



Special Issue Reprint

Spatial Planning and Land-Use Management

2nd Edition

Edited by
Eduardo Gomes, Eduarda Marques Da Costa and Patrícia Abrantes

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Spatial Planning and Land-Use Management: 2nd Edition

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Guest Editors

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About the Editors

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Preface

The fields of spatial planning and land-use management are constantly challenged by new realities. Following the first edition of this Special Issue, it became evident that rapid urban expansion, climate change, and demographic shifts demand continuous academic debate. This realization led us to organize this second collection, focusing specifically on translating theoretical planning concepts into practical implementation.

This Reprint explores integrated and multiscalar spatial governance across a wide spectrum. The contributions range from large-scale ecoregional conservation assessments to highly localized interventions, such as the implementation of dark infrastructures and the allocation of urban facilities. Rather than simply diagnosing land-use conflicts, this volume prioritizes applied solutions. We placed particular emphasis on nature-based interventions, green belt protection, and the value of participatory co-design processes.

We structured this Reprint to attract a broad, interdisciplinary readership. Academic researchers and graduate students will find updated spatial modeling techniques and methodological tools. Simultaneously, practicing urban planners, policymakers, and landscape architects can draw on these empirical case studies to design more resilient and equitable territories.

Finally, we thank all the contributing authors for sharing their research, as well as the reviewers whose critical feedback was essential to ensuring the quality of this publication.

Eduardo Gomes, Eduarda Marques Da Costa, and Patrícia Abrantes

Guest Editors

Editorial

Spatial Planning and Land-Use Management—2nd Edition: Expanding the Agenda of Integrated and Multiscalar Spatial Governance

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Abstract

This Editorial introduces the Special Issue “Spatial Planning and Land-Use Management: 2nd Edition” and discusses the eight articles published in it. Taken together, these contributions demonstrate that contemporary spatial planning and land-use management can no longer be understood as narrowly regulatory or sector-specific activities. Rather, they must be approached as integrative and adaptive practices capable of mediating between ecological integrity, territorial cohesion, infrastructure provision, social justice, public health, and participatory governance. The Special Issue brings together case studies from China, the United States, Australia, Iran, Portugal, Slovakia, and Belgium, as well as comparative evidence from peri-urban landscapes, and spans a wide range of spatial scales, from neighbourhoods and urban forests to metropolitan green belts, urban agglomerations, peri-urban territories, and ecoregions. Several major lines of inquiry emerge across the volume. First, the articles reaffirm the need for multiscale planning frameworks able to connect local action with regional and supra-regional structures. Second, they broaden the understanding of infrastructure by including not only transport and urban facilities, but also ecological, green, and even nocturnal infrastructures. Third, they show that many of today’s most difficult planning questions arise in spaces of transition and overlap, especially peri-urban areas, where conflicts among land uses, ecosystem services, development pressures, and governance arrangements become particularly acute across sectors and across spatial and temporal scales. Fourth, they underline that planning effectiveness increasingly depends on participation, co-design, and cooperation among diverse actors, including civic initiatives and local communities. Overall, the Special Issue highlights spatial planning as a strategic field of action through which societies can address land-use conflicts, reconcile environmental and social objectives, and design more sustainable, resilient, and liveable territories.

1. Introduction

Spatial planning and land-use management are increasingly central to contemporary territorial policy and research. This is not simply because land remains a finite resource under growing pressure, but because land-use decisions crystallise some of the most decisive contradictions of our time: economic growth versus ecological conservation, accessibility versus fragmentation, housing demand versus agricultural protection, infrastructural expansion versus territorial cohesion, and short-term political pressures versus long-term public interest [1–5]. In this context, spatial planning cannot be reduced to the technical

allocation of functions across space. It is, rather, a strategic and normative field in which societies negotiate competing values, distribute opportunities and burdens, and define the material conditions of future development [6,7].

The first Special Issue on “Spatial Planning and Land-Use Management” highlighted the relevance of planning instruments for addressing land-use change and improving land-use optimisation, particularly using spatial analysis and modelling approaches. That first volume also revealed an important gap between increasingly sophisticated analytical tools and the still limited integration of participation and stakeholder engagement in planning practice [8]. The present second edition both continues and broadens that agenda. While land-use change remains a central concern, the contributions published here move decisively beyond a predominantly modelling-oriented perspective and deepen the debate around ecological integration, governance, spatial justice, accessibility, public health, participation, and the institutional conditions under which planning succeeds or fails.

A particularly important contribution of this second edition lies in its capacity to show that the contemporary planning field is being reconfigured along at least four major axes. The first is the growing temporal and scalar complexity of planning, which must now respond to heightened uncertainty over time while simultaneously operating across multiple levels and sectors. Planning problems are no longer legible within a single scale of intervention. Biodiversity conservation requires thinking across ecoregions and ecological corridors. Mobility systems restructure metropolitan and supra-metropolitan space. Liveability and accessibility are experienced at the neighbourhood scale. And peri-urban conflicts arise in transitional spaces where multiple spatial logics overlap.

The second is thematic expansion. Infrastructure, for example, no longer refers only to transport or utilities, but also to green infrastructure, nature-based solutions, ecological networks, and even dark infrastructure.

The third is governance pluralisation. Formal state-led planning now coexists with bottom-up initiatives, civic stewardship, collaborative arrangements, and hybrid forms of co-design and co-governance. The fourth is normative reorientation, increasingly shaped by the need for adaptation and greater regulatory flexibility. The effectiveness of planning is judged not only by efficiency or growth outcomes, but also by its ability to advance sustainability, resilience, equity, inclusion, and territorial justice.

The eight papers included in this Special Issue reflect these shifts with unusual clarity. They cover highly diverse geographical and institutional contexts, but they converge in treating space not as a passive background to social and environmental processes, but as an active medium through which conflicts are organised, resources distributed, ecological systems connected or disrupted, and collective futures imagined and governed. In that sense, the Special Issue is not merely a collection of case studies. It offers a composite picture of how spatial planning and land-use management are being rethought in response to a world marked by accelerating environmental change, intensified socio-spatial inequalities, and growing demands for more adaptive forms of territorial governance.

2. From Continuity to Expansion: The Contribution of the Second Edition

One of the most significant features of this second edition is the way it extends the intellectual horizon of the first. If the first volume was strongly organised around land-use/land-cover change, its drivers, and the analytical tools required to understand and anticipate territorial transformations [8], the present volume introduces a more explicit relational and political reading of planning. The question is no longer only how land changes, or how such change may be modelled, but also how planning institutions interpret those changes, how societies prioritise among competing uses, how infrastructures reorganise

territorial relations, and how ecological and social concerns can be integrated into planning frameworks that remain operational under conditions of uncertainty and conflict.

This expansion is visible in the diversity of topics addressed. Mobility and regional interconnectivity are examined not merely as technical matters, but as structuring forces in the production of urban agglomeration space (Contribution 1). Conservation planning is approached not simply as a matter of protected-area designation, but as a multiscalar exercise requiring alignment between biodiversity targets, wildfire risk reduction, and climate change adaptation (Contribution 2). Ecological planning is further broadened by the proposal to integrate the nocturnal dimension of landscapes through dark infrastructure, thereby challenging the implicit diurnal bias that still characterises much planning thought and practice (Contribution 3). Peri-urban landscapes are analysed as arenas of ecosystem service trade-offs and governance failure, revealing that these territories are not residual or secondary spaces, but frontline territories where many of today's key planning contradictions become visible (Contributions 4 and 5). At the urban scale, questions of accessibility, health, and quality of life are addressed through sports facilities and urban green spaces, demonstrating that liveability is inseparable from spatial justice and everyday access to urban resources (Contributions 6 and 7). Finally, participatory planning is pushed beyond consultation towards co-design, co-governance, and civic stewardship, showing that the planning capacity of a territory increasingly depends on the ability to activate distributed knowledge and collective action (Contribution 8).

