabilities were impacted by different weighting schemes. Similar to *Single Vulnerabilities*, the sum of pixel values and their relative change between scenarios were calculated for the *Combined Vulnerability*.

5. Results

Before presenting the results of the assessment, it is pertinent to analyze the stakeholder weighting outcomes, which were used to calculate the *Single Vulnerabilities* into the *Combined Vulnerability values*. The stakeholders ranked the *single vulnerabilities,* from most to least relevant, resulting in: *Vulnerability of lack of local food, Vulnerability of loss of biodiversity, Vulnerability to heat, Vulnerability of lacking recreational space*. The weights are shown in Table 1, where *Vulnerability of lack of local food* was attributed 48 % and *Vulnerability of lacking recreational space* 9 %.

5.1. Combined vulnerability

The spatial distribution of the *Combined Vulnerability* in scenario S0, considering stakeholder weights, is primarily concentrated in the southeast of the AMB (see Fig. 4a), where the Barcelona municipality is located. In this region, we identify pixels exhibiting the highest vulnerability levels, peaking at 0.42 on the scale between 0 and 1 (0 represents no vulnerability and 1 represents the maximum theoretical *Combined vulnerability*, indicating the concentration of all *Single vulnerabilities* at their maximum levels). This region gathers most of the *Vulnerability of lack of local food, Vulnerability to heat* and *Vulnerability of lacking recreational space*, as it concentrates the highest population density in all AMB, making it the most sensitive area for the aforementioned vulnerabilities (see Appendix C, Sections 1.12, 2.11, 3.4). Characterized by extensive built-up areas with limited UA and green spaces (see Fig. 3), the Barcelona municipality experiences higher exposure levels in contrast to more vegetated zones. Similarly, the southwestern AMB also presents vulnerability concentrations, although less pronounced (pixel values reaching 0.31) and less widely spread. Similar to Barcelona municipality, this area maintains consistent population densities; however, it differs in having smaller built-up areas and higher prevalence of UA and green spaces. In contrast, regions lacking sensitivity, such as the eastern parts of the AMB, primarily consisting of UA and other green areas, experience low or no vulnerability.

Examining changes across scenarios, we observe that as UA expands, *Combined vulnerability* decreases. As shown in Table 2, when applying stakeholder weights, S3 - featuring the highest UA coverage - reduces vulnerability by 14.9 % while S2 does so by 6 %. Conversely, S1, with the smallest UA coverage, increases the *Combined vulnerability* by 3.1 %. This trend persists when applying equal weights as a robustness analysis, albeit the changes between scenarios are less significant (S3 decreases by 11 %, S2 by 4.4 % and S1 increases by 2.5 %). This common behavior can primarily be attributed to the reduced *Vulnerability of lacking recreational space* and *Vulnerability of lack of local food*, which outweighs the increases in *Vulnerability to heat* and *Vulnerability of loss of biodiversity* observed for S2 and S3 compared to S0.

From a spatial perspective (see Fig. 4), vulnerability reductions under S3 concentrate in AMB's southeastern and southwestern areas (see Fig. 4d). As previously mentioned, these areas compress higher sensitivities than other AMB sections, making them more susceptible to exposure changes. Thus, decreases in exposure arising from UA expansions in these areas have a more significant impact on its vulnerability (e.g., the highest vulnerability in S3 reaches 0.36). Moreover, the expansion of UA in other sections (e.g., northern areas) also reduces vulnerabilities in these southeastern and southwestern regions. This is related to the *Vulnerability of lack of local food*, as land-use changes at

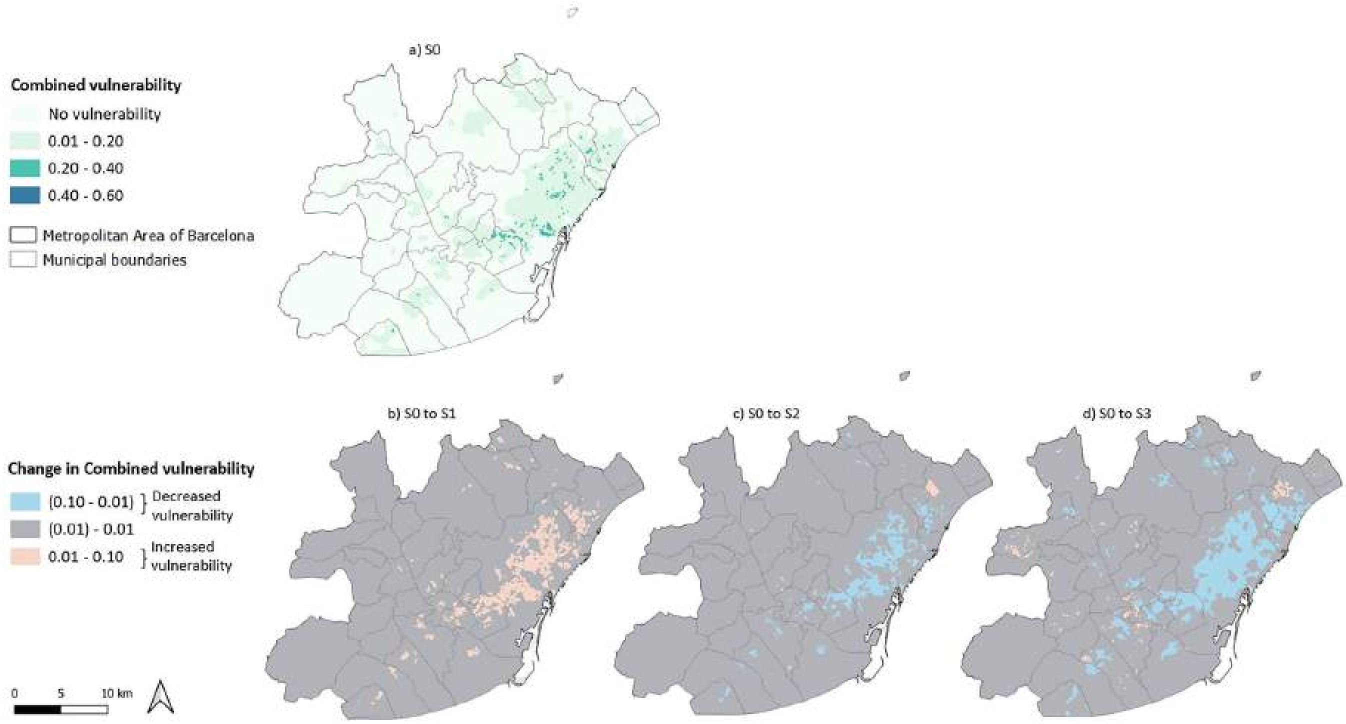

Fig. 4. Spatial distribution of the Combined vulnerability and changes across scenarios with stakeholder's weights. Gray areas represent no vulnerability changes between scenarios.

