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Angaben zur Veröffentlichung / Publication details:

Langemeyer, Johannes, Svea Busse, Agnieszka Arabas, Giulia Benati, Tomasz Bergier, Sara Maestre-Andrés, and Isabel Melo. 2025. "Social-ecological justice in cities: a spatial vulnerability approach." *npj Urban Sustainability* 5 (1): 46. https://doi.org/10.1038/s42949-025-00234-8.

Nutzungsbedingungen / Terms of use:

npj | urban sustainability

Article

Published in partnership with RMIT University

https://doi.org/10.1038/s42949-025-00234-8

Social-ecological justice in cities: a spatial vulnerability approach

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Ecological and social injustices are deeply intertwined, yet their integration into strategic spatial planning is widely lacking. This paper presents a spatial, participatory, multi-criteria approach to assess social-ecological vulnerabilities in the Metropolitan Area of Krakow (MK), Poland. Our approach incorporates co-created insights into urban vulnerabilities, considering social and ecological sensitivities alongside exposure to social and environmental hazards. In collaboration with local planning bodies, the co-creation process identified ten critical vulnerabilities, including to river flooding, to noise pollution, and to drought. A comprehensive data analysis with 47 indicators mapped social and ecological vulnerabilities spatially. This detailed assessment establishes a foundation for a strategic spatial planning in MK, suggesting a paradigm shift towards social-ecological needs-based green space planning and addressing spatially explicit social-ecological vulnerabilities under consideration of diverse preferences.

Global change, including planetary urbanization, climate change, and the mass extinction of species are escalating at an unknown pace, creating novel and enhancing existing vulnerabilities for ecosystems and people[1–3]. Urban areas, which host sensitive ecosystems and most people, are especially vulnerable. Yet, the degree to which people and ecosystems are vulnerable is highly uneven in space[4]—leading to spatial injustices. With healthy ecosystems being understood as the foundation for all species, including humans, to strive[5,6], strategic planning can contribute to enhanced social-ecological justice[7]. Yet, foundational to fostering social-ecological justice in the urban realm is the (spatial) recognition of social-ecological vulnerabilities[8]—ensuring that the needs of the most vulnerable (ecosystems and people) are considered and met[9]. Social-ecological vulnerabilities must be acknowledged in relationship to diverse social and environmental hazards, including for instance the lack of recreational opportunities, decline of biological connectivity, heatwaves, and flooding.

Over the past decade, nature-based solutions (NBS) have rapidly gained popularity[10] in addressing urban vulnerabilities, and now serve as an increasingly applied boundary concept in urban green planning[11]. We argue that the strategic planning of NBS can be a lever for advancing social-ecological justice in cities, as it sets out a new paradigm for sustainability transformations[12,13]. Unlike the maximization of benefits under Pareto-optimal assumptions, common for ecosystem service-informed planning[6,14], NBS planning aims at fostering “actions to protect, conserve, restore, sustainably use and manage […] ecosystems, which address social, economic and environmental challenges[15]. Hence, by definition, NBS planning places stronger emphasis on areas and communities facing the greatest vulnerabilities, thereby creating opportunity for shifting the paradigm of green planning from efficiency and optimization to equitable and just transformations.

To realize the potential of NBS to enhance social-ecological justice, both, social and ecological vulnerabilities and hazards need to be recognized[16–18]. Vulnerability, broadly defined as the susceptibility to harm[19,20], is understood in this context of social-ecological justice as the (spatial) intersection between exposure to social and ecological hazards and the sensitivity of integrated social-ecological systems, and any of its social or ecological components[21]. The exposure then describes the proximity of vulnerable people, structures, and ecosystems to social and ecological hazards, defined as a potential natural or human-induced events that can cause degradation, damage or loss. Sensitivity comprises the degree to which a (potential) hazard adversely impacts human well-being, societal assets, or ecosystems[8,22–24]. For instance, as climate change progresses, droughts are becoming an increasingly important hazard. Exposure to drought varies across spatial locations, for example due to differences in slope and availability of water supply networks. Many ecosystems—such as urban

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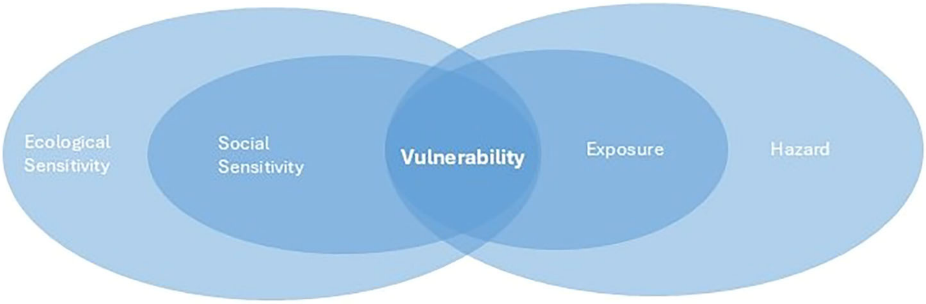

Fig. 1 | Social-ecological vulnerability as the intersection between ecological and social sensitivity and exposure to hazards.

agriculture—are particularly sensitive to drought, which constitutes an ecological sensitivity. This ecological sensitivity may coincide with social vulnerability, such as subsistent reliance on local food production. Where ecological and social vulnerabilities intersect with exposure to drought hazards, social-ecological vulnerability arises (see Fig. 1).

NBS planning—particularly in the urban realm—has so far primarily focused on the mitigation of social vulnerabilities against environmental hazards, particularly those induced by global climate change. This results in an anthropocentric perspective of NBS planning approaches in the consideration of sensitivities[25,26], and an environmental-centric perspective in the consideration of hazards. Current NBS approaches hence often fall short in relying on an integrated social-ecological understanding of vulnerabilities[27]; while overemphasizing environmental hazards such as flooding[28], and wildfires[29] over social hazards such as habitat fragmentation and noise pollution[30,31], they overemphasize human over ecological sensitivity.

Spatial analysis has a long-standing tradition of advancing the principles of justice. Initially pioneered by the field of environmental justice—which addresses the unequal distribution of environmental burdens and benefits among different social groups[32–34]—justice has more recently gained prominence in research on urban ecosystem services[35,36] and NBS[34]. An increasing number of studies now incorporate spatial vulnerability analyses as a means to promote justice in spatial planning[37,38]. For example, Acosta and Haroon[39] mapped vulnerabilities for NBS planning while considering income and health indices. For an integrated understanding and assessment of urban vulnerabilities, multi-criteria decision analysis (MCDA), a technique rooted in operational research, has been advocated for[14].

In addition of the spatial analysis of vulnerabilities, MCDA can facilitate the engagement with local contexts and dynamics, including the involvement of relevant stakeholders, which is a critical premise for enhancing social-ecological justice[17,40–42], from a plural knowledge and plural values perspective[43,44]. For instance, Camacho-Caballero et al.[21] proposed MCDA for the systematic integration of social-ecological vulnerabilities and stakeholder preferences into NBS scenario assessments to reduce limitations related to the replicability and structuring of stakeholder engagement processes.

When complemented by deliberative approaches, MCDA becomes a powerful tool for informing spatial NBS planning—especially when trade-offs between competing priorities are likely to arise[26,44,45], which can be generally assumed for spatial planning aiming for the mitigation of social-ecological vulnerabilities[4,14]. Deliberative approaches help avoiding the oversimplification of complex relationships within social-ecological systems[46] and addressing issues of incommensurability between diverse stakeholder priorities[47], thereby increasing the legitimacy of participatory processes[48,49].

Addressing Metropolia Krakowska (MK) as a case study, we propose a social-ecological vulnerability assessment that integrates deliberative stakeholder engagement approaches towards the promotion spatial planning under social-ecological justice premises. Specifically, we aim to incorporate both exposure to social and environmental hazards, as well as social and ecological sensitivities, and diverse stakeholder preferences into a comprehensive understanding of social-ecological vulnerabilities. Such understanding is meant to uncover spatial inequities and to create the foundation for fostering social-ecological justice through NBS planning.

Results

Spatial distribution of vulnerabilities

The vulnerability assessment conducted in MK addressed 10 social-ecological vulnerabilities that were defined through an iterative prioritization process involving local stakeholders. The assessment relied on rich local data and employed 47 spatial indicators of hazards and sensitivities (see Table 2 for an overview of the indicators) to describe the spatial distribution of single social-ecological vulnerabilities, each shown in Fig. 2 and briefly described in the following. All vulnerability indices range from 0 (low vulnerability) to 1 (high vulnerability), allowing for a continuous interpretation of spatial patterns and comparisons across different indicators. This scale is consistently reflected in the map legends, which display the full gradient of values.

Vulnerability to the lack of recreational opportunities: Most areas have access to green spaces for recreational use within a 1200 m walking distance, and only a few locations lack visual access to blue or green spaces entirely. However, some areas of the MK are more vulnerable to the lack of recreational opportunities. This vulnerability arises where low access (high exposure to the lack of recreational opportunities) coincides with high sensitivities. For example, in the neighborhood of Nowa Huta in the northeast of Krakow, the population density is very high, and the visibility of greenery is much lower than in more rural areas. Conversely, the lowest vulnerability is found around the Niepołomice forest in the east of the MK, where high access to recreational opportunities coincides with low population density and a relatively affluent municipality. Overall, the vulnerability index, build across single indicators measuring the lack of recreational opportunities, shows a mean value of 0.30. Areas with blue and green features can be identified by their lower vulnerability index values, small-scale variations are observable, particularly due to the visibility layers.