Taken together, these contributions suggest that the field of spatial planning and land-use management is entering a phase in which synthesis becomes more important than sectoral depth alone. This is not because specialisation has become irrelevant, but because the problems planning must address are themselves deeply interconnected. Land-use management now requires simultaneous attention to ecological continuity, settlement patterns, mobility systems, institutional design, and everyday practices of inhabitation. The most important lesson of this volume is therefore not that planning must do more, but that it must connect more: scales with scales, sectors with sectors, expertise with participation, and immediate intervention with long-term territorial vision.

3. A Thematic Reading of the Special Issue

3.1. *Mobility, Flows, and the Spatial Structuring of Urban Agglomerations*

A first major theme concerns the relationship between mobility infrastructures and territorial organisation. Luan, Xiang, and Jia (Contribution 1) examine the Beijing–Tianjin–Hebei urban agglomeration through the perspective of rail transit interconnectivity and show how transport systems are not merely functional supports for movement, but constitutive elements in the spatial structuring of regional urban systems. By combining the notions of urban quality and line quality, and by mobilising a framework that integrates AHP-CRITIC-TOPSIS, a modified gravity model, and social network analysis, the article demonstrates that interconnectivity increased substantially between 2010 and 2021, while also remaining unevenly distributed in a pattern characterised by strong core cities and numerous weak links.

The relevance of this contribution to the Special Issue lies in at least three aspects. First, it reinforces the understanding that transport planning and spatial planning cannot be treated separately. Rail interconnectivity does not simply respond to existing urban hierarchies. It also reproduces, reinforces, or potentially rebalances them. Second, it illustrates the analytical value of moving from static territorial representations toward a relational understanding of space organised through flows, exchanges, and networks. Third, it raises a critical planning question: greater interconnectivity does not automatically produce polycentricity. As the authors show, interconnectivity may enhance integration

and stability without necessarily reducing asymmetries among core and non-core cities (Contribution 1).

This finding is especially relevant in the broader context of sustainable territorial development. Contemporary planning discourse frequently presents transport integration as inherently beneficial. Yet the article reminds us that infrastructure-led integration can coexist with spatial polarisation. From a planning perspective, the challenge is therefore not only to expand networks, but to shape them in ways that support a more balanced territorial structure. This implies differentiated policies, stronger support for non-core nodes, and closer articulation between investment in transport systems and broader strategies of urban and regional development. In this regard, the paper makes a valuable contribution to debates on how metropolitan and supra-metropolitan planning can move beyond monocentric concentration towards more integrated and polycentric forms of territorial organisation.

3.2. Ecological Planning Across Scales: Ecoregions, Corridors, and Nocturnal Continuity

A second thematic cluster concerns the deepening ecological content of spatial planning. DellaSala et al. (Contribution 2) and Wynants and Schmitz (Contribution 3) address very different territories and scales, yet both show that ecological planning requires more than static conservation categories. It demands the capacity to identify functional relationships, critical gaps, and hidden pressures within broader territorial systems.

DellaSala et al. (Contribution 2) present a multi-scaled ecoregional conservation assessment for the Southern Rocky Mountains and the Santa Fe Subregion. Their analysis reveals significant imbalances in the representation of vegetation types, mature and old-growth forests, riparian areas, and habitats for focal species in relation to conservation targets such as 30×30 and 50×50 . Particularly important is the paper's effort to connect conservation planning with wildfire risk reduction and climate change. Rather than treating conservation and hazard management as competing agendas, the study shows that they can and should be articulated if interventions are spatially targeted and ecologically informed. The finding that most thinning treatments occurred far from the wildland–urban interface is especially telling, since it questions the territorial logic of certain risk-reduction strategies and opens space for a more selective and coherent planning response (Contribution 2).

From the perspective of spatial planning and land-use management, this article is valuable because it demonstrates the importance of planning beyond administrative boundaries. The ecoregional scale enables a form of territorial reasoning that is often difficult to achieve within conventional planning systems structured by jurisdictional fragmentation. At the same time, the nested analysis of the Santa Fe Subregion shows that broad-scale conservation targets must be translated into context-sensitive subregional strategies. In other words, the paper reinforces a key planning principle: strategic coherence across scales must be combined with territorial specificity.

Wynants and Schmitz (Contribution 3), in turn, propose a methodological framework for integrating dark infrastructure into the ecological network of an urban forest near Liège. A particularly valuable aspect of this article is that it draws attention to an issue that is still often overlooked in ecological planning: ecological continuity is not only spatial, but also temporal. Much of the existing work on ecological networks has focused on land cover, habitat patches, corridors, and other daytime landscape structures, while giving less attention to how ecological conditions change at night. By examining artificial light at night as a source of fragmentation, the article expands the discussion on ecological planning and shows that nocturnal conditions also need to be considered in the design of ecological networks.

The relevance of this contribution is both conceptual and practical. On the one hand, it argues that ecological continuity should not be understood only through the physical arrangement of land uses, but also through rhythms, cycles, and environmental conditions that vary over time. On the other hand, the study suggests that broad interventions across the whole site may not always be necessary. In some cases, more focused actions in critical corridor areas may be enough to improve ecological connectivity. In this sense, dark infrastructure is not merely an additional planning layer, but a useful way of recognising darkness itself as an important condition for biodiversity conservation (Contribution 3).

Read together, these two papers signal a broader transformation in ecological planning. Conservation is no longer restricted to the designation of protected areas, nor is ecological infrastructure reducible to green and blue systems alone. Instead, planning increasingly requires the identification of functional ecological relations across scales and through time, including those affected by climate, wildfire regimes, and nocturnal disturbance. This is one of the most innovative dimensions of the Special Issue.

3.3. Peri-Urban Territories: Areas of Conflict, Trade-Off, and Institutional Failure

A third core theme concerns peri-urban landscapes. Few territories better capture the tensions of contemporary territorial development than peri-urban territories, where urban expansion, agricultural uses, ecological functions, recreational demands, and fragmented governance structures collide. Two articles in the Special Issue provide particularly strong insights into this condition.

Spyra et al. (Contribution 4) examine ecosystem service trade-offs in peri-urban landscapes through a comparative analysis of 24 case studies. Their findings show that the most common trade-offs occur between cultural and provisioning services, and between regulating and provisioning services, with urban development identified as the main driver behind these tensions. Particularly relevant is the paper's emphasis on governance obstacles: the lack of adequate policies and planning documents, limited practical tools for dealing with trade-offs, and insufficient cooperation among actors. The article makes clear that peri-urban ecosystem service trade-offs are not merely analytical phenomena. They are governance problems that emerge when planning systems fail to mediate among competing claims over land and resources.

These findings have relevant implications for peri-urban planning. Planning in these areas cannot be limited to the designation of land uses or to a narrow approach centred only on growth control. Instead, it needs to be able to identify competing ecosystem service demands, address the tensions between them, and, where possible, support more balanced outcomes. The article also shows that these trade-offs are not usually solved through technical analysis alone. They depend on cooperation between actors, greater awareness of the issues at stake, and stronger institutional coordination, all of which remain difficult to achieve in many planning contexts (Contribution 4).

Buxton and Mercer (Contribution 5) provide a complementary perspective through their discussion of Melbourne's green belt, with a clearer focus on the political and institutional dimensions of planning. Their analysis shows that planning failure should not be understood only as a consequence of limited data or weak methods. In this case, it is closely related to political decisions, regulatory relaxation, and the gradual weakening of long-term strategic goals. By examining the loosening of planning controls, successive changes to strategic frameworks, green belt encroachment, and the fragmentation of peri-urban land, the authors demonstrate how deregulated planning approaches can progressively weaken agricultural functions, biodiversity values, and landscape protection.