Table 2
Percentage change (compared to scenario S0) of single vulnerabilities and combined vulnerability under both weighting schemes. Calculation is based on the difference in the sum of pixel values between scenarios.

Combined vulnerability	Evaluation schemes	S1-S0	S2-S0	S3-S0
	Stakeholder weighting	3.1 %	−6.0 %	−14.9 %
	Equal weighting	2.5 %	−4.4 %	−11.0 %
Single vulnerabilities	Vulnerability	S1-S0	S2-S0	S3-S0
	Vulnerability of lack of local food	3.5 %	−7.0 %	−17.6 %
	Vulnerability to heat	1.0 %	0.2 %	0.4 %
	Vulnerability of lacking recreational space	0.5 %	−0.3 %	−2.1 %
	Vulnerability of loss of biodiversity	−19.4 %	67.2 %	210.0 %

both the pixel level and the overall AMB influence its exposure and, consequently, its vulnerability. Yet, S3 also displays increased vulnerabilities, especially in the north-east, west and center-south of the AMB. This can be related to the concentration of *Vulnerability of loss of biodiversity* in these areas, exacerbated by the substitution of other types of green areas by UA and associated phosphorous discharges increasing the exposure level. S2 shows a resembling spatial pattern to S3 but is less pronounced (see Fig. 4c), as fewer UA areas substitute other green spaces. Meanwhile, S1 exhibited the opposite spatial behavior (see Fig. 4b), confirming the link between exposure changes and UA: reductions in UA, both the local and overall AMB levels, led to increased exposure. The spatial distribution of the changes in *Combined vulnerability* under equal weights follows a similar trend to that with stakeholder weights but with a larger proportion of areas remaining unchanged (see Appendix C, Section 5).

5.2. Vulnerability of lack of local food

Vulnerability of lack of local food is the most dominant vulnerability in the AMB under the assumptions of our study (i.e., sum of pixel values; see Appendix D). Its spatial distribution for scenario S0 (see Fig. 5a) concentrates the highest vulnerabilities in the southeastern AMB, where the Barcelona municipality is located. This area experiences the highest sensitivity and exposure in the AMB, resulting in pixel values of 0.79 on a 0–-1 scale. The area's high sensitivity is due to its dense population, while exposure is defined by limited crop diversity and lack of local fruit/vegetable production (see Appendix C, Sections 1.1–1.3) as well as to the overall fruit/vegetable production at the AMB for S0. Similar conditions are observed in small patches in the north-eastern and south-western AMB. From a land-use perspective, these AMB areas are densely built up and lack UA compared with less vulnerable sections. Meanwhile, areas with similar exposure, like the southern AMB (see Appendix C, Section 1.10), do not face *Vulnerability of lack of local food* due to experiencing the lowest population density in the AMB, and thus, exhibit minimal sensitivity (see Appendix C, Section 1.12).

Overall, the *Vulnerability of lack of local food* is reduced by the expansion of UA (see Table 2). In scenarios S2 and S3, where UA is more prevalent compared to S0, vulnerability decreases by 7 % and 17.6 %, respectively. S1, which decreases UA by expanding built-up areas, increases vulnerability by 3.5 %. This same pattern is observed for the exposure indicators (see Table 1). For example, the production of vegetables and fruits in the AMB significantly increases under S3 by 25,836t (65.9 %) and 13,820t (148.8 %) respectively.

When analyzing how these vulnerability changes are distributed across space, we notice concentrations in sensitive areas, including the south-east (Barcelona municipality), north, south-west and center (see Fig. 5b–d). In the AMB center, S1 showed increased vulnerability (see Fig. 5b), primarily linked to heightened exposure resulting from UA losses. Meanwhile, the Barcelona municipality experiences greater sensitivity and comparatively smaller UA reductions, witnessing extensive vulnerability increases. By contrast, S2 and S3 experienced vast vulnerability decreases in the Barcelona municipality (see Fig. 5c, d)