Vulnerability to air pollution: The concentration of air pollutants is evident in strongly urbanized areas and along larger roads, such as the E77 crossing the municipality of Mogilany in the South of MK. Around larger green spaces, lower exposure values occur for all three selected pollutants, such as in the Rudniański Landscape Park in Czernichów, the westernmost municipality of the MK. High vulnerability to air pollution is observed especially in the city of Krakow, where high pollution coincides with high population density and, in some areas, a high percentage of elderly population. Air pollution vulnerability has an average value of 0.14 throughout the metropolitan region. Sensitive land uses around healthcare facilities, schools, and playgrounds are clearly visible throughout the study area.

Vulnerability to noise pollution: The vulnerability to noise pollution is concentrated in areas with dense road networks, not only in the city of Krakow but also in smaller municipalities such as Skawina (southeast of MK) and Wieliczka (southwest of Krakow). In Krakow, districts like Nowa Huta and Bieńczyce, as well as areas around Park Krowoderski, are particularly vulnerable to noise. Here, noise emissions from nearby highways intersect with the sensitive green spaces and densely populated areas. Values

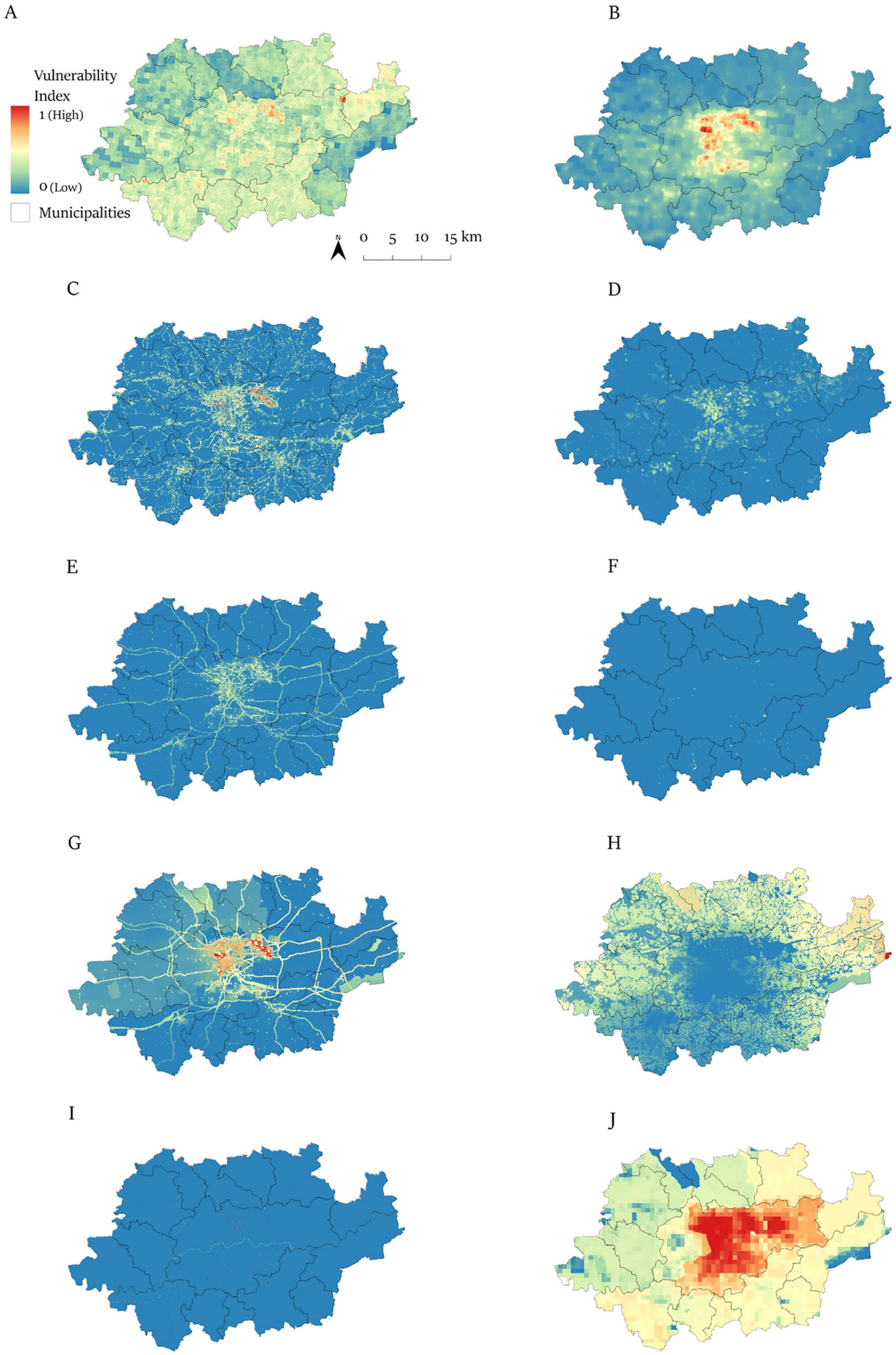

Fig. 2 | Spatial distribution of social-ecological vulnerabilities in Metropolia Krakowska, Poland. **A** Vulnerability to the lack of recreational opportunities; **B** vulnerability to air pollution; **C** vulnerability to noise pollution; **D** vulnerability to heat; **E** vulnerability to river flooding and runoff; **F** vulnerability to landslides; **G** vulnerability to wildfires; **H** vulnerability to drought; **I** vulnerability to habitat fragmentation; **J** vulnerability to biodiversity degradation.

show an average of ~0.047 across the study area, indicating relatively low overall exposure compared to other categories.

Vulnerability to heat: Most of the study area does not experience heat stress (the mean overall heat vulnerability is 0.013); exposure is concentrated in highly urbanized areas, including not only the city center of Krakow but also smaller towns such as Skawina. Here, the occurrence of heat islands overlaps with higher population density and sensitive land use, vulnerability peaks are especially observed around health and care facilities. In the center of Krakow, features that already reduce heat stress, and consequently the vulnerability to heat, are clearly visible, such as the green belt around the old city center and the Vistula River. In addition to urban centers, areas like the airport or industrial zones also have surface temperatures exceeding 30 °C during heatwaves, though sensitivity is lower in these areas, especially because of lower population density.

Vulnerability to river flooding and runoff: Exposure to river flooding and runoff is concentrated around river shores, where there is a risk of fluvial floods, and in areas with a high degree of soil sealing, where significant runoff is generated. Sensitivity is highest in the north of Krakow, where high population density meets many critical infrastructures. This area also yields high vulnerability index scores, finely differentiated by the infiltration capacities of different land uses. The highest vulnerability values are obtained along the river shore of the Vistula and its tributaries, particularly in the center of Krakow. In the surrounding municipalities, major streets and other critical infrastructures explain the higher vulnerability. Across the study area, the mean value is 0.023.

Vulnerability to landslides: The mean landslides vulnerability is 0.00074, suggesting minimal average risk. Landslides are a challenge mainly in the municipalities of Skawina, Mogilany, Świątniki Górne, Wieliczka, and Biskupice, located in the Outer Western Carpathians and the Northern Subcarpathian. Here, geological structure and relief increase the risk of mass movements. In Krakow, areas next to major roads are also affected. Since the MK is relatively densely populated, these exposed areas are all close to either residential areas or critical infrastructure, resulting in significant vulnerability, though the extent varies greatly.

Vulnerability to wildfires: The risk of wildfire, according to the fire weather index, is particularly high in Igołomia-Wawrzeńczyce in the east of the MK. However, since the population density is low in this municipality and there are no areas under nature conservation, vulnerability concentrates around critical infrastructures. High vulnerabilities occur in Krakow, where high population density and critical infrastructures coincide with a relatively high fire risk. In Wielka Wieś and Zielonki, the high ecological importance of the Ojców National Park causes vulnerabilities. The protected habitats in the west of the MK also exhibit lower but still notable vulnerabilities due to their ecological importance. Fire vulnerability presents a mean of 0.087 over the study area.

Vulnerability to drought: Drought vulnerability reaches an average level of 0.206. It reaches it most critical values in less urbanized areas, where agricultural areas and protected habitats are located. Exposure is higher in the northeast due to lower water-retaining capacity of the soil and lower precipitation rates, leading to higher vulnerability in this part. Additionally, the Ojców National Park scores relatively high on the vulnerability index.

Vulnerability to habitat fragmentation: Vulnerability to habitat fragmentation is mapped exclusively for major potential ecological corridors. Large water bodies, such as the Vistula River, act as barriers to pollinator insects, resulting in medium vulnerability values. In urban areas, buildings and major roads, such as the highway connecting the A4 with road 94 at the border of Krakow and Wieliczka, potentially limit ecological connectivity within major corridors. The mean value is 0.0018, indicating extremely low exposure on average.

Vulnerability to biodiversity degradation: The biodiversity intactness index, indicating exposure to biodiversity degradation, has a mean value of 0.51—relatively higher than other categories—and displays a heterogeneous spatial pattern across the MK. While species richness has increased in a few areas, such as the Niepołomice forest, most areas, especially the city of Krakow, exhibit a clear decline in species richness. Large parts of the city are not covered by any form of nature protection, making these areas particularly vulnerable to further biodiversity degradation.