One of the main contributions of this article to the Special Issue is the idea that land-use planning remains a key force in the evolution of peri-urban areas. Rather than merely

reacting to broader economic dynamics, planning actively influences these trajectories. It actively conditions land prices, subdivision patterns, permitted uses, and future options. In that sense, the Melbourne case is exemplary far beyond Australia. It reveals how difficult it is to preserve multifunctional peri-urban territories when planning is subordinated to short-term growth agendas and when cross-sectoral integration is weak or absent (Contribution 5).

These two peri-urban papers together make a major contribution to the volume. They show that peri-urban areas are not transitional leftovers awaiting urbanisation, but strategic territories where core planning questions become sharply visible: how to preserve ecological and agricultural functions under development pressure, how to address trade-offs among competing services and uses, and how to design governance systems capable of protecting long-term territorial value. They also underline that effective land-use management depends as much on institutional consistency and regulatory capacity as on analytical sophistication.

3.4. Liveability, Accessibility, and Spatial Justice in Urban Everyday Life

A fourth theme emerging from the Special Issue relates to the social and everyday dimensions of planning. Spatial planning is often approached through broad territorial strategies and major structural interventions, but its relevance is also measured in more immediate and ordinary ways. It matters in how people experience the city on a daily basis, including their access to green spaces, the distribution of essential facilities, and the extent to which urban environments contribute to health, leisure, and overall well-being.

Asgari Gandomani et al. (Contribution 6) explore these questions through the case of sports facility allocation in Tehran. Using GIS and spatial multi-criteria decision analysis, the authors show that the existing distribution of sports facilities is uneven and spatially concentrated, while the most suitable areas for future provision are located mainly in the central and southern parts of the city. The significance of the article lies in the fact that it goes beyond a purely technical reading of location-allocation. Instead, it presents the issue as one of spatial justice. Access to sports facilities has implications for health, social interaction, and quality of life, and uneven provision tends to reproduce wider socio-spatial inequalities.

From a planning standpoint, the paper is especially valuable for showing how spatial analysis can support more equitable territorial decisions. The emphasis on underserved areas and on the relationship between compatibility criteria, accessibility, and social need illustrates how urban planning can be mobilised to redistribute opportunities more fairly within highly unequal metropolitan contexts (Contribution 6). The article thus expands the thematic field of land-use management by bringing public health and social justice into direct relation with facility planning.

Cunha, Marques da Costa, and Morgado (Contribution 7), in turn, explore the role of urban green spaces in a Lisbon neighbourhood during the COVID-19 pandemic. Their mixed-methods approach, combining spatial analysis, field observation, and survey data, shows that proximity and quality jointly shape the use of urban green spaces and their contribution to liveability and health. Proximity matters, particularly for older people and children, but quality also matters because well-maintained, safe, and multifunctional spaces attract users even when they are somewhat farther away.

This article makes several important contributions. First, it provides neighbourhood-scale evidence that liveability is materially grounded in spatial accessibility and in the quality of public environments. Second, it reinforces the idea that urban green spaces should be understood as essential public health infrastructure rather than optional urban amenities. Third, it shows that planning for liveability must consider not only quantity or

distance metrics, but also maintenance, safety, diversity of uses, and the perspectives of users themselves (Contribution 7).

When considered together, the Tehran and Lisbon studies give greater depth to the social dimension of this Special Issue. Both show that planning for sustainability also involves questions of fairness and the ways people use and experience urban space in everyday life. Accessibility, in this context, should be understood not only as a matter of transport, but also as an issue of how urban opportunities are distributed. In a similar way, liveability is not just a general planning objective, but something shaped by daily interactions between people and places. These contributions show that spatial planning is most valuable when it helps improve the everyday spaces of urban life.

3.5. Participation, Co-Design, and Civic Capacity in Contemporary Planning

A final theme running through the Special Issue concerns participation and the evolving role of civic actors in planning. In their study of Slovakia, Slobodníková and Tóth (Contribution 8) examine civic initiatives linked to green infrastructure and nature-based solutions and show that these actors often do more than simply support formal planning processes. In many cases, they step in where institutional action has been slow, bring in specific forms of knowledge, help create or recover green spaces, give new uses to neglected land, and strengthen environmental awareness and local stewardship. An important point made by the article is that civic action should not be understood only as a substitute for institutional shortcomings. It can also play an active part in reshaping governance practices and in encouraging more participatory approaches to planning.

This is a highly relevant contribution to the broader debate on spatial planning and land-use management. It suggests that the effectiveness of planning increasingly depends on distributed capacities that exist beyond formal administrative structures. In other words, planning is not only what planning authorities do. It is also what emerges when communities, associations, experts, and local actors co-produce territorial transformation. The article therefore challenges narrow understandings of participation as consultation and instead foregrounds longer-term processes of co-design, co-governance, and stewardship (Contribution 8).

Importantly, this participatory dimension resonates well beyond the Slovak cases. The governance challenges identified in peri-urban ecosystem service trade-offs (Contribution 4), the need for stronger cross-sectoral planning in Melbourne (Contribution 5), and the user-oriented lessons emerging from Lisbon (Contribution 7) all point in the same direction: planning systems work better when they can incorporate multiple knowledges, foster cooperation across actors, and remain open to adaptive and place-sensitive forms of intervention. Participation, however, is not presented here as a normative slogan. The Special Issue makes clear that participation requires enabling frameworks, institutional receptivity, and long-term support. Without these, civic energy risks remaining fragmented, under-recognised, or unable to scale.

For this reason, the Slovak paper occupies an important place in the Special Issue's overall architecture. It provides concrete evidence that inclusive planning is not merely about adding stakeholders to predefined processes, but about rethinking how authority, expertise, and responsibility are distributed in the making and care of space. In this sense, it offers one of the clearest bridges between environmental planning and democratic innovation.

4. Cross-Cutting Contributions to Spatial Planning and Land-Use Management

Beyond the contribution of each individual article, this Special Issue also points to a number of broader issues that are relevant to the field of spatial planning and land-use management.

First, the papers clearly show that planning is inherently multiscale. The cases discussed in this volume range from neighbourhoods and urban green spaces to peri-urban territories, green belts, urban agglomerations, forests, and ecoregions. This diversity is meaningful because it shows that planning problems do not emerge at a single scale. They are shaped by interactions between local, regional, and wider territorial processes. For that reason, effective land-use management requires the ability to connect these different levels of analysis and intervention. Scale, therefore, is not just a technical way of framing a problem, but part of the problem itself.

Second, the Special Issue broadens the understanding of infrastructure. Across the different articles, infrastructure includes not only rail transport systems and urban facilities, but also green infrastructure, nature-based solutions, ecological networks, urban green spaces, and dark infrastructure. This wider perspective is important because it shows that infrastructure is not limited to supporting movement or economic activity. It also shapes access, influences how places are experienced, contributes to biodiversity, and affects the long-term organisation of territories. A broader understanding of infrastructure is therefore increasingly important in contemporary planning.

Third, the volume shows that conflict and trade-offs are central to land-use management. Questions related to peri-urban ecosystem services, green belt protection, biodiversity conservation, wildfire management, transport development, or the allocation of urban facilities all involve competing interests and uneven impacts. In this sense, planning cannot be seen simply as a neutral tool for organising space. It is also a political and institutional process through which tensions are recognised, discussed, and managed. Its effectiveness depends largely on how these tensions are addressed and on whether adequate frameworks exist to negotiate between competing demands.

Fourth, the volume places significant emphasis on the institutional conditions of planning. Several contributions show that good intentions, strategic visions, or advanced methods are insufficient where governance is fragmented, deregulated, weakly coordinated, or disconnected from civic initiative. Conversely, stronger integration, cooperation, and participatory capacity can significantly improve planning outcomes. This suggests that one of the central tasks for future spatial planning research is to connect territorial analysis more directly with questions of institutional design and governance performance.

Finally, the Special Issue reinforces the normative relevance of spatial planning. The articles do not treat planning as a purely descriptive or procedural field. They engage, explicitly or implicitly, with major public values: sustainability, resilience, liveability, inclusion, biodiversity protection, and spatial justice. This is important. At a time when planning systems are frequently pressured by short-term demands and sectoral fragmentation, the volume reminds us that planning remains one of the few public arenas in which long-term collective interests can still be articulated spatially.