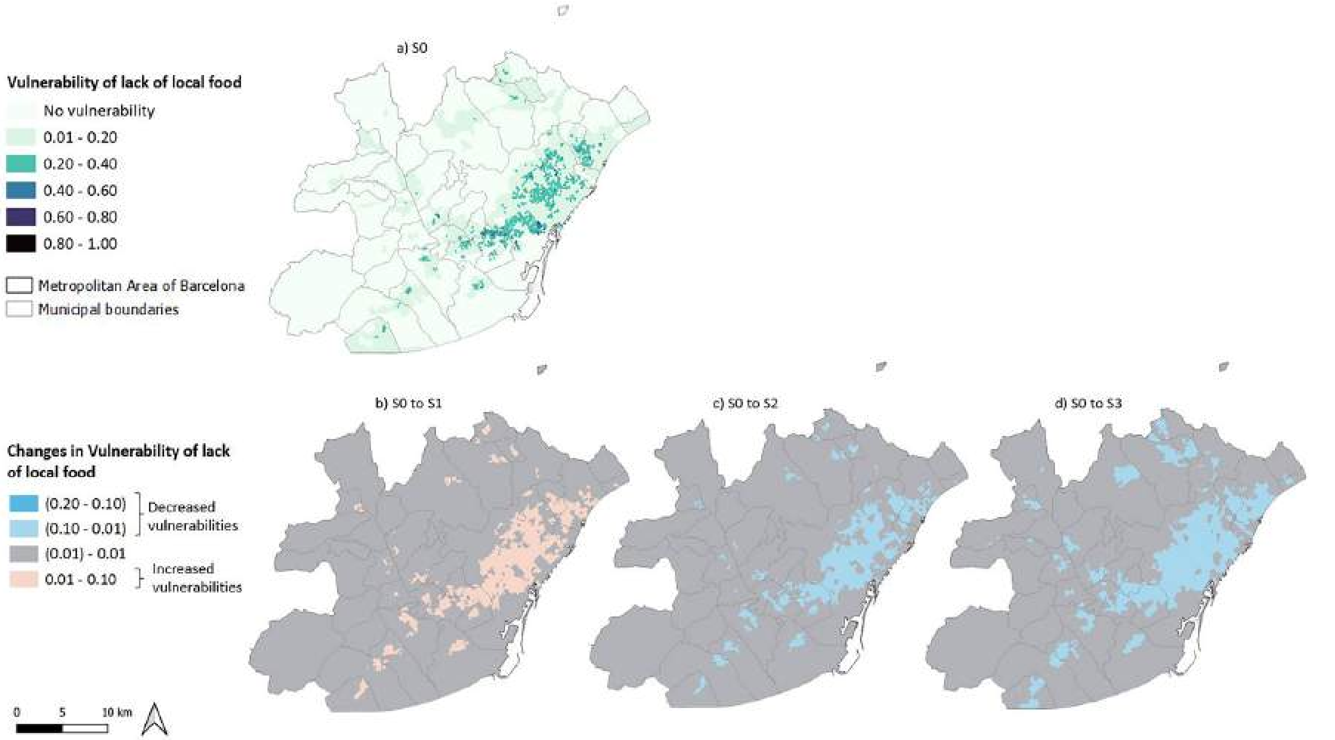

Fig. 5. Spatial distribution of Vulnerability of lack of local food and changes across scenarios. Gray areas represent no vulnerability changes between scenarios.

even with limited increases in UA for this area. Changes in vulnerability within Barcelona municipality are also impacted by UA transformations in other areas which alter the overall exposure of the AMB. A similar trend is observed in the central-north and north-west sections, also sensitive areas, where UA increased minimally or not at all, yet vulnerability decreased for both S2 and S3. Conversely, in areas with lack of sensitivity, such as the western AMB, vulnerabilities remained unchanged despite substantial local and overall exposure changes due to UA expansion (see Appendix C, Section 1.11). Finally, *Vulnerability of lack of local food* can be decreased even when UA locations do not coincide with sensitivity areas, highlighting the significance of UA quantity over its specific location.

5.3. Vulnerability to heat

Vulnerability to heat is the second most pressing vulnerability in the

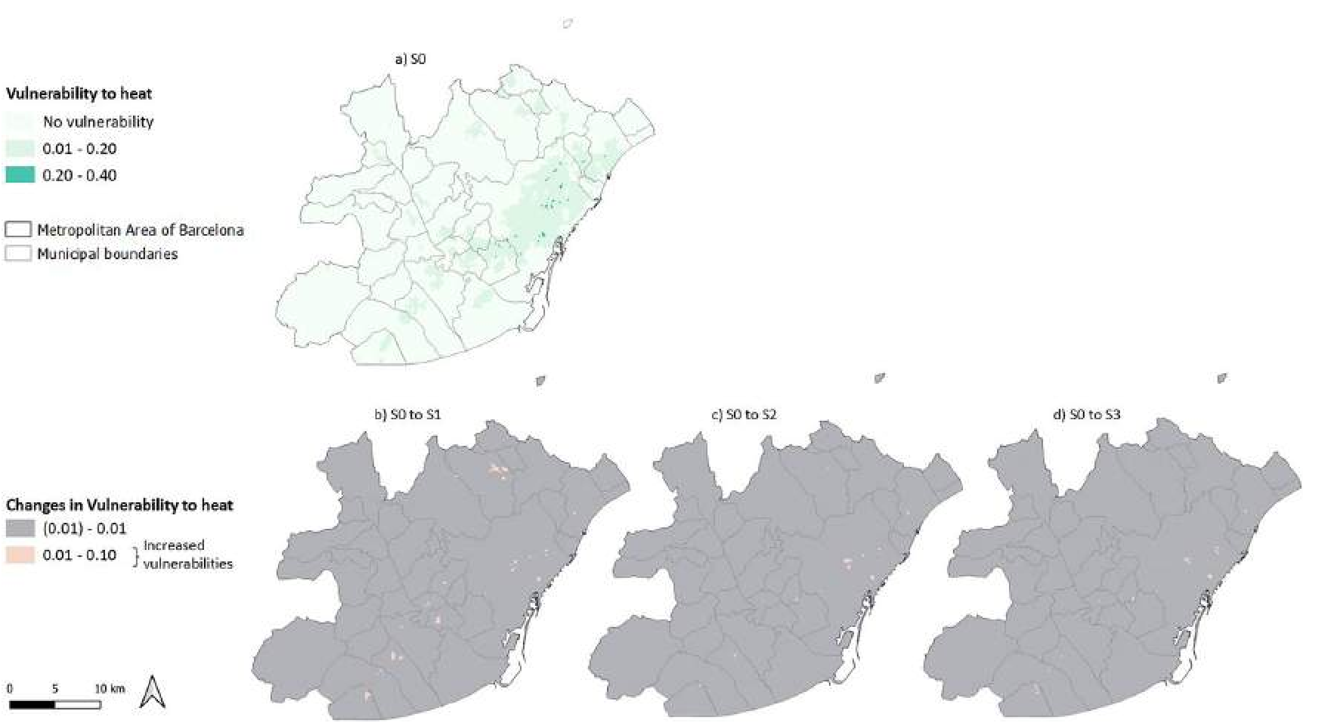

Fig. 6. Spatial distribution of *Vulnerability to heat* and changes across scenarios. Gray areas represent no vulnerability changes between scenarios.

AMB (see Appendix D). For S0, this vulnerability is concentrated in the southeastern AMB (Barcelona municipality) (see Fig. 6a), a region characterized mostly by built-up areas and scarce green spaces compared to other AMB sections. In the southwestern AMB, some vulnerability patches are found, though they are less prominent. This is because exposure values in this area are lower (see Appendix C, Section 2.4), primarily due to fewer built-up areas. The northern AMB, characterized by urban areas and green spaces, experiences the highest exposure levels due to its lower altitude and distance from the sea, which prevents it from accessing cooling sea breezes. Remarkably, due to its lack of sensitive areas, no vulnerability is observed. In contrast, the southeastern AMB, with lower exposure values, exhibits maximum vulnerability (0.31) due to its high population density, particularly among the elderly (see Appendix C, Sections 2.9, 2.10). This area has some of the highest heatwave night temperatures in the AMB, while daytime temperatures are not as extreme (see Appendix C, Sections 2.1 and 2.2). In addition, as most day temperatures stay below their threshold (32 °C), the primary factor affecting overall exposure is elevated nighttime temperatures consistently exceeding their 23 °C threshold (see Table 1).