Table 1 | Weighting of the vulnerabilities in Metropolia Krakowska, Poland

Vulnerability	GROUP I	GROUP II	Average
Lack of recreational opportunities	7	6	6.5
Noise pollution	9	10	9.5
Air pollution	14	9	11.5
Heat	7	15	11
River flooding and runoff	20	23	21.5
Landslides	4	3	3.5
Wildfires	5	4	4.5
Droughts	17	8	12.5
Habitat fragmentation	7	9	8
Biodiversity degradation	10	13	11.5
TOTAL	100	100	100

Results of the Pebble Distribution Method determining the relative importance of different criteria.

Spatial distribution of combined social-ecological vulnerability

As a second step of the analysis, we aggregated the single vulnerabilities into a combined social-ecological vulnerability map, under consideration of stakeholder weights. Results of the deliberative group valuation exercise to define weights of different vulnerabilities are shown in Table 1.

As presented above, the spatial distribution of single social-ecological vulnerabilities varies greatly. Nevertheless, some areas score consistently higher across different vulnerabilities, as shown in the combined social-ecological vulnerability map (Fig. 3a). The overall vulnerability ranges from 9.57×10^{-16} to 1.00, with a mean of 0.227. According to the analysis, there is a gradient of social-ecological vulnerability in the MK, with lower values in rural parts and higher values in highly populated urbanized areas where critical infrastructures are also concentrated. The highest vulnerability index scores are found in densely populated areas of Krakow such as Krowodrza, Bieńczyce, and Nowa Huta, where challenges like air pollution, heat, and biodiversity degradation are prominent. Local hotspots can also be identified in the densely populated areas of the cities of Skawina and Wieliczka. While the vulnerability to biodiversity degradation is lower in these areas, other challenges, including noise, are just as prevalent as in the regional capital. Higher scores are also observed along major streets throughout the study area.

When averaged at the municipal scale, Krakow again shows the highest vulnerability with a mean index value of 0.316, followed by the municipalities of Igołomia-Wawrzeńczyce (0.285) and Kocmyrzów-Luborzyca (0.239). While Igołomia-Wawrzeńczyce has a low population density, it has the highest share of the population receiving social assistance. Additionally, the area faces greater vulnerability to drought due to its relatively low soil moisture content and high share of agricultural land. The lowest vulnerability is observed in Zabierzów with a mean of 0.160, followed by Czernichów (0.163) and Wielka Wieś (0.165).

Robustness of the results

A critical assumption underpinning our study is the relevance of population density as a sensitivity analysis. From a social justice perspective this assumption is critical, and when not considering population density but rather population presence (see Fig. 3b, c), the vulnerability index score rises to 1 in its maximum, and a mean of 0.34. Still, the highest values are observed in urbanized areas of Krakow. In this layer, areas close to the Vistula River also score relatively high vulnerability, as the sensitivity to flooding and runoff becomes more homogeneous, and areas prone to flooding and surface runoff impact the overall result to a larger extent. Additionally, the area at the border between Krakow and Igołomia-Wawrzeńczyce gains relative

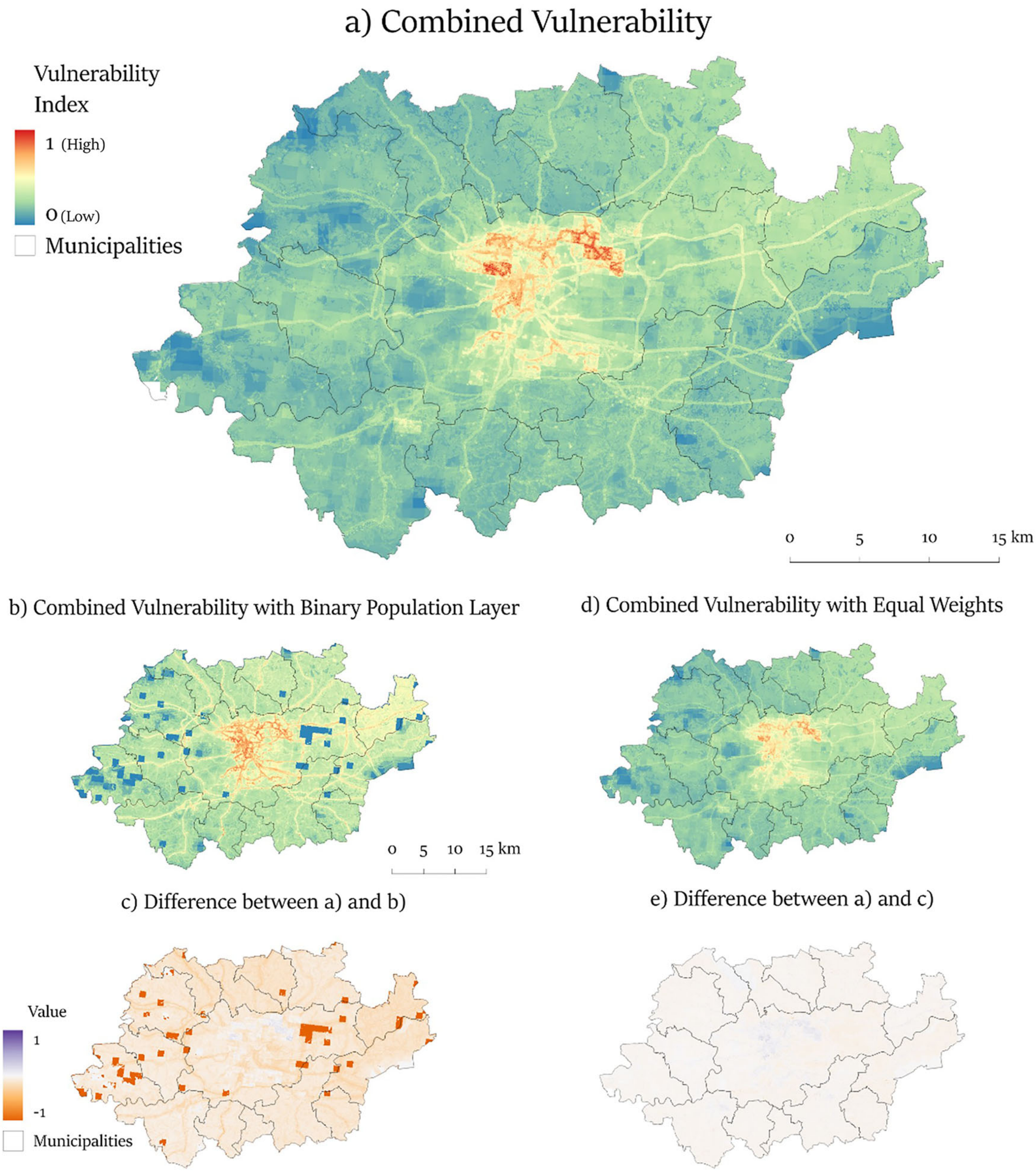

Fig. 3 | Spatial prioritization of social-ecological vulnerabilities and sensitivity analysis. a Combined social-ecological vulnerability under consideration of stakeholder preferences; **b** Combined social-ecological vulnerability with binary population layer; **c** Combined social-ecological vulnerabilities without stakeholder preferences; **d** Difference between map (**a**) and map (**b**); **e** Difference between map (**a**) and map (**d**).

importance in this scenario. Here, no single vulnerability stands out; rather, consistently high values are observed across multiple vulnerability dimensions.

The relative importance of the vulnerabilities determined through the co-creation process also alters the results (see Fig. 3d, e). When weighing all vulnerabilities equally, the overall social-ecological vulnerability index reaches only a maximum score of 0.9. The difference between the combined social-ecological vulnerability under stakeholder weights and under equal weights can again be attributed to the vulnerability to river flooding and runoff, which is considered local stakeholders as the most important vulnerability (see Table 1).

Discussion

Enhancing social-ecological justice in urban environments through NBS requires a radical shift of planning paradigms[13]. This shift involves moving away from seeking net ecosystem services benefits under Pareto-optimal and efficiency conditions towards a novel perspective that focusses on the needs of ecosystems and people[6]. Our study proposes a participatory MCDA approach to enhance the integrated understanding of social-ecological vulnerability under this premise, which aligns with and advances the field of urban vulnerability research[21,27,37,39]. The social-ecological vulnerability approach builds on an understanding of vulnerability driven by the integration of multiple social and environmental hazards and respective exposure indicators, as well as by the differentiated consideration of social and ecological sensitivities that characterize a specific location. The discussion section will first address the relationship between social-ecological vulnerability and spatial-distributional justice; secondly, it will discuss the social-ecological vulnerability approach from a recognition justice perspective[5]; thirdly, it will highlight procedural considerations and critically debate the engagement with and role of stakeholders; finally, we will elaborate on the transferability of our study and highlight future research needs and directions emerging from it.