5. Conclusions

“Spatial Planning and Land-Use Management: 2nd Edition” brings together a diverse but remarkably coherent set of contributions. Across different geographical contexts, methodological approaches, and thematic concerns, the eight papers converge in showing that spatial planning and land-use management are indispensable for addressing the intertwined social, environmental, and territorial challenges of the present. They also show

that these challenges can no longer be addressed through narrow sectoral perspectives or through planning systems that operate at a single scale and in institutional isolation.

This volume points to several broader conclusions about contemporary spatial planning and land-use management. One of the clearest is that planning needs to work in a more integrated way, particularly through improved coordination across vertical and horizontal scales. Many of the issues discussed in this Special Issue lie at the intersection of ecological conservation, infrastructure, public health, governance, and social justice, rather than within a single sector. The articles also show that planning problems unfold across different spatial levels, from neighbourhoods to ecoregions, which means that responses need to connect local, regional, and wider territorial perspectives. At the same time, the volume suggests that planning must remain open and adaptable. Although conventional land-use categories are still important, they are no longer enough on their own to capture territories shaped by flows, changing environmental conditions, shifting actor relationships, and overlapping spatial dynamics. Another important point is that planning needs to be genuinely participatory, not only in a formal sense, but also in its ability to include civic initiatives, user perspectives, and shared forms of territorial care in the shaping of spatial change.

The Special Issue further suggests that the future of land-use management will depend not only on stronger analytical methods, but also on stronger institutional capacity. Effective planning requires clear and coherent regulatory frameworks, better coordination across sectors, strategies that respond to the specificities of place, and meaningful engagement with stakeholders and communities. Without these conditions, even technically advanced planning approaches may struggle to protect ecological systems, address inequalities, or contribute to more liveable and resilient territories.

In this regard, the contributions assembled here do more than document contemporary challenges. They provide conceptual and empirical guidance for rethinking planning as a strategic practice of territorial mediation. Whether the issue is rail interconnectivity in a large urban agglomeration, ecosystem service trade-offs in peri-urban landscapes, the erosion of a metropolitan green belt, the equitable allocation of urban facilities, the everyday value of green spaces, civic-led nature-based solutions, or the protection of nocturnal ecological continuity, the central lesson is the same: spatial planning matters because land matters, and land matters because it is where ecological processes, infrastructures, institutions, and social life meet.

This second edition therefore confirms the continued relevance of spatial planning and land-use management as core instruments for promoting sustainability, territorial cohesion, ecological integrity, and human well-being. It also reinforces the need for continued interdisciplinary dialogue among researchers, planners, policymakers, and practitioners. Such dialogue is essential if planning is to remain capable of guiding territorial change toward more equitable, resilient, and environmentally responsible futures.

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Article

An Ecoregional Conservation Assessment for the Southern Rocky Mountains Ecoregion and Santa Fe Subregion, Wyoming to New Mexico, USA

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Abstract: We conducted a multi-scaled Ecoregional Conservation Assessment for the Southern Rockies (~14.5 M ha) and its trailing edge, the Santa Fe Subregion (~2.2 M ha), from Wyoming to New Mexico, USA. We included a representation analysis of Existing Vegetation Types (EVTs), mature and old-growth forests (MOG), and four focal species—Canada lynx (*Lynx canadensis*), North American wolverine (*Gulo gulo luscus*), Mexican spotted owl (*Strix occidentalis lucida*), and northern goshawk (*Accipiter gentilis*)—in relation to 30 × 30 and 50 × 50 conservation targets. To integrate conservation targets with wildfire risk reduction to the built environment and climate change planning, we overlaid the location of wildfires and forest treatments in relation to the Wildland–Urban Interface (WUI) and included downscaled climate projections for a lower (RCP4.5) and higher (RCP8.5) emission scenario. Protected areas were highly skewed toward upper-elevation EVT (most were >50% protected), underrepresented forest types (<30% protected), especially MOG (<22% protected) and riparian areas (~14% protected), and poorly represented habitats (<30%) for at least three of the focal species, especially in the subregion where nearly all the targets underperformed compared to the ecoregion. Most (>73%) forest-thinning treatments over the past decade were >1 km from delineated WUI areas, well beyond the distance at which vegetation management can effectively reduce structure ignition risk (<50 m from structures). Extreme heat, drought, snowpack reductions, altered timing of peak stream flows, increasing wildfires, and potential shifts in the climate, favoring woodlands over conifer forests, may impact forest-dependent species, while declining snowpack may impact wolverines that den at upper elevations. Strategically targeting the built environment for fuel treatments would improve wildfire risk reduction and may allow for expansion of protected areas held up in controversy. Stepped-up protection for roadless areas, adoption of wilderness proposals, and greater protection for MOG and riparian forests are critical for meeting representation targets.

Keywords: biodiversity; climate change; ecoregion; conservation; Santa Fe; Southern Rockies

1. Introduction

The Southern Rocky Mountains Ecoregion (SRME) spans ~14.5 M ha of a rugged terrain characterized by abrupt transitions from many of the tallest peaks (>3660 m) in North America to expansive lowland valleys, primarily within portions of southern Wyoming, central and western Colorado, and northern New Mexico, USA [1,2]. A prominent feature is the Continental Divide that splits the Pacific (to the west) and Atlantic (to the east) drainages. The beta diversity of fauna and flora is especially pronounced across elevational life zones, with distinct shifts in species assemblages traversing lower montane/foothills, upper montane, subalpine, and alpine areas [1,3]. The World Wildlife Fund considered the ecoregion the Colorado Rockies Forests (Ecoregion #45) and ranked it “bioregionally outstanding” and “relatively stable” due mainly to large intact areas, including national parks,

wilderness areas, and Inventoried Roadless Areas (IRAs) [1,4]. NatureServe listed the ecoregion as the Southern Rocky Mountain Montane Forest & Woodland Macrogroup [M022] [5]. The USDA Forest Service identified five distinct subsections, including the Northern Parks and Ranges, South-Central Highlands, Northern-Central Highlands and Rocky Mountains, Southern Parks and Rocky Mountain Ranges, and Northern Rio Grande Basin [3]. Within the SRME, some 184 plant and animal species are endemic, 100 are globally imperiled (G1–G2), 23 are listed under the Endangered Species Act, and 7 have been extirpated [1,3]. Importantly, species reintroductions have taken place in portions of the ecoregion, including the Mexican gray wolf (*Canis lupus*), bison (*Bison bison*), black-footed ferret (*Mustela nigripes*), river otter (*Lutra canadensis*), and Canada lynx (*Felis lynx canadensis*, in Colorado), with a wolverine (*Gulo gulo luscus*) reintroduction program recently approved in Colorado that will begin soon (Colorado Senate Bill 24-171; <https://leg.colorado.gov/bills/sb24-171> (accessed on 25 May 2024)).

Large-scale conservation proposals (e.g., 30% protected by 2030, “30 × 30”; 50% protected by 2050, “50 × 50”) [6] are a cornerstone of conservation biology approaches worldwide [7], as well as of long-standing conservation efforts in this ecoregion [1,3,8,9]. For instance, The Nature Conservancy identified 188 conservation priority areas, totaling 50% of the SRME, to meet conservation goals of targeted species and natural and ecological systems [3]. In the Southern Rockies, protected areas may function as important climate refugia with relatively low climate velocities compared to their developed surroundings [9], especially where there are large roadless area complexes, wilderness areas, and national parks [1,8].