All potential future scenarios result in increased vulnerability: S1, marked by urban expansion and reduced UA, leads to a higher vulnerability compared to S0 (1 %) (see Table 2). In S3 and S2, where UA expands while other green spaces decrease, vulnerability also increases, but to a lower degree (0.4 % and 0.2 % respectively). Examining spatial shifts across scenarios reveals an overarching trend: reductions in exposure fail to align with sensitivity hotspots within the AMB, resulting in minimal overall changes in the vulnerability across scenarios (cf. Fig. 6b–d). Despite observed temperature reductions in S2 and S3 (e.g., average day temperatures decreased by 0.01 ºC in S2 and 0.03 ºC in S3; see Table 1), their impact on the city's overall vulnerability remained limited, as these temperature reductions did not align with sensitive zones. An example is seen in Fig. 7c, where exposure to heat decreases in the northern area of the AMB for scenario S3 due to the cooling effect of the irrigated agricultural fields. However, there is no sensitive population in that area, thus the expansion of UA does not result in reducing vulnerability.

Another reason S3 does not result in reducing *Vulnerability to heat* as much as might be expected is because the cooling effect of the additional vegetation remains local during the day, while at night the temperature reductions are more widespread throughout the AMB. Thus, night temperatures have a more influential role in shaping exposure than daytime temperatures. This is illustrated in Fig. 7, which captures the differences between S0 and S3 for normalized *heatwave day temperatures, heatwave night temperatures*, and aggregated exposure. While the changes in normalized day temperatures are localized, shifts in normalized night temperatures are more evenly distributed (Fig. 7a, b). Despite both indicators having similar average value variations (-0.03 °C and +0.01 °C respectively; see Table 1), fluctuations in night temperatures are the primary drivers of exposure changes (see Fig. 7c). However, reducing exposure does not reduce vulnerability for the main reason mentioned before in this section: the reductions do not affect sensitive areas. In addition to the location of the sensitive population, the threshold value for exposure also plays an important role in vulnerability. Although reductions in absolute nighttime temperatures did occur, even within built-up areas, these remained below the 23 °C threshold and consequently did not reduce the exposure.

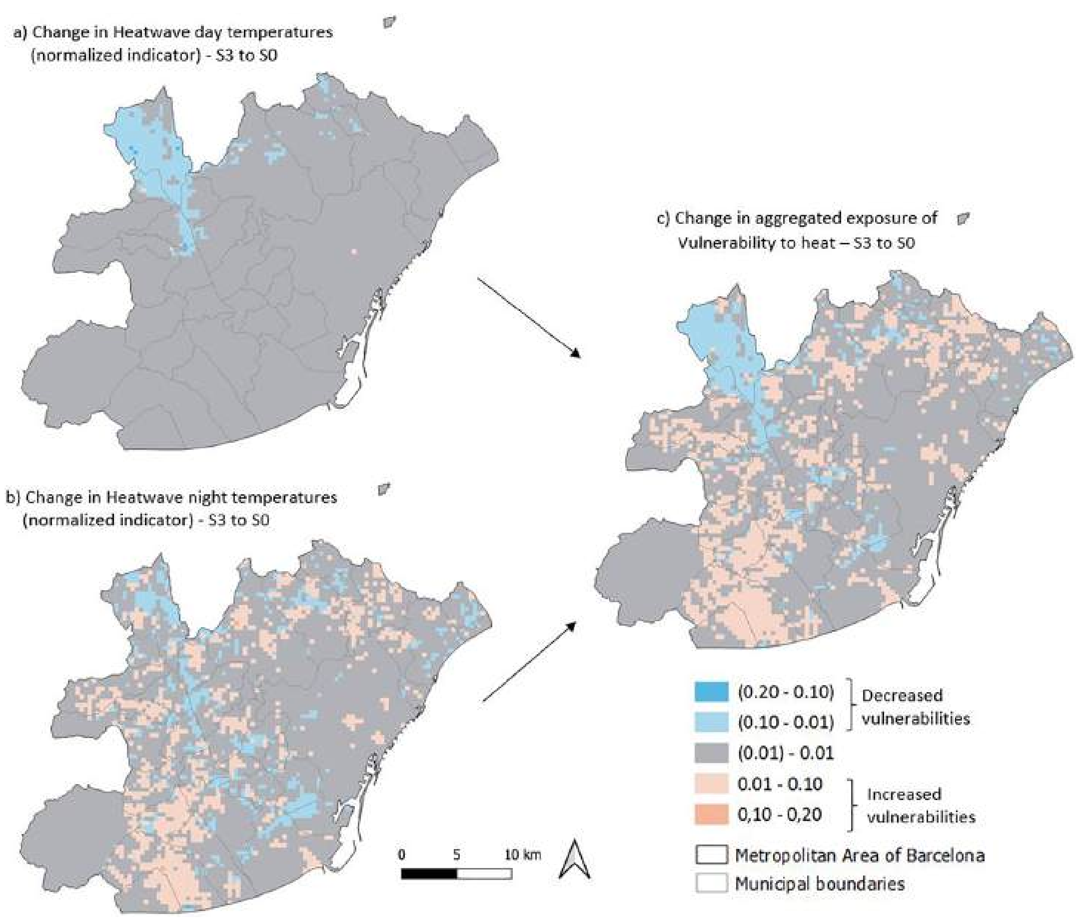

Fig. 7. Spatial distribution of changes between Scenario 3 and Scenario 0 in normalized indicators Heatwave day temperatures and Heatwave night temperatures, and aggregated exposure of *Vulnerability to heat*. Gray areas represent no change in normalized temperatures/exposure.

5.4. Vulnerability of lacking recreational space

Vulnerability of lacking recreational space is the third most prominent vulnerability in the AMB (see Appendix D). In terms of location, vulnerability in S0 is concentrated in the southeastern part of the AMB (see Fig. 8a), where the Barcelona municipality is located. Here, pixel values reach 0.74, due to exceptionally high sensitivity attributed to the dense population and limited green spaces within 300 m (see Appendix C, Sections 3.1, 3.4). This vulnerability pattern owes itself to the significant presence of built-up areas and the limited availability of green spaces in comparison with other areas with lower exposure. Interestingly, the southern parts of the AMB experience higher exposure than the Barcelona municipality but lower population density, preventing this vulnerability.