Spatial justice implications: First, the case study application to MK highlights the capability of participatory MCDA mapping to identify spatially heterogeneous and unequally distributed socio-ecological vulnerabilities, as foundation for spatial and social-ecological justice-driven NBS planning. It thereby adds to previous calls for integrating socio-ecological vulnerabilities into environmental planning[50]. For instance, within each municipality of the MK, local vulnerability areas can be identified, indicating potentially higher needs for NBS interventions. Notably, in the case of MK, most areas with the lowest social-ecological vulnerabilities are in the periphery, while—according to this analysis—the vulnerabilities to be addressed with priority are found in the city of Krakow, particularly in the neighborhoods of Krowodrza, Bieńczyce, and Nowa Huta (*cf.* Fig. 2). By offering detailed maps for individual vulnerabilities, considering sensitivities across social and ecological domains, our approach provides actionable insights for targeted, localized (NBS) interventions and addresses the common critique of overly simplified spatial vulnerability assessments cf. [27,38]. The granular detail of our analysis—driven by our decision to use a fine-scale raster-based approach instead of aggregation at broader administrative units—reveals small-scale variations of specific vulnerabilities at a sub-municipal level, such as those related to the road network in the case of vulnerability to noise pollution.

To further improve the social-ecological vulnerability assessment, future studies are encouraged to develop mapping approaches stronger considering adaptive capacities, which relate to the ability of society and ecosystems to adjust to occurring changes or cope with the effects of a hazard[8,22,23]. Future studies could for instance integrate indicators such as economic status or species composition in forests that would provide deeper insights into coping capacities from a social and ecological perspective[51,52]. However, compared to other vulnerability constituents, the adaptive capacity of social-ecological systems is even more complex and site- and individual-behavior-specific, making it highly challenging to be properly expressed in a spatially explicit way, especially in data-poor study areas. Nevertheless, adaptive capacities can be assumed to (partially) mitigate the vulnerabilities addressed in this study and should thus find stronger consideration in future social-ecological justice research.

Recognition justice implications: Second, the integration of MCDA with deliberative, participatory approaches employed in this vulnerability assessment operationalizes the demand for plural values integration[43], which is foundational from a recognition justice perspective[5,53]. Beyond the assessment of 'objective' vulnerability indicators, our study integrates the localized recognition of needs from a human stakeholder perspective[54]. The MCDA vulnerability approach employed here provides a transparent and replicable integration of both co-creation processes and indicator-based spatial vulnerability assessments—such systematic integration was widely lacking in the NBS and wider spatial planning literature. The combination of objective and subjective information allows for an informed and balanced planning process in a post-normal situation by integrating scientific evidence and stakeholders' needs and preferences alike[21,55].

However, our study shows that the selection of spatial indicators is a critical—and biased choice— building on strong normative assumptions. For instance, the omission of sensitivity of elderly to flooding, or the strong sensitivity to population density—a root indicator in our study—highlights the importance of normative decisions in the selection of indicators that determine the results and eventually the planning outcomes. Furthermore, This simple methodological indicator choice represents a major normative decision and spatial justice consideration: whether to strive for equal conditions everywhere or to adopt an optimizing approach that prioritizes vulnerabilities affecting a larger number of people[6,7]. What is currently lacking is clearer theoretical guidance from a social-ecological justice perspective regarding the kind of knowledge to be integrated to strengthen recognition justice.

Furthermore, there is no satisfying theoretical approach to account for ecological justice from the perspective of recognition justice[56,57]. While social-ecological vulnerability assessments provides an essential practical foundation for the systematic recognition of injustices in the configuration of space and existing social and ecological vulnerabilities, methodologically we are not able to guarantee ecological recognition justice, in the sense of Schlosberg[5], beyond this, while human-animal or human-plant talk proclaimed by some[56], remain futuristic. An entry-point for further enhancing recognition justice from an ecological perspective, comes with recent calls for more systematic and justified integrations of plural knowledge streams[43]. Many studies have proven that by integrating and comparing different local and scientific knowledge sources, it may be possible to develop a more rigorous understanding of ecological injustices, recognizing social and ecological needs more equally[58,59].

Procedural justice considerations: Third, this study has made the effort to engage with relevant stakeholders as early as in the definition of the vulnerabilities MK is facing, whereby a deliberative valuation with diverse stakeholders was considered the best, practical approach. Following this pragmatic approach, in addition to expert stakeholders from different domains, our engagement process focused on elected representatives with a democratic mandate. This allowed us to represent the individual municipalities of the MK and their respective priorities in a context of post-normal decision-making, where stakes are high and decisions urgent[42]. Stakeholder engagement processes are commonly limited by the breadth and depth with which stakeholders can be considered[60]. While far from being socially inclusive and reaching wider local and social representation of different types of stakeholders[61]—particularly in representing minority and marginalized groups in society—our approach prioritized stakeholders that were able to bring an in-depth knowledge and expertise on the challenges faced at the MK and at the municipality scale.

We consider a justified stakeholder selection is at the root of a just process. Very often stakeholders are identified and selected through a non-systematic and subjective assessment of their relative influence, expertise and legitimacy leading to a misrepresentation of stakeholders[9,62]. Being clear about the rationale behind the selection of stakeholders is key. From our study, it can be argued that procedural justice is not only driven by the selection of stakeholders and their interests—something generally well accounted for in the co-creation literature[58]—but also by the very framing of the process cf. [6], and the complex social dynamics applying during different procedural steps. A structured, procedural approach—as implemented in this study through a thorough, stepwise, participatory MCDA framework—enhances the procedural transparency and replicability of the stakeholder process. Standardized methodological approaches, such as the trade-off approach used for the weighting of criteria, cannot fully avoid the challenges in terms of replicability in results stemming from different social dynamics during the application, but they complement the structured approach by providing an informed deliberation of preferences that is replicable as a process. This enhances the legitimization of the study and its results.

Our results show these procedural justice considerations not to be trivial and solely theoretical, as becomes evident when comparing combined social-ecological vulnerabilities with and without stakeholder weights. Stakeholder preferences significantly shape the final NBS prioritization results. Especially when the results are directly taken up by planning, it is critical to question the scientific robustness and replicability of the stakeholder engagement process more thoroughly. For instance, while heat vulnerability showed the lowest maximum vulnerability compared to all other values and had a relatively limited spatial extension, it was still considered one of the five most important criteria from a stakeholder perspective. This calls for a sophisticated justification, representation and engagement strategy. Future research might further disentangle the eventual trade-offs related to representation and engagement. These trade-off are consisting in either fostering a more inclusive stakeholder engagement process from a social perspective[63]—with the risk of an anthropocentric domination—or aspiring a stronger representation of ecological interests. The latter would involve foreseeable biases due to human-represented, ecological interests, and eventual procedural injustices due to lacking inclusivity and social diversity.

While the procedural decisions might be disputed with regard to the theoretical (justice) perspective, from a practical perspective the stakeholder engagement employed in our study might be judged as successful. The active involvement of administrative and planning practitioners facilitated the co-creation process. It also increased the practical utility of this study for the MK, and likely enhanced the uptake of results in the MK strategic planning approach[64]. We observed this strongly in the aftermath of the study, with representatives from municipalities and the MK association recognizing the value of our vulnerability maps in filling a critical gap in current metropolitan assessments and the immediate integration of the study results into the *Climate Strategy of the Krakow Metropolitan Area 2024-2030*.

Transferability and future research

Finally, we want to address the transferability and future research directions emerging from our study. This study has benefited from a rich availability and high accessibility of data in the MK, facilitated by the close collaboration with the MK and municipal administrations. Data accessibility and cooperation with local stakeholders can thus be seen as major facilitators for the social-ecological vulnerability approach, but also as potential barriers for its transferability to other locations and scales, as we have experienced during the replication of this study in the Interurban Ecological Corridor of Maria Aguilar, in Costa Rica. While cooperation with local stakeholders was similarly successful as in the MK, the availability of well-documented data was much poorer, which considerably hampered the implementation of the assessment. Therefore, we assume centralized, findable data with detailed meta-data are still as fundamental for fostering interdisciplinary social-ecological vulnerability assessments and their integration into spatial planning. This is particularly true for ecological data, where our study shows the strongest limitations. Furthermore, the capacity to steer a co-creation process for identifying and weighing the vulnerabilities is fundamental for a legitimized approach, as it shapes the entire stepwise MCDA process.

The transfer to other spatial locations and scales would hence need to depart from the selection of relevant vulnerabilities—operationalized following other studies in the MCDA environment as the evaluation criteria[21]—and the consecutive weighting of these vulnerability criteria. For instance, downscaling an NBS strategy under spatial justice premises in one of the MK's municipalities would require capturing localized stakeholder needs. The social-ecological vulnerability approach can constitute a pragmatic, approach also at local scale, but it does not overcome the dilemma of how to capture ecological preferences, when it comes to the relative weight of vulnerabilities. Furthermore, stakeholder preferences might strongly deviate with regard to the spatial scale being considered[26]. Thus, while the spatial prioritization of NBS interventions based on a differentiated social-ecological vulnerability analysis conducted in this study is a step towards social-ecological justice, it does not automatically ensure just planning outcomes, as preferences and needs for vulnerability mitigation might differ with the fine-grain social composition in each spatial location, while ecological needs might still be undervalued. Future research and planning endeavors that focus on operationalizing social-ecological justice at lower spatial scales might replicate the approved deliberative Pebble-Distribution-Method. They might also explore alternative tools, such as emerging participatory mapping approaches capable of capturing people's preferences in a spatially explicit way[65,66].