Notably, the trailing edge of ecoregions may be especially vulnerable to higher climate velocities because species assemblages and climatic conditions are at their margins. A case in point is the Santa Fe Subregion (SFSR) at the southern edge of the SRME that climatically differs from most of the ecoregion via seasonal monsoons that affect natural disturbance dynamics. Climate change-related shifts in monsoon delivery may affect the onset and length of the wildfire season [10]. The SFSR also includes a dense population center nearby, Santa Fe, that has experienced periodic wildfires in the surroundings, with some wildfires spilling into nearby communities that abut the two primary national forests in this subregion: the Santa Fe and Carson (a small portion of the Rio Grande National Forest in Colorado is also included in the SFSR). The Santa Fe National Forest is close to numerous homes in harm’s way of wildfires. The overwhelming response by the USDA Forest Service has been unprecedented: aerial fire suppression, along with expansive forest thinning and burning proposed by researchers (e.g., prescribed fire and pile burning), [11–14] as well as road building to access sites for vegetation management.

There is scientific debate and public controversy about whether such aggressive fuel-reduction treatments are an effective strategy in a changing climate [15], particularly considering the cumulative ecosystem damages associated with some of the treatments [16], whether too much forest biomass is being removed and too frequently [17], or whether fire-risk reduction for communities should instead target areas closest to homes [18,19], the smoke and human health risks of frequent and extensive prescribed burns, and prescribed fires that sometimes escape containment (e.g., Calf Canyon/Hermit’s Peak fire of 2022) [20]. Importantly, The Nature Conservancy identified ~46% of the Santa Fe National Forest as a priority for coarse and fine-filter conservation [21]. However, little progress has been made toward these broader conservation targets, mainly due to the controversy over forest management and wildfires.

Our objective is to present a multi-scaled Ecoregional Conservation Assessment (ECA) that incorporates the conservation needs of both the larger SRME and the SFRS nested within it. Multi-scaled ECAs are necessary to ensure that a particular area of interest (subregion) is contextually analyzed for its relative conservation contributions within the backdrop of climate change, forest management, and wildfires. It is also necessary to demonstrate that large-scale conservation (e.g., priority areas, focal species distribu-

tions) can be compatible with wildfire risk reduction in the built environment and climate change planning.

We selected the Canada lynx, a federally threatened species under the U.S. Endangered Species Act; wolverine, federally threatened; northern goshawk (*Accipiter gentilis*), a USDA Forest Service “sensitive species;” and Mexican spotted owl (*Strix occidentalis lucida*), federally threatened, to represent a mixture of forest conservation and landscape connectivity needs at the two spatial scales (ecoregion, subregion), and to compare levels of protection of these focal species between the two scales using 30% and 50% targets. ECAs that include both landscape and focal species can be useful in advancing conservation proposals in regions facing multiple threats from development, wildland fires affecting towns, climate change, and controversial forest management practices. Our ECA approach to the SRME builds on a related ECA for the Mogollon Highlands in Arizona, just to the southeast, which are facing some of the same conflicts over protection vs. forest management and wildfire risks [22]. ECAs like these may provide a means to advance conservation in high fire-risk environments where protected area proposals have stalled due to land-management agencies and/or elected official calls for increased forest management via logging, burning, and road building.

2. Materials and Methods

2.1. Study Area

We used the Environmental Protection Agency (EPA) Level III ecoregional classifications, as others have used [2], to map the SRME study area (i.e., EPA Ecoregion 21) and overlaid a climate change projection boundary based on the study area’s grid coordinates in the Climate Toolbox online portal (climatetoolbox.org (accessed on 3 May 2024)) (Figure 1). The study area boundary was confirmed by regional experts in a May 2024 workshop. For the purpose of a continuous ecoregional analysis, we did not include small, isolated fragments in Utah that are, despite their discontinuity, considered part of EPA Ecoregion 21.

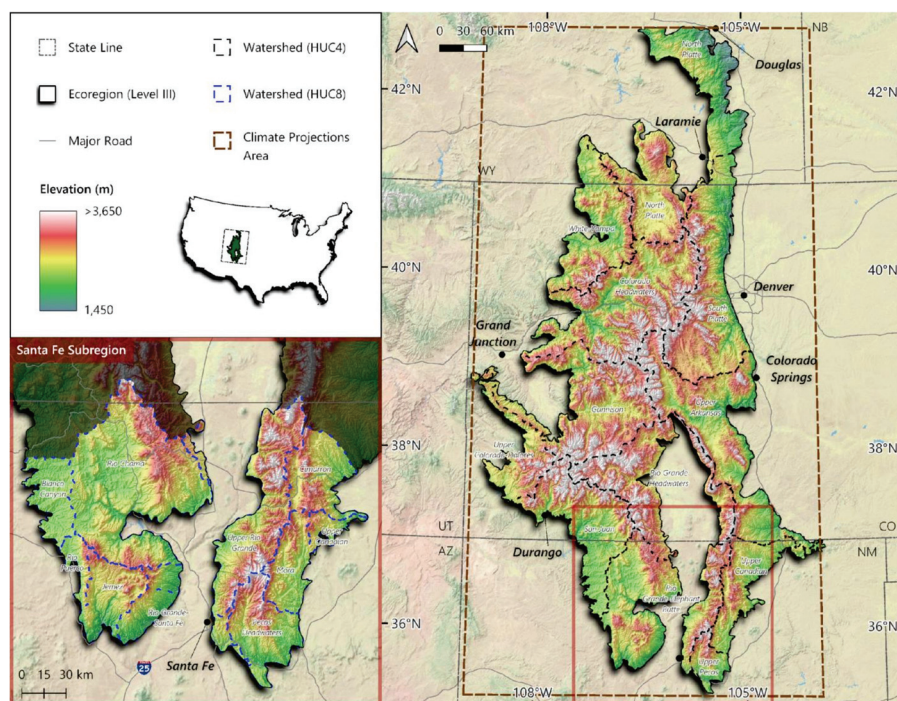


Figure 1. Southern Rocky Mountains Ecoregion showing elevation, HUC4 watersheds at the ecoregion scale, HUC8 watersheds at the Santa Fe subregion scale, and the climate change projection area rectangle derived using the Climate Toolbox (<https://climatetoolbox.org> (accessed on 3 May 2024)). See Table S1 for HUC8 watersheds.

Watershed boundaries were overlaid on the study area using 4-digit Hydrologic Unit Codes [HUCs] [23] for the ecoregion and 8-digit HUCs for the SFSR in order to provide the necessary detail for a scaled analysis. We delineated the SFSR as the 10 southernmost 8-digit HUCs in the SRME (Table S1) (Figure 1). All spatial analyses were conducted at both the SRME and SFSR scale. Based on our mapping approach, the SRME totaled 14,475,519 ha and the SFSR totaled 2,188,050 ha (~15% of the SRME) (Figure 1).

We clipped all spatial datasets to the study area and re-projected to a CONUS Albers projection (EPSG:5070) using QGIS version 3.36 (<https://qgis.org>; accessed on 10 May 2024). To reduce processing time, we converted most of our vector datasets to 30 m raster datasets aligned with LANDFIRE (2022, LF 2.3.0) rasters, such as the elevation dataset that we used to create Figure 1. This allowed us to combine rasters representing different metrics, each having a set of unique pixel values corresponding to surface ownership, vegetation type, forest structure class, etc. The only exceptions to this raster approach were our analyses involving wolverine habitat connectivity as well as the analyses involving USDA Forest Service thinning activities, which were both conducted using clipped vector datasets.

2.2. Landowners and GAP Status

For the Wyoming and New Mexico portions of the SRME, we used surface landowner data from the PAD-US 3.0. For the Colorado portion of the SRME (which comprises the majority of the ecoregion), we extracted landowner data from the Colorado Ownership Management and Protection Map (COMaP, v20230223), as it has greater accuracy than the PAD-US across the state. We grouped landowner polygons into nine ownership categories for all analyses that involved surface ownership. We also included the National Forest Boundaries from the USDA Forest Service Enterprise Data Warehouse, as described in DellaSala et al. [22].