We find that UA increases correlate with reductions in *Vulnerability of lacking recreational space* (see Table 2). Notably, S2 and S3, experiencing increases in UA, decreased the vulnerability by 0.3 % and 2.1 % respectively. Conversely, S1, which expands built-up areas and decreases UA, increased the vulnerability by 0.5 %. These trends are consistent with exposure values (cf. Table 1), where the total area with green spaces accessible beyond 1000 m shifts from 54.7 km^2 in S0 to 65.1 km^2 in S1 (indicating increased exposure), while S3 shifts to 53.6 km^2 (the most substantial reduction in exposure). However, S2 presents an exception, with an exposure value increase (55.7 km^2 compared to 54.7 km^2 from S0). This illustrates that *Vulnerability of lacking recreational space* can be reduced even when exposure increases.

The spatial changes of *Vulnerability of lacking recreational space* show uneven distribution across the AMB. In S1 (see Fig. 8b), vulnerabilities increased in the Barcelona municipality, the most sensitive area of the AMB. These arise from an increased exposure because of the reduction in accessible green spaces associated with the expansion of built-up areas near the municipality. While spatially limited, these land uses notably affect vulnerability due to the high population density in the area. Interestingly, vulnerabilities within the Barcelona municipality decreased in S2 and S3 (see Fig. 8c, d) due to the strategic replacement of built-up areas with UA, leading to a vulnerability reduction despite an increased overall exposure in S2. Furthermore, the south-center region, another sensitive AMB section, displays less dispersed vulnerability changes across scenarios, attributed to more extensive land-use alterations compared to the Barcelona municipality. In S3, this area's vulnerability diminishes due to reduced exposure produced by a UA expansion replacing built-up areas. However, it is worth noting that not all reductions in built-up spaces that modify green areas lead to vulnerability shifts. For instance, the northern AMB experienced exposure reductions from increased UA in S2 and S3 (see Appendix C, Section 3.3); yet, these changes do not correspond to any sensitive area that would translate into vulnerability changes. Thus, highlighting the significance of NBS locations over their quantity.

5.5. Vulnerability of loss of biodiversity

Vulnerability of loss of biodiversity emerges as the least pronounced vulnerability (see Appendix D). The spatial distribution of this vulnerability in S0 is concentrated in the southwestern AMB (see Fig. 9a), with pixel values reaching 0.02. This area has the highest exposure in the AMB as it concentrates the greatest amount of *Phosphorous discharges from fertilizer use* (see Appendix C, Section 4.1). However, after normalization, this indicator is limited to a pixel value of 0.05, as the overall phosphorous discharge from AMB is far from its threshold value (see Table 1). Regarding sensitivity, this location has a pixel value of 0.6, while the most sensitive areas typically score 0.8 (see Appendix C, Section 4.6). The eastern AMB encounters comparable exposure and sensitivity, resulting in a similar vulnerability, albeit over a smaller area. Meanwhile, the northeastern AMB experiences similar exposure values, but vulnerability does not manifest due to the lack of sensitivity. From a land-use perspective, regions exhibiting vulnerability coincide exclusively with UA areas.

Generally, this vulnerability increases as UA expands (see Table 2): the *Vulnerability of loss of biodiversity* increases by 67.2 % and 210 % for S2 and S3, respectively. Conversely, S1, which reduces UA in the AMB,

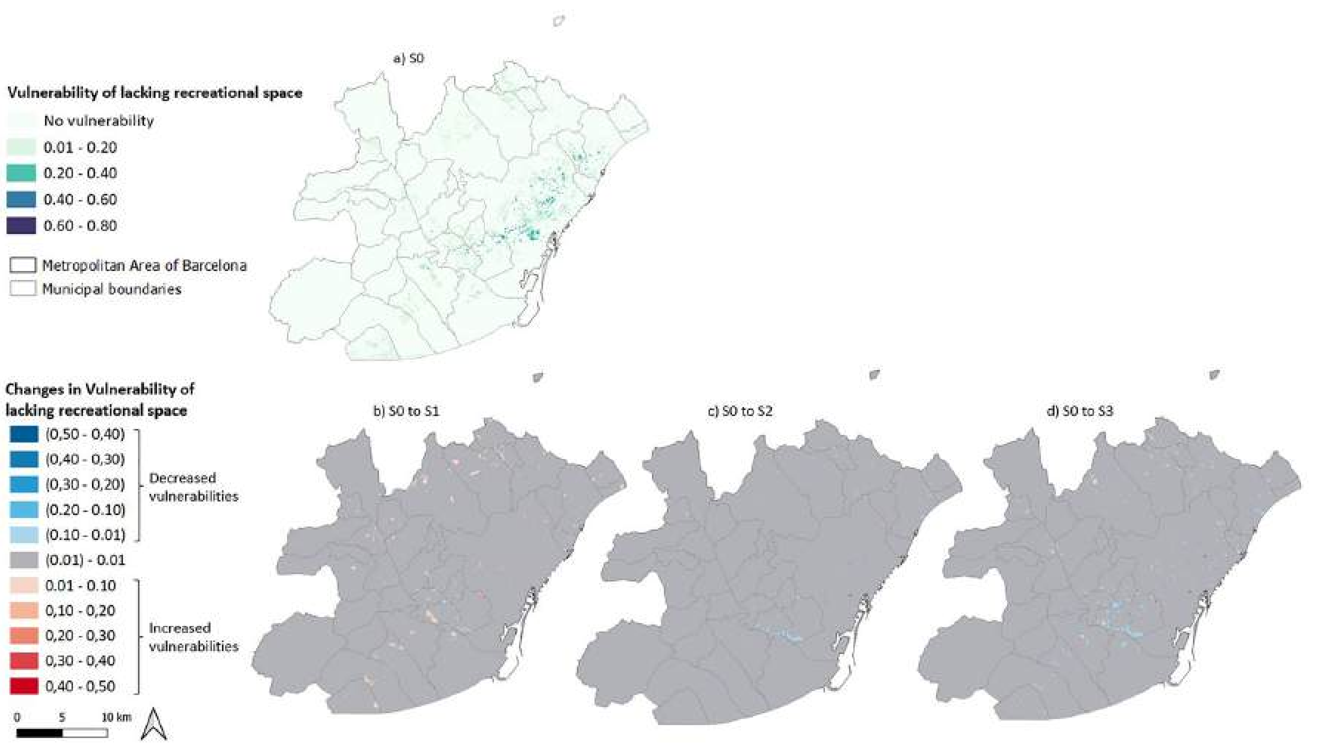

Fig. 8. Spatial distribution of Vulnerability of lacking recreational space and changes across scenarios. Gray areas represent no vulnerability changes between scenarios.