Furthermore, the study of social-ecological vulnerability can only be the starting point for informed NBS planning. Additional insights regarding the feasibility of NBS implementation need to be considered. For example, assessing green roof feasibility could link to space availability and institutional arrangements and ownership that influence or hamper implementation[4,67]. Anguelovski and Corbera[68] further call for a rigorous assessment of NBS effectiveness. Along with Langemeyer & Connolly[6], we advocate for assessing NBS effectiveness under social-ecological justice premises, not as net ecosystem service benefits, but against pertinent vulnerabilities. Recent studies indicate that there might be strong trade-offs between ecosystem services provided by NBS and even unwanted effects[69], and that there might be a mismatch in the NBS provision of benefits compared to the priority areas for vulnerability mitigation[21]. Our study suggests that there is an additional temporal dimension to this eventual mismatch between NBS benefits and vulnerability mitigation. For instance, air pollution—one of the most prioritized vulnerabilities in MK—has been shown to be primarily determined by high winter emissions from heating, which strongly mismatches with the vegetation's leafing period and corresponding air pollution mitigation capacities in the region.

Concluding remarks

In conclusion, by considering social and ecological sensitivities towards a wide array of urban hazards, the spatial social-ecological vulnerability assessment presented in this study supports strategic spatial planning from a social-ecological justice perspective. This novel framing can facilitate the targeted use of NBS in structurally diverse urban regions to tackle unequal distributions of vulnerabilities. It aims to enable a mode of urban planning that targets social-ecological spatial justice—primarily considering spatial injustices but also acknowledging recognition and procedural dimensions by adopting an iterative co-creation process throughout the whole study. Despite complementary research needs, stakeholder feedback indicates the general usefulness of the social-ecological vulnerability approach presented here. Our approach contributes to the growing body of spatial assessments and co-created MCDA applications for NBS planning[4,14,21]. Furthermore, by adopting a social-ecological vulnerability lens rather than an ecosystem services approach, this work responds to a major paradigm shifts from conserving and enhancing natural elements for net ecosystem service provision to using ecosystem features to solve defined problems and to reduce social-ecological inequalities[10,15].

Social-ecological vulnerability analyses provide a more appropriate starting point for NBS planning, ensuring that interventions are both equitable and effective in addressing the complex socio-ecological challenges of urban environments. While the identification of social-ecological vulnerabilities alone does not guarantee an equitable distribution of benefits and burdens of NBS, it lays the necessary foundation for subsequent planning steps to reach this objective. Using NBS to address diverse global challenges issues has had a strong anthropocentric connotation, and most previous research and practice—NBS justice research not being an exception—have interpreted NBS through an anthropocentric lens. Instead of vaguely assuming the delivery of co-benefits for ecosystems through the implementation of NBS, our study suggests a to shift focus towards explicitly targeting ecological vulnerabilities alongside social ones in the strategic planning of greening interventions. Humanity has irreversibly altered life on the planet[70]—urban areas only being an extreme case—and human vulnerabilities are embedded within and deeply interwoven with ecological vulnerabilities. Tackling shared social-ecological vulnerabilities simultaneously is the foundation for human and ecological flourishing alike.

Methods

Study area Metropolia Krakowska

The study has been conducted as part of the INTERLACE project (www.interlace-project.eu) and was part of a wider framework development for the evaluation of NBS across planning, design, and implementation phases[71]. The approach presented in this study was developed following an AGILE development approach[72], implemented in the Interurban Ecological Corridor of Maria Aguilar, Costa Rica, and the MK, the metropolitan area surrounding Poland's second-largest city, Krakow. In this study, we will exclusively focus on the application to MK.

MK, located in the southern voivodeship Małopolska (Lesser Poland), embeds the city of Krakow as well as the 14 neighboring municipalities: Biskupice, Czernichów, Igołomia-Wawrzeńczyce, Kocmyrzów-Luborzyca, Liszki, Michałowice, Mogilany, Niepołomice, Skawina, Świątniki Górne, Wieliczka, Wielka Wieś, Zabierzów, and Zielonki (see Fig. 4). MK was formed in 2014 with the goal to tighten cooperation, jointly realize development projects, and work towards a joint spatial planning approach[73]. MK stretches over 1275 km² and lies within the Upper Vistula River basin, with the principal stream of the Vistula River crossing MK from west to east[73].

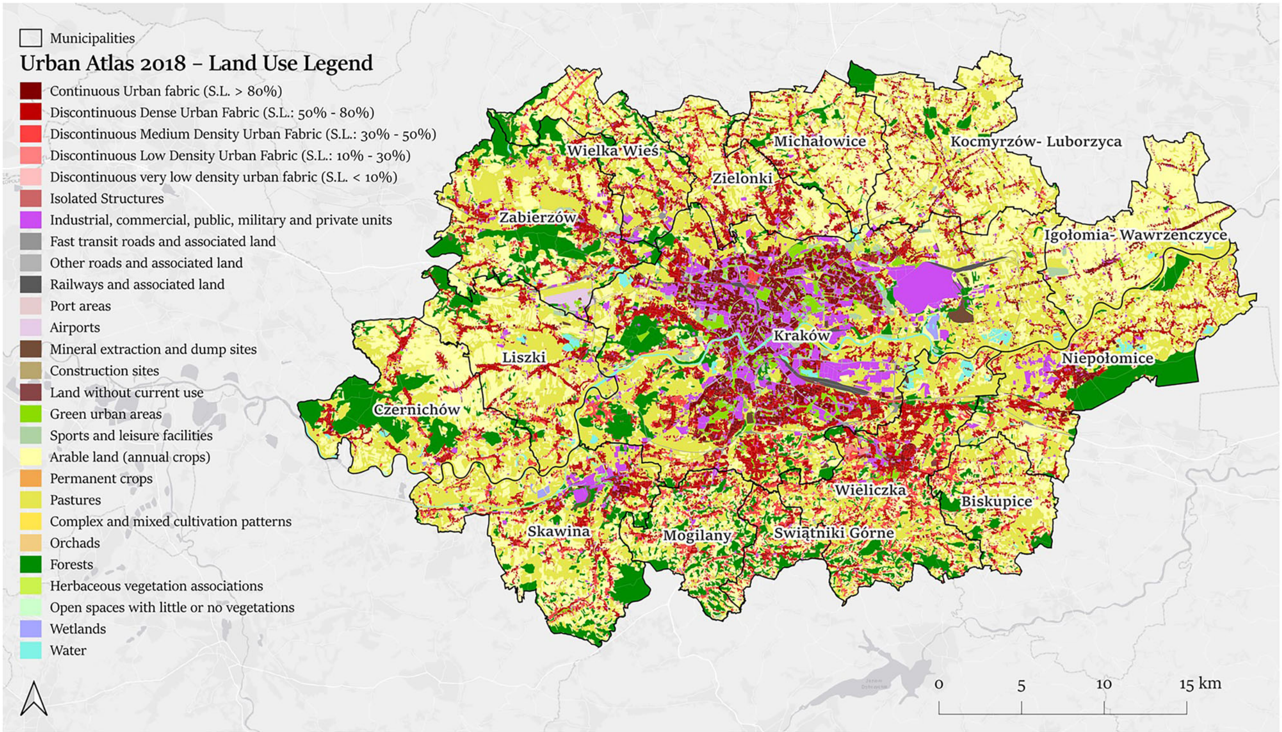

Fig. 4 | Land-cover of the Metropolia Krakowska (MK), with land use and land cover from (Source: Urban Atlas 2018, Copernicus Land Monitoring Service).

As of 2019, MK was inhabited by 1.07 million people, of which ~72% are living in the City of Krakow, where the population density is nine times higher (2384 people/km²) than the region's average (267 people/km²). In the past years, except for the municipality of Igołomia-Wawrzeńczyce, the population increased in all municipalities and this trend is projected to continue in the future mainly due to a positive migration balance[74], additionally fostered through the Russian invasion of Ukraine and related refugee immigration[75]. Within Poland, the MK is a rather affluent area, however, significant income differences exist between the different municipalities. In addition, the region is characterized by a clear aging trend and social inequalities are deepening[74].

NBS have recently gained some relevance across MK, for example in the form of green bus stops or green walls as sound-absorbing screens[76]. While these efforts still lack a coherent planning approach, Olczak et al.[67] previously conducted a spatial analysis to identify priority areas for the implementation of NBS for the city of Krakow. In their study, however, only exposures to hazards were considered, namely heat stress, air, and noise pollution, while different sensitivities representing the needs of society and ecosystems were not reflected. The latter, considering age and income factors of the population, has been more strongly centered in a study examining green space accessibility in the City of Krakow[77]. Yet, both a larger spatial extension of those studies and the consideration of multiple overlapping vulnerabilities are currently lacking.

Following pioneering work in the region, such as the strategic development and management plan for green areas in the City of Krakow[79] or the strategic planning of NBS for ecosystem services provision in Skawina[79], the MK set up the *Krakow Metropolitan Area 2030 Strategy*, in which the municipalities formulate the joint vision of reaching an environmentally friendly and climate-neutral region with a high quality of life[73]. As part of the INTERLACE project, the MK sought to explore the use of NBS to advance toward these goals. More specifically, the MK aimed for a coherent spatial planning approach to NBS that explicitly integrates social-ecological justice concerns into the MK's planning processes. Accordingly, the approach outlined in the following has been used by MK in order to inform both the *Climate Strategy of the Krakow Metropolitan Area 2024–2030* and the *Action Plan for Cooperation in the Field of Spatial Management*.