We extracted U.S. Geological Survey (USGS) GAP Analysis Project (GAP) status codes 1–4 from the USGS Protected Areas Database (PAD), supplemented with data from the National Conservation Easement Database (NCEDB). USGS Gap Status Codes are assigned status codes based on degrees of protection, with GAP 1 (permanent protection, e.g., designated wilderness and national parks) and GAP 2 (maintained primarily in natural state, e.g., national monuments and wildlife refuges) having the highest protection vs. GAP 3 (extractive use) and GAP 4 (private lands with no protections) (see https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/files/GAP%20Status%20Code%20Assignment_2021.pdf (accessed on 1 August 2024)). We combined USDA Forest Service IRA data from the national dataset (2001 Roadless Area Conservation Rule) for IRAs in New Mexico and Wyoming and from the 2012 Colorado Roadless Rule dataset for IRAs in Colorado (<https://www.fs.usda.gov/main/roadless/coloradoroadlessrules> (accessed on 10 May 2024)). The Colorado Roadless Rule differs from the 2001 national rule as it classified portions of IRAs as either “upper tier” or “non-upper tier”. Upper-tier IRAs have even greater protection than those under the national rule (e.g., in Wyoming or New Mexico), so we assigned upper tiers as GAP 2. We assigned IRAs in Wyoming and New Mexico as well as non-upper-tier IRAs in Colorado as GAP 2.5, as these areas have enhanced protection beyond what is typical for GAP 3 lands (see [22]). Because the PAD-US data combined with IRA and NCEDB data include overlapping polygons, our final GAP status dataset represents the lowest GAP status code (i.e., the highest level of protection) for any given area. Any areas outside of this combined dataset were assigned GAP 4. We combined the final GAP status rasters with rasters for the metrics below to determine the proportion of each area (e.g., Canada lynx suitable habitat) in each GAP status.

We obtained wilderness area boundaries in several proposed federal legislation efforts that we had spatial data for, including the Colorado Wilderness Act, Colorado Outdoor Recreation and Environment Act, Gunnison Outdoor Resources Protection Act, and the Sarvis Creek Wilderness Completion Act (a total of 210,486 ha proposed as wilderness in these bills). We created a separate GAP status dataset with existing wilderness boundaries

adjusted and new wilderness areas added, assuming all these bills were signed into law. We then calculated the GAP status distribution across the SRME and SFSR under this scenario.

2.3. Existing Vegetation Types (2020 Update)

We accessed Existing Vegetation Type (EVT) data for the study area using LANDFIRE (2022, LF 2.3.0), which represents the current distribution of terrestrial ecological systems, developed by NatureServe for the western hemisphere. There were 97 EVTs within the SRME (Table S2), which we grouped into 19 broader categories, with a focus on the forest types most likely used by our focal species, including alpine, aspen (*Populus* spp.) and mixed-conifer forest, aspen forest and woodland, lodgepole pine (*Pinus contorta*) forest, mixed-conifer forest, pinyon (*Pinus* spp.)–juniper (*Juniperus* spp.), ponderosa pine, and subalpine forest. The EVTs within the SFSR were generally similar to those of the ecoregion described by Vander Lee et al. [21], with some noted exceptions such as the lack of lodgepole pine forest and limber pine woodland.

Characteristic tree species in the study area include Engelmann spruce (*Picea engelmannii*), blue spruce (*Picea pungens*), subalpine fir (*Abies lasiocarpa*), Rocky Mountain Douglas fir (*Pseudotsuga menziesii* var. *glauca*), Rocky Mountain white fir (*Abies concolor* subsp. *concolor*), Rocky Mountain bristlecone pine (*Pinus aristata*), limber pine (*Pinus flexilis*), lodgepole pine, ponderosa pine (*Pinus ponderosa*), Colorado pinyon pine (*Pinus edulis*), Rocky Mountain juniper (*Juniperus scopulorum*), and gambel oak (*Quercus gambelii*). Interestingly, southwestern white pine (*Pinus strobiformis*) and limber pine commingle at or near the limits of their geographical ranges to form a unique hybrid zone in the SFSR [24]. Riparian areas are characterized by abundant forbs and shrubs (when not grazed by cattle), narrowleaf cottonwood (*Populus angustifolia*), quaking aspen (*Populus tremuloides*), plains cottonwood (*Populus deltoides*), peachleaf willow (*Salix amygdaloides*), Rocky Mountain maple (*Acer grandidentatum*), and thinleaf alder (*Alnus tenuifolia*) (see [4]). Alpine zones (above tree line) support a variety of shrubs, wildflowers, krummholz (stunted trees) and many non-vascular plants on exposed rocks [2].

2.4. Mature and Old-Growth Forests (MOG)

We obtained spatial datasets on mature and old-growth (MOG) forest distributions from DellaSala et al. [25], who used three proxies to define MOG forests at 30 m resolution: tree height, canopy coverage, and above-ground biomass. As in DellaSala et al. [25], we grouped the nine forest structure classes in this dataset into three broader categories: young, intermediate, and mature forests. Because some of the proxy data used to create the original MOG dataset were obtained several years prior, we determined that the dataset needed to be screened for relatively recent high-severity fire events to ensure that we did not consider areas with greater than about 75% tree mortality from fire as MOG. We extracted high-severity fire data from the four-class composite burn index (CBI-4) annual mosaics, 2012 through 2023, in the USDA Forest Service Rapid Assessment of Vegetation Condition after Wildfire (RAVG) database and censored out any overlapping MOG pixels from our final analyses and maps (<https://burnseverity.cr.usgs.gov/ravg/data-access> (accessed on 14 April 2024)).

Using the RAVG mosaics allowed us to include fire severity data from the 2022 Hermits Peak/Calf Canyon Fire, which burned a substantial portion of the SFSR but which was not yet included in the Monitoring Trends in the Burn Severity (MTBS) dataset. Data for some fires in the earlier years of the annual mosaic range were affected by the Landsat 7 Scan Line Corrector error. Any areas within the mosaics that were within the swaths lacking data due to this well-known error were also censored from the final MOG dataset.

2.5. Focal Species

2.5.1. Wolverine

Wolverines occupy isolated subalpine areas at low population densities and have been used to model metapopulation dynamics and landscaped connectivity with dispersing

animals following low-resistance pathways that connect high-quality habitats [26]. We used a habitat connectivity dataset provided by Carroll et al. [26] via Data Basin, who used Circuitscape 4.0 to produce habitat connectivity scores for the western USA at an approximately 25 km resolution. We clipped this raster dataset to the SRME, then extracted the raster pixels with connectivity scores at the 90th percentile or above and again at the 95th percentile or above for the ecoregion. We converted these two sets of extracted pixels to vector formats and then clipped our GAP vector layer to them and calculated the GAP distribution for each dataset (GAP refers to the U.S. Geological Survey Gap Analysis Project; <https://www.usgs.gov/programs/gap-analysis-project> (accessed on 1 August 2024)). We repeated this again for the SFSR, but the 90th and 95th percentile values were still based on the entire SRME.

2.5.2. Canada Lynx, Northern Goshawk, and Mexican Spotted Owl

Canada lynx use mid-elevation boreal and subalpine zones with deep snowpack, selecting forests with a high proportion of beetle-killed large trees and with extensive horizontal cover, used by its principal prey species, the snowshoe hare (*Lepus americanus*) [27]. Northern goshawks select mature forests with large trees and extensive canopy closure [28] and in parts of their range will nest in dense aspen and lodgepole pine forests [29]. The Mexican spotted owl typically uses forests with extensive canopy cover in mixed-conifer and pine-oak forests and woodlands and is known to be sensitive to habitat fragmentation [30].