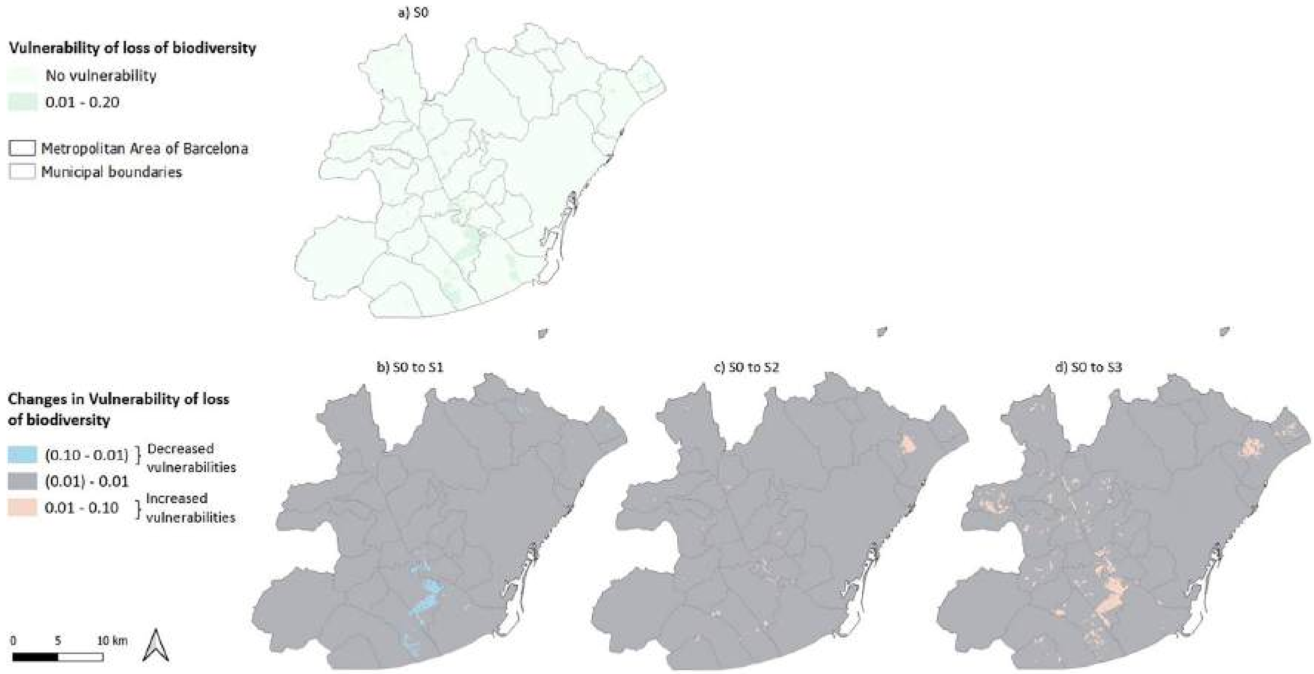

Fig. 9. Spatial distribution of *Vulnerability of loss of biodiversity* and changes across scenarios. Gray areas represent no vulnerability changes between scenarios.

reduces vulnerability by -19.4 %. This trend is also reflected in the exposure value *Phosphorous discharges from fertilizer use* (see Table 1), which escalates from 21 tons in S0 to 38 tonnes in S3. Despite the percentage increases in this vulnerability being larger compared to other vulnerabilities, the actual extent of these changes is limited because exposure values are relatively low when compared to its threshold. This can be appreciated as the biggest exposure value observed is 0.1 in S3 (see Appendix C, Section 4.2).

Even with limited exposure, the vulnerability's spatial distribution was altered. In S1 (see Fig. 9b), vulnerability is primarily reduced in the southern AMB due to an exposure reduction coming from the substitution of UA by built-up areas. Similar changes occur in the northeastern AMB. Conversely, increased vulnerability in S2 is mainly concentrated on the eastern AMB (see Fig. 9c). These changes arise from increased exposures linked to UA substituting other green areas, intersecting with sensitive areas. In S3, a similar land-use dynamic increased vulnerabilities in the central and north-central regions of the AMB (see Fig. 9d).

Yet, not all increases in UA uniformly impact vulnerabilities. In S3, northeastern AMB shifts other green areas to UA, raising its exposure. Similarly, the southeastern area, within the Barcelona municipality, experiences higher exposure as UA expands by diminishing built-up areas. However, as these UA expansions do not align with sensitive zones, vulnerability remains unchanged. This demonstrates that UA expansions can occur without escalating this vulnerability, provided they happen in low-sensitivity areas. The Barcelona municipality exemplifies this, with one of the lowest sensitivities in the AMB. These reduced sensitivities coincide mostly with the built-up areas of the AMB and its surroundings, highlighting an opportunity for UA expansion that does not increase the *Vulnerability of loss of biodiversity*.

6. Discussion

6.1. Land-use changes in the Metropolitan Area of Barcelona shift vulnerabilities unevenly

The NBS-vulnerability framework revealed how various agricultural configurations influenced vulnerability. Generally, UA expansions reduced vulnerabilities (e.g., S2, S3), and UA contractions raised vulnerabilities (e.g., S1). This direct relationship between enhanced UA and decreased vulnerabilities was especially evident for *Vulnerability of lack of local food* which, compared to S0, was reduced by 17.6 % in S3 by an increase in the UA area of 12 %. The opposite was true for *Vulnerability of loss of biodiversity*, as the agriculture expansion caused a 210 % increase due to phosphate discharges into areas with critical biological status. More discrete changes were observed for *Vulnerability to heat* with an increase of 0.4 % in S3, and for *Vulnerability of lacking recreational space*, which decreased by 2.1 % in S3.