Spatial social-ecological vulnerability assessment

The spatial vulnerability assessment framework developed in this study employed participatory MCDA as an approved approach to dissecting complex decision problems[47,80], drawing inspiration from previous research such as Langemeyer et al.[4] and Camacho-Caballero et al.[21]. [21]Here, a social-ecological vulnerabilities approach is employed to identify spatial inequities and create the foundation for planning for social-ecological justice through NBS. Building on the growing body of index-based spatial vulnerability assessments, including Raška et al.[37], Kok et al.[38], and Thiault et al.[8], the MCDA process unfolded in five distinct yet interconnected sequential steps: (1) Selection of criteria (i.e., the selection of locally relevant vulnerabilities), (2) Establishing spatial indicators, (3) Mapping vulnerabilities, (4) Weighting of vulnerabilities, and the final integration through a (5) Spatial prioritization map (Fig. 5).

As a preparatory step towards this sequence, the overarching planning objectives are defined to determine the scale and scope in which the analysis takes place. Furthermore, the assessment builds on a stakeholder identification and engagement process involving local government representatives, environmental NGOs, urban planners, and academia[71]. Adopting co-creation practices in NBS research and planning is already widely established. However, stakeholder engagement often comes into play in a late stage of the NBS planning cycle, for instance, in the weighting of criteria or selection of NBS design alternatives when most decisions have already been taken[22,73]. Including relevant stakeholders from the start of the process is expected to increase the chances for effective impact[64]. Consequently, the research design of this study was set up in close collaboration with the administration of MK and supported by the Polish Sendzimir Foundation, functioning as a knowledge broker between science and practitioners, to ensure that the study would be feasible, well embedded in the local context, and provide valuable and usable knowledge.

Selection of criteria

An iterative participatory process was used to identify the vulnerabilities that local stakeholders consider as affecting social-ecological well-being the most. An initial list of relevant vulnerabilities in the MK was obtained in a first stakeholder discussion held in March 2021. The group of stakeholders in this workshop comprised representatives of the participating municipalities, the MK office, the Lesser Poland Marshall's office, the state forest service and Ojców National Park, the State Water Holding "Polish Waters", as well as researchers. Based on the *Krakow Metropolitan Area 2030 Strategy*[73] and a literature review, this initial list of vulnerabilities was expanded. The new proposal was presented to the stakeholders in a first online workshop held in spring 2022. The 14 participants (Table 2) were asked about the relevance of the selected vulnerabilities and had the possibility to add additional vulnerability aspects not previously covered. The following sections describe the vulnerabilities that were identified as most relevant by the stakeholders to negatively impact social and ecological well-being in the region.

Vulnerability to the lack of recreational opportunities: Compared to the rest of the country, citizens of southern Poland are less satisfied with the quality of green areas in their neighborhood, although the majority are pleased with the current offer[81]. Especially the city of Krakow has put efforts into increasing greenery in the urban landscape[78]. Still, a lack of coherent protection and management leads to unattractive green spaces and some areas of the MK lack access to recreational green spaces[73].

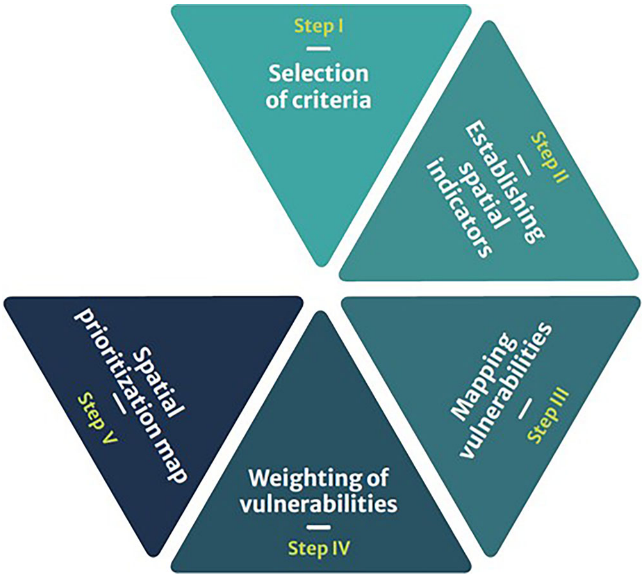

Fig. 5 | Spatial vulnerability assessment for the prioritization of Nature-Based Solution.

Vulnerability to air pollution: In Poland, citizens consider air pollution one of the most pressing environmental problems[82]. Emissions in the MK are high due to the combustion of solid fuels for heating, industrial, and traffic-related pollution[83,84]. The Vistula valley's location exacerbates the issue by slowing pollutant dispersion[67]. This poses significant health risks to people, including cardiovascular and respiratory diseases[86,87].

Vulnerability to noise pollution: In Europe, 113 million people are affected by traffic noise above 55 dB, and 22 million are exposed to railway noise[88]. The *Krakow Metropolitan Area 2030 Strategy*[73] highlights noise stress along railway lines and highways[85]. Noise pollution poses health risks, leading to cardiovascular conditions and decreased attention in children[89,90]. Reducing noise is crucial for health and well-being of humans and animals.

Vulnerability to heat: Due to climate change, a warming trend is already visible in Krakow, and the number of hot days with a temperature above 30°C is projected to increase further[91]. The formation of urban heat islands and a lack of ventilation aggravate the vulnerability in the study areas[85]. A wide body of literature has proven the adverse effects of heat stress on human health, leading to an increase in respiratory, cardiovascular, and all-cause mortality[92–94].

Vulnerability to river flooding and runoff: River flooding from the Vistula and its tributaries is a recurring phenomenon in the MK area[95]. Additionally, surface runoff from heavy precipitation events, which can lead to sewage overflows, poses significant challenges[85]. Climate change is projected to increase the frequency and intensity of river flooding and heavy precipitation events globally and in the MK area[96,97].

Vulnerability to landslides: Landslides and hillside erosion occur predominantly in the south of the MK, mainly due to the geological structure of the Carpathian Flysch Belt and heavy, prolonged precipitation[85,98]. Landslides often arise as secondary or cascading threats[99]. Constructions around foothills and the expansion of the road network also trigger mass movement in the region[98].

Vulnerability to wildfires: Poland experiences more wildfires than the European average, and about 80% of its forest cover is threatened by fire[100]. The formation of wildfires is influenced by weather patterns, land-use, fuel management, and heat sources[101]. While heat sources can be of natural origin, e.g., through lightning, most fires nowadays are caused by human interference[101]. With climate change altering weather patterns, the frequency of wildfires is projected to increase[70]. Fires pose a direct threat to life,

Table 2 | Participants of workshop 1, conducted 09-02-2022, for the selection of criteria

Participant	Institution	Professional background	
1	Liszki Municipality	Urban planner	Workshop 1 (09-02-2022)
2	Marshal Office	Urban planner, sustainable development	
3	Metropolia Krakowska	Air quality, greenhouse gas emissions, energy efficiency, renewable energy	
4	Metropolia Krakowska	spatial planner, metropolitan areas, sustainable development	
5	Metropolia Krakowska	Smart management, sustainable development, EU funds	
6	Metropolia Krakowska	Smart management, sustainable development, EU funds	
7	Municipal Unit Climate-Energy-Water Management, Krakow City Hall	Climate adaptation, sustainable development, water and greenery management, EU funds	
8	Myślenice Forest District	Forest engineering, forest management, biodiversity	
9	Skawina Municipality	Urban planner	
10	Skawina Municipality	Urban planner	
11	Skawina Municipality	Water and greenery management, biodiversity	
12	The Sendzimir Foundation	Urbanist, social dimensions of spatial planning, place making	
13	The Sendzimir Foundation; AGH University of Kraków	Environmental and ecological engineer; NBS, sustainable water management, phyto-remediation and -retention	
14	Uniwersytet Ekonomiczny w Krakowie	Water management, blue-green infrastructure, sustainable development, environmental management, social economy	

Table 3 | Exposure and sensitivity indicators to spatially assess vulnerabilities in Metropolia Krakowska, Poland