We used the 2001 GAP Analysis Project habitat suitability dataset (30 m resolution) for each of the three species. Because of the age of these datasets, we censored out any suitable habitat pixels that had experienced high-severity fire from 2001 to 2023, which is a conservative approach that ensures suitable habitat distribution was not overestimated. We extracted high-severity pixels from RAVG annual mosaics for the 2012–2023 period, as described in the MOG section above. We then extracted the high-severity class of pixels from the MTBS annual fire severity raster mosaics for the 2001–2011 period (RAVG data were not available for the region prior to 2012) and combined these with the high-severity fire pixels from the RAVG dataset to create a mask layer that we used to censor out any suitable habitat pixels in the 2001 GAP Analysis datasets. We combined our censored habitat suitability datasets with the GAP status datasets for both the SRME and SFSR to calculate the GAP status distributions for each species' total area of suitable habitat.

2.6. Wildland–Urban Interface/Intermix (WUI), Wildfires, and Forest Thinning

We extracted the six 2020 categories of WUI areas from the national WUI dataset produced by Radeloff et al. [31]: low-density intermix, medium-density intermix, high-density intermix, low-density interface, medium-density interface, and high-density interface. We rasterized the dataset as we had with the other datasets above and combined it with our GAP status raster for both the SRME and SFSR.

We extracted all wildfires from the MTBS national dataset from 1984 to 2022, amended with the final fire perimeter for the 2022 Hermits Peak/Calf Canyon Fire, and then dissolved these perimeters to delineate the portions of the SRME and SFSR that burned at least once during that time period. We did not analyze fire severity distributions as that was beyond the scope of this study. We rasterized the fire footprint data as described previously and combined it with our GAP status raster as well as our WUI raster. We also created a raster denoting existing wilderness, upper-tier IRAs in Colorado, and non-upper-tier Colorado IRAs, as well as IRAs in Wyoming and New Mexico, and then combined this with the fire footprint raster.

To determine where mechanical thinning operations have been taking place on national forest land in the SRME and SFSR relative to WUI areas, we extracted from the USDA Forest Service's Forest Activities Tracking System (FACTS) database (<https://data.fs.usda.gov/geodata/edw/datasets.php> (accessed on 18 April 2024)) all activity polygons with a completion date during or after 2014 and before 2024 and which had a treatment type of "thinning" in the hazardous fuels dataset in FACTS, or an activity name

of “commercial thinning” in the timber harvest dataset in FACTS, or an activity name of “precommercial thinning” in the timber stand improvement dataset in FACTS. We merged and dissolved these polygons to delineate the 2014–2023 mechanical thinning footprint in national forests across the SRME and SFSR. Next, we dissolved our WUI dataset and added to it four buffer zones at 250 m increments from the edge of any WUI outer boundary. We then intersected our thinning footprint vector dataset with these buffer zones to determine the area and percentage that was conducted within 250 m, 500 m, 750 m, 1 km, and >1 km of a WUI area.

2.7. Downscaled Climate Projections

The extreme topographic relief of the Rockies (Figure 1) drives much of the climatic variability within the SRME. The climate is considered a temperate semiarid steppe regime with annual average temperatures ranging from 1.6 °C to 7.2 °C, reaching 10 °C in low-lying valleys [3]. Eastern slopes are much drier due to the montane rain-shadow. Late-summer monsoonal precipitation is characteristic of the SFRS [10]. Overall annual precipitation ranges from <254 mm at the base of mountains to >1.4 m at higher elevations, primarily as snowfall [3].

We used the Climate Toolbox online portal (<https://climatetoolbox.org> (accessed on 3 May 2024)), which includes a collection of web tools visualizing past and present climate and vegetation of the contiguous USA, to project potential climate change scenarios for the study area. Methods, data, and sources for the many different tools are available on the Climate Toolbox website. We calculated historical trends using the “Historical climate tracker” tool, delineated with a rectangle that encompassed the entire study area (see Figure 1). For future climate trend projections across the study area, we input a custom shapefile in the Climate Toolbox portal. In general, future projections were more precisely delineated than historical climate assessment.

Historical values were calculated using the gridMET dataset, which is a gridded surface meteorological dataset covering the continental USA from 1979 to the present, mapping surface weather variables at ~4 km spatial grain [32]. Future projections were produced using a Multivariate Adaptive Constructed Analogs (MACA) version 2 output, based on an ensemble of 20 GCMs (bcc-cs1-1, bcc-csm1-1-m, BNU-ESM, CanESM2, CCSM4, CNRM-CN5, CSIRO-Mk3-6-0, GFDL-ESM2M, GFDL-ESM2G, HADGem2-CC365, HADGem2-ES365, inmcm4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, MRI-CGCM3, NorESM1-M) and 2 scenarios (RCP 4.5 and 8.5) that were downscaled to a ~4 km resolution for compatibility with the gridMET data [32].

We accessed output from the MC2 dynamic global vegetation model [33,34] through the Climate Toolbox Future Vegetation web tool. MC2 was forced with downscaled MACAv2-PRISM data. Historical and future vegetation data, which are sourced from the Integrated Scenarios Project (https://d2k78bk4kdhbpr.cloudfront.net/media/content/files/Integrated_Scenarios_Draft_Final_Report_2014-06-30_V2-1_1.pdf (accessed on 23 March 2024)) were used to simulate potential vegetation changes based on climate variables. The high uncertainty of these projections stems from numerous non-modeled factors such as species dispersal capabilities, competition among species, and natural successional dynamics.

We accessed streamflow projections through the Climate Toolbox Future Streamflows web tool, also sourced from the Integrated Scenarios Project (https://d2k78bk4kdhbpr.cloudfront.net/media/content/files/Integrated_Scenarios_Draft_Final_Report_2014-06-30_V2-1_1.pdf (accessed on 3 May 2024)). Streamflow data were generated from the non-regulated stream routing of VIC (version 4.1.2) hydrologic outputs, utilizing a large-scale river-routing scheme [35] and forced with MACAv2-LIVNEHv13 downscaling of the CMIP5 global climate model outputs.

3. Results

3.1. Landownerships and Gap Status

Nearly half (48.5%) of the 14.5 M ha SRME is managed by the USDA Forest Service; 34% is private surface ownership, 8.2% is managed by the U.S. Bureau of Land Management (BLM), 3.9% is by various state agencies, 2.9% is by Native American tribes, 1.3% is by the National Park Service, and the remainder is managed by multiple agencies and entities (Figure 2, Table 1). Landownership distribution is similar in the SFSR (e.g., 46.3% is managed by the USDA Forest Service), with the exception of distinctly more tribal ownership (12.1%) and the complete lack of BLM land (Table 1 vs. Table 2).

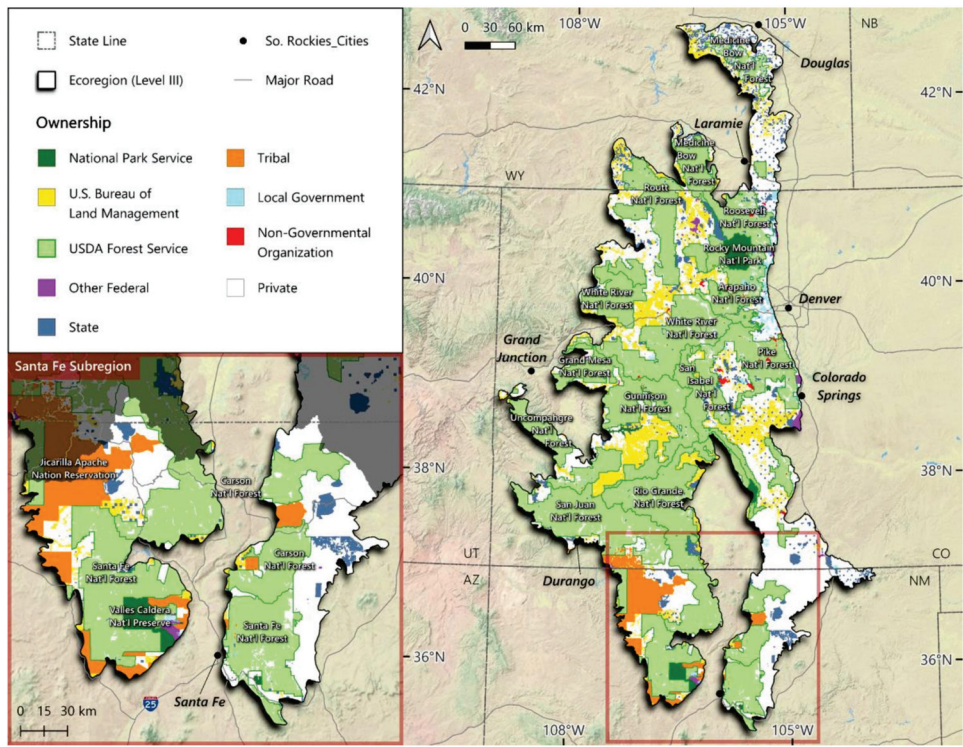


Figure 2. Surface ownership distribution across the Southern Rocky Mountains Ecoregion and Santa Fe Subregion, Wyoming to New Mexico.