Consistent with previous research on the ES socio-spatial distribution (Herreros-Cantis & McPhearson, 2021), the impacts of increased UA are influenced by their locations. Beyond the overall UA expansion, vulnerabilities are shaped by the spatial distribution of these increases. *Vulnerability of lacking recreational space* illustrates this point. In S2, exposure levels exceed those in S0 due to the decreased greenery in the AMB. Despite this, the vulnerability is reduced. This can be attributed to the redistribution of green areas, as specific built-up areas are substituted with UA across sensitive regions. Furthermore, the impact of UA locations is also present in the *Vulnerability of loss of biodiversity,* which significantly increases in S3 compared to S0, despite the rise in exposure due to phosphorous discharges being somewhat smaller. This disproportionate vulnerability surge is linked to the convergence of exposure increases within sensitive areas, which intensifies its impact. *Vulnerability of lack of local food,* however, presents an exception regarding how UA locations change vulnerabilities. As observed in the Barcelona municipality, the most sensitive area of the AMB, significant vulnerability shifts occurred across all scenarios despite experiencing minimal UA changes. These shifts were mostly driven by UA changes in other sections of the AMB. This outcome is attributed to the normalization method of the exposure values of this vulnerability, enabling exposure changes driven by UA shifts to affect sensitivities even when these are not geographically aligned.

Our study also reveals that vulnerability changes are not always as expected, as observed in *Vulnerability to heat*. While the literature agrees on the heat mitigation abilities of NBS (Shao & Kim, 2022), the impacts of the UA scenarios remain inconclusive. *Vulnerability to heat* increased in all scenarios; however, the most substantial increase occurred in S1, the scenario with the smallest amount of UA. Vulnerability increases were less in S2 and S3, where UA is more prevalent than in S0, implying that UA changes alone do not homogeneously impact this vulnerability. From a land-use perspective, the northeastern AMB experienced vulnerability increases in S1 when built-up areas replaced UA and green spaces, and in S2 when UA increased by reducing other green spaces. Similarly, the Barcelona municipality saw increased vulnerability in all scenarios, either when substituting green spaces with built-up areas or UA. These cases indicate that expanding built-up areas and converting green spaces to UA heighten the *Vulnerability to heat* alike. However, this deduction requires careful interpretation, as the dynamics between land-use and temperature are influenced by various factors, including green space types, irrigation practices, wind patterns and building configurations (Segura et al., 2021). Additionally, calculating vulnerability is highly sensitive to the threshold values chosen. This is especially evident with temperature changes: an increase in nighttime temperature above the threshold significantly increased the *Vulnerability to heat*, while daytime temperatures, in general, were less likely to exceed their threshold and had a comparatively smaller effect in reducing vulnerability. Slightly changing these thresholds could change these vulnerability calculations significantly.

In short, land-use changes have differentiated impacts on vulnerability. *Vulnerability of lack of local food* decreases when UA expands in high or low population density areas. For *Vulnerability to heat,* new UA does not reduce the vulnerability, regardless of whether these expansions match or not with sensitive areas. Yet, vulnerability does increase if UA expansions reduce other green spaces within built-up areas. For *Vulnerability of lacking recreational space*, both UA and other green space expansions are more effective at reducing vulnerability in regions with higher population density than in low or uninhabited areas. Finally, for *Vulnerability of loss of biodiversity*, the creation of new UA areas does not increase it when happening within built-up environments. However, the vulnerability does increase when UA expansions happen in less urbanized regions.

6.2. Advancing Nature-based solutions planning through an integrated vulnerability assessment

The complexity around how to distribute NBS effectively has been recognized as a major challenge in urban NBS planning (Langemeyer et al., 2020) and yet, the integration of NBS evaluation with spatial urban planning remains partial (Pan et al., 2021). The proposed framework advances NBS planning on three main aspects: (a) NBS-vulnerability integration, (b) spatially and context-specific impact assessment, and (c) multi-dimensional ex-ante assessment of NBS impacts.

First, we introduce a unique interdisciplinary framework that integrates UM, ES, and spatially explicit vulnerabilities. This approach diverges from previous work by simultaneously considering these dimensions for evaluating NBS. To our knowledge, no interdisciplinary approach of this kind has been developed. Traditionally, researchers have focused on identifying vulnerable areas for NBS implementation (e.g., Baró et al. 2021) or studying the relationship between vulnerable regions and the anticipated ES supply from NBS (e.g., Langemeyer et al. 2020). Other researchers have addressed the relationship between ES demand and supply (e.g., Basnou et al. 2020) or NBS environmental impacts through UM approaches (e.g., Mendoza Beltran et al. 2022). Some studies have related UM impacts to ES or benefits from NBS (Padró et al., 2020). The simultaneous consideration of diverse outlooks has been described as necessary for NBS evaluation (Dumitru et al., 2020) and for the comprehensive assessments of land-use changes regarding urban sustainability policies (Kalantari et al., 2019). Our framework meets these demands by calculating diverse NBS impacts through MCDA, a useful approach for the holistic assessments of NBS (Venter et al., 2021). This streamlines and enhances the overall understanding of NBS effects, improving the NBS planning process.

Second, our framework establishes a coherent spatial integration between the fields of ES, UM and vulnerability. Our case study underscores the importance of this comprehensive approach, revealing different spatial vulnerability patterns, and expanding our understanding of how NBS influence urban contexts. Furthermore, the framework focuses on context-specific objectives to identify local vulnerabilities (e.g., AMB acknowledges *Vulnerability to heat* as a pressing challenge), while also considering local thresholds when calculating exposure values (e.g., excess of heat during nighttime). This approach helps us avoid using standardized measurements detached from the specific context, which can lead to misleading interpretations (Kuhlicke et al., 2011) and ineffective NBS implementations. Moreover, involving stakeholders in weighting vulnerabilities enhances the framework's ability to generate customized outcomes for the local context, enabling the consideration of unique challenges and priorities of the region. This is crucial for minimizing uncertainties about NBS impacts in urban settings (Nesshöver et al., 2017).

Third, the framework aims to aid NBS planning by foreseeing various impacts (intended and unintended) via ex-ante assessments of different NBS scenarios. The ex-ante approach, advised for ensuring NBS effectiveness (Mussinelli et al., 2021), remains a critical knowledge gap in urban planning, especially at the intersection of NBS and vulnerabilities. Our framework addresses this by incorporating the underlying principles of vulnerability assessments, recognizing that systems exposed to hazards manifest multiple dimensions with spatial and temporal variations (IPCC, 2012). Based on this, our framework converges diverse vulnerabilities and projects them through various NBS-driven land-use scenarios, allowing us to foresee potential vulnerability changes.