Vulnerability Criteria	Exposure Indicators, Relative Importance (RI)	Sensitivity Indicators, Relative Importance (RI)
Vulnerability to lack of recreational opportunities	Physical access to green spaces above 0.5 ha[77,115,116], RI: 20%	Percentage of population under the age of 14[117,118], RI: 33.33%
	Physical access to green spaces below 0.5 ha[77,115,116], RI: 20%	Percentage of population receiving social assistance[119], RI: 16.67%
	Visual access to green spaces[120–122], RI: 20%	Percentage of unemployed population in working age[77], RI: 16.67%
	Visual access to blue spaces[120–122], RI: 20%	Population density[77], RI: 33.33%
	Distance to non-green recreational facilities[123], RI: 20%	
Vulnerability to Air pollution	Average concentration of PM10[124,125], RI: 33.33%	Percentage of population above 65 years, RI: 12.50%
	Average concentration of PM2.5[124,125], RI: 33.33%	Distance to health and care facilities[126,127], RI: 12.50%
	Average concentration of NO2[124,125], RI: 33.33%	Percentage of population below the age of 14[87,128,129], RI: 12.50%
		Distance to elementary schools[130,131], RI: 6.25%
		Distance to playgrounds[130,131], RI: 6.25%
		Percentage of population receiving social assistance[132,133], RI: 12.50%
		Percentage of unemployed population in the working age[132,133], RI: 12.50%
		Population density, RI: 12.50%
Vulnerability to Noise pollution	Traffic noise level above 50 dB[88], RI: 100%	Land use sensitivity based on Polish legislation[134], RI: 50%
		Population density[135], RI: 50%
Vulnerability to Heat	Heat island intensity[67,136], RI: 100%	Percentage of population above 65 years[92,93], RI: 16.67%
		Distance to health and care facilities[137], RI: 16.67%
		Percentage of population receiving social assistance[138], RI: 16.67%
		Percentage of unemployed population in working age, RI: 16.67%
		Population density, RI: 33.33%
Vulnerability to River flooding and runoff	Official flood risk maps, RI: 50%	Density of critical infrastructures[139,140], RI: 50%
	Simple runoff coefficient[4,141], RI: 50%	Population density, RI: 50%
Vulnerability to Landslides	Landslide risk by Małopolska Landslide Protection System datasets, RI: 100%	Density of critical infrastructures[99,142], RI: 50%
		Population density, RI: 50%
Vulnerability to wildfires	Fire weather index[143,144], RI: 100%	Density of critical infrastructures[99], RI: 33.33%
		Population density, RI: 33.33%
		Ecosystems with high conservation value[103,145], RI: 33.33%
Vulnerability to drought	Soil moisture content[143,146], RI: 100%	Areas under nature conservation[104,145], RI: 50%
		Areas of agricultural production[147], RI: 50%
Vulnerability to habitat fragmentation	Functional connectivity for pollinators[109,148], RI: 100%	Major ecological corridors[149], RI: 100%
Vulnerability to biodiversity degradation	Biodiversity intactness indicator[150,151], RI: 100%	Areas under nature conservation differentiated by strictness[152–154], RI: 100%

Moreover, a comprehensive overview of data sources and scale for each indicator is provided in Table 5. Datasets and methods follow the FAIR principles[155] and detailed processing steps are available in our Mapping Protocol (https://zenodo.org/records/14624072).

reduce well-being and health by creating psychological stress, and lead to damage and loss of property and infrastructure[102]. They further adversely affect the environment by disturbing ecosystems[103].

Vulnerability to drought: Droughts are another challenge in the MK, though more prominent in other parts of Poland[98]. In 2020, Krakow signed a declaration on drought cooperation, indicating awareness of the issue[85]. While, until now, no significant increase in droughts has been observed in Poland, the frequency of hydrological extremes is expected to rise due to climate change[70]. Droughts pose stresses onto ecosystem health and functioning, making plants more vulnerable to pests and disease[104]. This in turn, can also threaten food security by reducing crop yields[105].

Vulnerability to habitat fragmentation: Habitat fragmentation combines habitat loss and the breaking apart of habitats at a landscape scale, adversely impacting individual species, biodiversity and ecosystem functioning[106]. This, in turn, also affects the delivery of ecosystem services to humans[107]. In urban areas, connectivity of green spaces is crucial for pollination, with urban landscapes potentially serving as refuges for pollinator communities[108,109]. While green spaces in the MK are increasing, habitats remain fragmented, lacking ecological corridors for species movement due to a lack of coherent planning[85].

Vulnerability to biodiversity degradation: Human actions, including land-use changes, exploitation of organisms, climate change, pollution, and the spread of invasive species, lead to biodiversity declining worldwide[2].

Table 4 | Participants of workshop 2, conducted 09-11-2023, for the criteria weighting

Participant	Institution	Professional background	
1	Świątniki Górne Municipality	Environmental protection, sustainable development, water management	Workshop 2 (09-11-2023)
2	Zielonki Municipality	Air quality, environmental protection	
3	Krakow City Hall	Sustainable development	
4	Niepołomice Municipality	Blue-green infrastructure, water and greenery management, biodiversity, sustainable development	
5	Zabierzów Municipality	Environmental protection	
6	Liszki Municipality	Environmental protection	
7	Zabierzów Municipality	Urban planner, sustainable development	
8	Krakow Municipal Greenery Management	Blue-green infrastructure, water and greenery management, biodiversity	
9	Igołomia-Wawrzeńczyce Municipality	Environmental protection	
10	Skawina Municipality	Environmental protection, circular economy	
11	Metropolia Krakowska	Sustainable development	
12	Metropolia Krakowska	Sustainable development, blue-green infrastructure, water and greenery management, biodiversity	
13	The Sendzimir Foundation; AGH University of Kraków	Environmental and ecological engineer; NBS, sustainable water management, phyto-remediation and -retention	

Around 25% of all species are threatened, with about 1 million facing extinction within decades if current trends are not reversed[2]. The loss of biodiversity significantly alters ecosystem health and functioning and in turn the provision of ecosystem services[110]. In the Małopolska voivodeship, preserving biodiversity is a main goal for the Spatial Development Plan[111]. While the area of green spaces in the MK has increased in recent years[85], the area under protection is stagnating[98].

Establishing spatial indicators

Once the vulnerability criteria were selected, exposures and sensitivities were represented through spatial indicators. The selection of indicators followed the logic to represent vulnerabilities considering social and ecological sensitivities against social and environmental hazards. While some of the hazards, such as "lack of recreational opportunities" are understood as primarily affecting social sensitivities, others including "habitat fragmentation" are primarily affecting ecological sensitivities. A third category of hazards, including drought and wildfires, are affecting both social and ecological sensitivities.

The indicators were selected based on a review of the literature and complemented through detailed discussions with a subset of stakeholders, including scientific representatives, members of the Sendzimir Foundation, and representatives of the MK office. These stakeholders possess extensive knowledge on the local vulnerabilities as well as data availability, ensuring that the chosen indicators accurately represented exposures and sensitivities, and that spatially explicit datasets were both available and applicable. This integration ensured that the vulnerability assessments were place-specific and grounded in reliable, accessible local data, while being strongly embedded in the respective scientific literature. Table 3 shows the spatial exposure and sensitivity indicators employed to assess a diversity of vulnerabilities in MK.

Some limitations were given regarding the data availability and accessibility, which affect the robustness of the indicator-based vulnerability assessment. For example, project-driven time constraints limited the refinement and addition of individual indicators; some datasets, like Krakow's noise map and finer-scale socio-demographic data, were unavailable or inaccessible in the context of this study. The calculation of functional connectivity for pollinators using Circuitscape and Linkage Mapper was hindered by limited computing capacities, indicating room for improvement in habitat fragmentation vulnerability assessments in the future. Additionally, flow-based modeling could enhance runoff exposure results, and long-term analyses could improve drought and fire risk indicators.

Vulnerability mapping

To determine the spatial distribution of vulnerabilities, the selected indicators were individually mapped using ArcMap 10.8, ArcGIS Pro, and QGIS 3.16 Hannover. After the initial preparations, all vector data were converted into raster format to integrate different resolutions, as realized in Langemeyer et al.[4]. A cell size of 10 × 10 m was chosen as a compromise between accuracy and computing capacity. Raster data with coarser resolutions were resampled. Finally, all indicators were scaled from 0-1 to integrate different scales and units, using the following equation, where 0 corresponds to low vulnerability and 1 to high vulnerability.:

$$Xi\ scaled = \frac{Xi - Xmin}{Xmax - Xmin} \qquad (1)$$

where $Xi\ scaled$ is the rescaled value of the indicator X at cell i, $X\ min$ is the minimum and $X\ max$ is the maximum value of the indicator X within the study area.

For each vulnerability criterion, an exposure map and a sensitivity map were generated averaging the respective indicators, thus assigning them equal relative importance. Some indicators were composed of sub-indicators, which in turn were also given equal weights. Table 2 displays all indicators and sub-indicators with their resulting relative importance for the

Table 5 | Overview of data sources and resolution for each indicator

Vulnerability	Indicator	Data Source	Resolution
Lack of recreational opportunities	Physical access to green spaces <0.5 ha (Walking distance)	- OSM - BDOT land-use data - Strategy MK 2030 Spatial Model	Shapefiles (polygons, lines) → 10 m raster
	Physical access to green spaces >0.5 ha (Walking distance)	- Same datasets as above (OSM, BDOT, Strategy MK 2030)	Shapefiles (polygons, lines) → 10 m raster
	Visibility of green (NDVI-based)	- Sentinel-2 imagery (NDVI) - DSM from geoportal.gov.pl (0.5–1 m resampled to 10 m)	Raster at 10 m resolution
	Visibility of blue	- BDOT "PTWP" (water bodies)	Raster at 10 m resolution
	Distance to non-green recreation	- OSM (POI)	Shapefiles (points, lines) → 10 m raster
	% population <14 years	- Polish Statistical Office, 2011	1 km^2 → 10 m raster
	% population receiving social assistance	- Polish Statistical Office (Local Data Bank), 2021	1 km^2 → 10 m raster
	% unemployed population (working age)	- Polish Statistical Office (Local Data Bank), 2021	1 km^2 → 10 m raster
	Population density	- Polish Statistical Office	1 km^2 → 10 m raster
Air pollution	Average PM10, PM2.5, NO2	- European Environment Agency (EEA), 2022	1 km^2 → 10 m raster
	Distance to elementary schools	- Strategy MK 2030 Spatial Model ("Szkoly_podstawowe_gminy_MK", "szkoly_branzowe_Krakow")	Shapefiles (points) → 10 m raster
	Distance to playgrounds	- OSM (POI "playgrounds")	Vector points → 10 m raster
	% population >65 years	- Polish Statistical Office	1 km^2 → 10 m raster
	Distance to health & care facilities	- OSM (fclass "doctors") + BDOT ("KUOZ")	Shapefiles (points) → 10 m raster
Noise pollution	Traffic noise level >50 dB	- Official noise maps of Krakow (City of Krakow 2017) - Strategy MK 2030 Spatial Model for roads/rails	Shapefiles + raster combination (50–80 dB) → 10 m raster
	Land use sensitivity (Polish legislation)	- BDOT ("land cover") + merging with schools, health, social care (OSM/ BDOT) - Classification based on Ministerstwo Środowiska (2007)	Shapefiles (polygons)→ 10 m raster
Heat	Heat island intensity (>30 °C)	- Landsat 8 scene (07 Aug 2013) band 4,5,10 - Land Surface Temperature (LST) calculated	30 m → 10 m raster
	% population >65 years	- Polish Statistical Office	1 km^2 → 10 m raster
	Distance to health & care facilities	- OSM (fclass "doctors"), BDOT "KUOZ"	Shapefiles (points, lines, polyogons) → 10 m raster
	% population receiving social assistance	- Polish Statistical Office, 2021	1 km^2 → 10 m raster
	% unemployed population	- Polish Statistical Office	1 km^2 → 10 m raster
	Population density	- Polish Statistical Office	1 km^2 → 10 m raster
River flooding & runoff	Official flood risk (0.2%, 1%, 10% probability)	- Polish Water Holdings (Wody Polskie)	Shapefiles(polygons)→ 10 m raster
	Runoff coefficient (land use + slope)	- BDOT classes for land cover + slope factor from DTM (geoportal.gov.pl)	10 m raster
	Critical infrastructure	- Strategy MK 2030 (main streets, rail) - OSM (POI with "atm," "embassy," "fire_station," "police," "supermarket," "town_hall," etc.)	Shapefiles (lines, points) → 10 m raster
Landslides	Landslide risk (active, inactive, prone)	- Polish Geological Institute "SOPO_GIS" datasets	Shapefiles (polygons)→ 10 m raster
	Critical infrastructure + population density	- Same "critical infrastructure" (Strategy MK 2030, OSM POI) - Population density (Polish Statistical Office)	Shapefiles (points, polygons) → 10 m raster
Wildfires	Fire Weather Index (FWI)	- Nykiel & Figurski (2020), daily FWI from Mar–Sep 2019	1 km^2 → 10 m raster
	Critical infrastructure	- Same approach as in "River flooding & runoff" (major streets, rails, OSM POI)	Shapefiles (lines)→ 10 m raster
	Population density	- Polish Statistical Office	1 km^2 → 10 m raster
	Ecosystems with high conservation value	- BDOT, IUCN categories (Natura 2000, national parks, reserves) - Strategy MK 2030 Spatial Model	Shapefiles (polygons)→ 10 m raster
Drought	Soil moisture content	- Nykiel & Figurski (2020), 1 km^2 data for Mar–Sep 2019	1 km^2 → 10 m raster
	Areas under nature conservation (IUCN)	- Strategy MK 2030 Spatial Model, IUCN-based classification (Natura 2000, national parks, reserves, etc.)	Shapefiles (polygons)→ 10 m raster
	Areas of agricultural production	- BDOT "PTUT01" (allotment), "PTUT02" (plantation), "PTUT03" (orchard), "PTTR02" (arable land)	Shapefiles (polygons)→ 10 m raster
Habitat fragmentation	Functional connectivity for pollinators (friction)	- Johansson et al.[109] friction values - BDOT, OSM, NDVI (to classify land uses)	Shapefiles (polygons) + assigned friction → 10 m raster
	Major ecological corridors	- Strategy MK 2030 Spatial Model shapefile of potential corridors	Shapefiles (polygons)→ 10 m raster
Biodiversity degradation	Biodiversity intactness index	- Scholes & Biggs (2005)	1 km^2 → 10 m raster
	Areas under nature conservation (inverse sensitivity)	- Strategy MK 2030, IUCN categories (II, IV, V) with assigned inverse sensitivity values	Shapefiles (polygons)→ 10 m raster

respective exposure and sensitivity map. For example, the indicators composing the sensitivity to the lack of recreational opportunities are (1) the population density (33%), (2) the share of the population below the age of 14 (33%), and (3) the share of people with a low economic status. The latter is described by two sub-indicators, namely (3a) the percentage of the population receiving social assistance (16.67%) and (3b) the percentage of the unemployed population of working age (16.76%).

Once mapped, the combined indicators were used to calculate the individual vulnerabilities. Vulnerability in this study is understood as the intersection of exposure and sensitivity. Mathematically, this is represented as the product of the two. The exposure and sensitivity maps were thus multiplied in the ArcMap Raster Calculator to obtain the vulnerability map for each challenge, following Eq. (2):

$$Vulnerability_x = \sum Exposure\ indicators_x * \sum Sensitivity\ indicators_x \tag{2}$$

An in-depth description of the GIS processing for each of the 47 individual indicators has been published here https://doi.org/10.5281/zenodo.14624071.

Weighting of vulnerability criteria

In a co-created approach, the weightings of the vulnerability criteria were identified using the "pebble distribution method" to determine their relative importance[4,112,113]. This participatory tool, often used to gauge people's perceptions and preferences in ecosystem service research and decision-making processes about natural resources[4,112,113], involves distributing a limited number of points to reflect the trade-offs in planning decisions[4,112–114].

A workshop held on November 9th, 2023, involved 13 stakeholders, including municipal representatives from various local offices and environmental management bodies (see Table 4). Participants were divided into two break-out groups of five individuals, each led by a facilitator from the MK office. The facilitator guided the discussion, explained the methodological steps, and ensured that all opinions were expressed and represented.

Participants were provided with the previously established evaluation criteria in written form, printed on large sheets of paper. Each break-out group received 100 points to distribute according to the importance of each criterion. In the first round, each participant selected one vulnerability criterion and explained its relevance, which laid the groundwork for a common understanding of the criteria. In the second round, participants promptly distributed all pebble-points across the criteria. In the third round, participants debated the initial distribution and adjusted the placement of pebbles based on the discussion about the relative importance of each criterion. This process continued until a consensus on the final distribution of weights was reached.

This method allowed for a thorough and participatory weighting process, ensuring that the final vulnerability assessment reflected a balanced view of the relative importance of each criterion, grounded in the collective insights of all stakeholders involved.

Spatial prioritization map

To finally calculate the combined vulnerability map, the individual vulnerabilities for the different criteria were combined using the weightings obtained from the two stakeholder weighting exercises (see Table 2). In addition, two robustness tests were performed: first, to examine the importance of population density, the entire analysis was repeated with a binary population layer, indicating solely whether people live in an area but not how many. Additionally, a combined vulnerability map assuming equal weights for all criteria was prepared to display the importance of the stakeholder weighting.

Data availability

All raw data can be made available by the Krakow Metropolis Association, Poland, contacting Agnieszka Arabas (agnieszka.arabas@metropoliakrakowska.pl). Additional descriptions on the data processing have been published here: https://doi.org/10.5281/zenodo.14624072.

Received: 13 November 2024; Accepted: 4 June 2025;

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Acknowledgements

This study was conducted as part of and co-funded through the European Union's Horizon 2020 project INTERLACE (GA:869324). We acknowledge the Spanish Ministry of Science, Innovation and Universities, through the "Maria de Maeztu" programme for Units of Excel-lence (GA:CEX2019-000940-M), and the funding and recognition awarded to the research group LASEG (GA:2021-SGR-00182) by the Generalitat de Catalunya. S.B. acknowledges a scholarship from the German Academic Scholarship Foundation and an ERASMUS+ grant awarded by Kiel University. J.L. acknowledges additional funding from the European Union's Horizon Europe project Commit2Green (GA:101139598) and from the Spanish Ministry of Science, Innovation and Universities through the Biodiversa+ project FairNature (PCI2025-163216). We want to thank Natalia Gałązka, Karolina Baron, Maria Piątkowska, and Julita Ewert-Stawowy from the Krakow Metropolis Association office for their assistance in obtaining and collecting data and organizing meetings and workshops with stakeholders. Special thanks go to Dr. Paweł Godzina from the Marshall office of the Lesser Poland Voivodeship, Maciej Zacher from the Planning Department of Skawina municipality, Prof. Dr. Ksymenia Rosiek from the Kracow University of Economics and Monika Łągiewka from the Krakow Municipal Greenspace Authority who patiently took time to share their expertise for selecting relevant indicators.

Author contributions

J.L. developed the initial research idea, supervised the project, conceptualized the research approach, and addressed the reviewer requests. S.B., A.A., T.B., I.M. and S.M. contributed to the conceptualization. S.B. collected the data, conducted the data analysis, with contribution by G.B. S.B. and J.L. wrote and revised the manuscript. T.B., A.A., J.L. and S.B. moderated stakeholder workshops, S.M. supported the preparation of the stakeholder processes and contributed to the manuscript writing. All authors read and approved the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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