The proposed framework constitutes an important advancement for NBS planning, offering a spatially and context-specific, ex-ante assessment approach to urban vulnerabilities. Employing vulnerabilities as a shared analytical language to interpret NBS impacts within socio-ecological systems has significant potential to help evaluate trade-offs and reduce uncertainties in NBS implementation in urban environments. Moreover, through collaborative comprehension of the various impacts of NBS on vulnerabilities, the framework allows for strategic planning to enhance urban resilience against hazards (e.g., mitigating *Vulnerability to heat*) and promote sustainability (e.g., addressing the *Vulnerability of loss of biodiversity*). This integrated approach positions the framework as a valuable tool for urban planners and policymakers seeking to promote effective NBS within the urban metropolitan scale.

Considering these advancements, we want to raise some methodological considerations that can enhance the future uptake of our framework.

6.3. Considerations for the future application of the Nature-based solutions vulnerability framework

Our proposed framework innovatively integrates ES and UM into a vulnerability analysis, providing spatially explicit results at different levels of detail (indicators, single vulnerabilities and combined vulnerability). This aspect represents a desirable trait for NBS assessments (Mendoza Beltran et al., 2022) that allows a differentiated understanding of its outcomes. However, the implementation of our framework highlights aspects for future improvement.

First, scenarios cannot fully capture vulnerabilities as systems and populations are not solely affected by nearby hazards. Vulnerabilities can extend beyond local boundaries through cascading effects (Little, 2010), which relates to the extent of ES supply (Metzger et al., 2005) and UM impacts (Kissinger & Stossel, 2021). For instance, *Phosphorous discharges from fertilizer use* associated with the UA expansion within the AMB could cause water eutrophication beyond the region, impacting the *Vulnerability of loss of biodiversity* in such areas. While the NBS-vulnerability framework is limited by its spatial scope, it does allow for the contextualized consideration of vulnerabilities within this area. For instance, the normalization of the indicator *Production of vegetables in the AMB* considered the food production at the pixel level (local scale) and at the overall AMB level (regional scale) enabling the assessment of part of the cascading effects within the urban system. However, delving deeper into these dynamics could improve our understanding of NBS effects on (peri-)urban vulnerabilities.

Second, vulnerabilities cannot be grasped only by quantitative sources (Salter et al., 2010), so stakeholders' involvement is essential to reveal context-specific root causes (Schneiderbauer et al., 2017). Our framework incorporates participatory methods only for the weighting of vulnerabilities. A similar approach could also be applied to the weighting of indicators: instead of assigning equal weights, engaging a stakeholder panel to evaluate their relevance could offer a more robust justification for their significance in the urban context. Nevertheless, Madruga De Brito et al. (2018) suggest broader participatory approaches throughout the entire vulnerability process, not just limited to weighting stages. This would ensure the accuracy of factors like vulnerability selection and data standardization, thus enhancing the feasibility of the selected measures. For our assessment, this aspect gains relevance as the selection of vulnerabilities and weights significantly impacts the results. Consequently, stakeholder input can further enhance the framework's reliability. Taking the UA evaluation as an example, stakeholders in the AMB often highlight water scarcity as a relevant concern (Pratt et al., 2019), which could complement the current assessment. However, assessing water scarcity as a vulnerability is not straightforward as UA is vulnerable to water scarcity while also being a major stressor. Engaging stakeholders in this discussion can help clarify the treatment of these vulnerabilities.

Finally, our assessment supports a better grasp of urban environments' complexity and their relation to NBS by placing greater emphasis on environmental justice considerations. According to Kato-Huerta and Geneletti (2023), a closer link between environmental justice principles and urban planning tools is necessary to enhance the evaluation of areas needing green interventions. The distributive equity approach relies on understanding the spatial location of environmental risks, amenities and social disadvantages. In our case, social disadvantages were not highlighted: social sensitivity indicators were represented by population densities, without considering more sophisticated demographics or the intersectionality in the sensitivity to hazards (i.e., Anguelovski et al., 2020). Furthermore, we did not include adaptative capacity proxies in our assessment. Adaptive capacities can reduce sensitivities (e.g., higher household income can improve sensitivity to heat by the utilization of air conditioning) Ortiz et al. (2022), introducing another level of complexity to the assessment. Moreover, procedural and recognitional justice aspects, centered on diverse social and cultural values and equitable engagement spaces, are crucial for ensuring environmentally just cities and effective NBS (Langemeyer & Connolly, 2020), and yet, they have not been fully integrated into the NBS evaluation frameworks (Kato-Huerta & Geneletti, 2023).

Finally, while the presented framework enhances our comprehension of NBS impacts in urban settings, there is room for enhancing its capabilities. This involves considering broader cascading effects, expanding stakeholder involvement, and further integrating environmental justice considerations. Subsequent research and applications can explore these aspects, bolstering the framework's effectiveness in addressing NBS planning in urban environments.

7. Conclusion

This study aimed to develop a framework for assessing NBS' impact on urban vulnerabilities, advancing beyond the net-impact assessments seen in ES and UM research. The framework employs a stepwise approach based on MCDA to estimate shifts in urban vulnerabilities across diverse land-use scenarios driven by NBS interventions. By bridging ES, UM and spatially explicit vulnerabilities analyses, our assessment broadens the evaluative space for NBS in urban planning.

The application of this framework in the UA case study within the AMB showcased its effectiveness in gaining a differentiated and spatially specific comprehension of NBS impacts. We observed that vulnerabilities exhibited multifaceted outcomes and trade-offs in their spatial distribution when responding to UA changes (e.g., agricultural expansions decreased the vulnerability of lack of local food, even when happening far from sensitive areas, and increased *Vulnerability of loss of biodiversity*, except when confined within built-up areas).

The collaborative nature of our approach is expected to enhance sustainable and resilient practices in urban environments by providing a spatially explicit foresight into potential changes in socio-ecological vulnerabilities associated with NBS implementation. These estimations, characterized by their spatial specificity and alignment with context-specific objectives, foster the strategic planning of NBS at the urban metropolitan scale.

As we explore future applications of the framework for the evaluation of different types of NBS and at different urban scales, we acknowledge potential improvements that need to be considered, such as further cascading vulnerability effects, extending stakeholder involvement beyond weighting stages, and integrating further environmental justice considerations.

CRediT authorship contribution statement

David Camacho-Caballero: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Johannes Langemeyer:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Ricard Segura-Barrero:** Methodology, Formal analysis. **Sergi Ventura:** Visualization, Methodology, Formal analysis. **Angelica Mendoza Beltran:** Methodology, Formal analysis. **Gara Villalba:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

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