Table 1. Landownerships and GAP status for the Southern Rocky Mountains Ecoregion.

Southern Rocky Mountains Ecoregion						
Owner Category	GAP ha					Total Owner Category ha
	(%)					
	1	2	2.5	3	4	(%)
National Park Service	139,643 (72.3)	40,539 (21.0)	1 (0.0)	8684 (4.5)	4302 (2.2)	193,170 (1.3)
U.S. Bureau of Land Management	20,911 (1.8)	104,967 (8.8)	143 (0.0)	1,059,753 (88.8)	7847 (0.7)	1,193,622 (8.2)
USDA Forest Service	1,486,778 (21.2)	510,940 (7.3)	1,396,938 (19.9)	3,614,900 (51.5)	9478 (0.1)	7,019,033 (48.5)
Other Federal ¹	20 (0.0)	10,866 (21.6)	0 (0.0)	497 (1.0)	39,025 (77.4)	50,408 (0.3)
State	79 (0.0)	52,332 (9.4)	353 (0.1)	303,385 (54.3)	202,997 (36.3)	559,145 (3.9)

Table 1. Cont.

Southern Rocky Mountains Ecoregion						
Owner Category	GAP ha					Total Owner Category ha
	(%)					
	1	2	2.5	3	4	(%)
Local Government	1284 (1.5)	24,838 (28.3)	43 (0.0)	8924 (10.2)	52,801 (60.1)	87,889 (0.6)
Tribal	1 (0.0)	274 (0.1)	64 (0.0)	174 (0.0)	413,551 (99.9)	414,064 (2.9)
Non-Governmental Organization	128 (0.4)	22,579 (70.2)	10 (0.0)	2263 (7.0)	7185 (22.3)	32,165 (0.2)
Private	2326 (0.0)	209,099 (4.2)	2174 (0.0)	108,796 (2.2)	4,603,628 (93.5)	4,926,023 (34.0)
Total GAP ha (%)	1,651,170 (11.4)	976,433 (6.7)	1,399,726 (9.7)	5,107,376 (35.3)	5,340,813 (36.9)	14,475,519

¹ Includes U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, U.S. Department of Agriculture (non-Forest Service), U.S. Department of Defense, U.S. Department of Energy, U.S. Department of Interior (non-Bureau of Land Management, non-National Park Service, non-Fish and Wildlife Service), and U.S. Fish and Wildlife Service.

Table 2. Landownerships and GAP status for the Santa Fe Subregion.

Southern Rocky Mountains Ecoregion						
Owner Category	GAP ha					Total Owner Category ha
	(%)					
	1	2	2.5	3	4	(%)
National Park Service	12,605 (24.6)	38,609 (75.4)	0 (0.0)	0 (0.0)	0 (0.0)	51,214 (2.3)
U.S. Bureau of Land Management	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
USDA Forest Service	162,852 (16.1)	10,581 (1.0)	99,897 (9.9)	740,343 (73.0)	36 (0.0)	1,013,710 (46.3)
Other Federal ¹	1 (0.0)	8003 (13.3)	2 (0.0)	41,924 (69.6)	10,287 (17.1)	60,217 (2.8)
State	0 (0.0)	31,818 (44.7)	1 (0.0)	8781 (12.3)	30,634 (43.0)	71,234 (3.3)
Local Government	0 (0.0)	2 (0.3)	1 (0.1)	0 (0.0)	893 (99.6)	897 (0.0)
Tribal	1 (0.0)	274 (0.1)	64 (0.0)	45 (0.0)	264,245 (99.9)	264,630 (12.1)
Non-Governmental Organization	0 (0.0)	215 (100.0)	0 (0.0)	0 (0.0)	0 (0.0)	215 (0.0)
Private	86 (0.0)	1272 (0.2)	380 (0.1)	7311 (1.0)	716,884 (98.8)	725,933 (33.2)
Total GAP ha (%)	175,546 (8.0)	90,775 (4.1)	100,345 (4.6)	798,404 (36.5)	1,022,980 (46.8)	2,188,050

¹ Includes U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, U.S. Department of Agriculture (non-Forest Service), U.S. Department of Defense, U.S. Department of Energy, U.S. Department of Interior (non-Bureau of Land Management, non-National Park Service, non-Fish and Wildlife Service), and U.S. Fish and Wildlife Service.

Notably, only 18.2% and 12.1% of the SRME and SFSR, respectively, are within designated protected areas (GAP 1 and 2) (Tables 1 and 2). With stepped-up protection for

IRAs (i.e., IRAs+), protection levels would rise to 27.8% for the SRME, which is close to the 30×30 target but considerably below the 50×50 target (Table 1). The SFRS is even further below both targets with just 16.8% if IRAs+ were added (Table 2). Even if all currently proposed wilderness (210,486 ha) areas in Colorado were signed into law, protection levels would only marginally increase across the SRME (18.9% or 28.2% with IRA+ added). The SFSR would not see any changes as none of the lands are included in any of the wilderness proposals for which we had spatial datasets.

The USDA Forest Service, the major landowner within the SRME, has protected just 28.5% of its lands across the ecoregion, with an additional 19.9% within IRAs+, which would approach (48.4% total) the 50×50 target. In contrast, the agency has protected just 17.1% of national forest lands within the SFSR, with an additional 9.9% within IRAs+, which would fall below (27%) even the 30×30 target.

3.2. Existing Vegetation Type Representation Analysis

Not surprisingly, for both the SRME and SFRS, only the upper-elevation areas (sparse, subalpine forest, snow–ice, barren, and alpine) met either the 30×30 or 50×50 targets (Tables 3 and 4). By contrast, none of the low–mid-elevation forest types, where forest management and development are concentrated, were even close to the targets. For example, 65.9% of the alpine habitat already has GAP 1 or 2 status across the SRME, despite accounting for only 1.3% of the entire ecoregion. Similarly, 40.4% of the subalpine forest in the SRME has GAP 1 or 2 status, and this would increase to 57% with IRA+ added. However, only 5.4% of the ponderosa pine forest—which accounts for about 15.2% of the SRME—is within designated protected areas, and this number would only increase to 10.5% with IRA+ added (Table 3). Such low levels of protection for lower-elevation forests are even more apparent in the SFSR, where only 5.1% of ponderosa pine forests has GAP 1 or 2 status, despite accounting for 30.2% of the total area of the SFSR (Table 4).

Table 3. GAP status of Existing Vegetation Type categories (see Table S2 for definition of categories) for the Southern Rocky Mountains Ecoregion.

Southern Rocky Mountains Ecoregion						
Existing Vegetation Type (EVT) Category	GAP ha					Total EVT Category ha
	(%)					(%)
	1	2	2.5	3	4	
Agricultural	269 (0.1)	11,263 (4.4)	1008 (0.4)	22,927 (8.9)	221,516 (86.2)	256,983 (1.8)
Alpine	90,446 (49.9)	29,059 (16.0)	22,827 (12.6)	29,109 (16.1)	9781 (5.4)	181,223 (1.3)
Aspen and Mixed-Conifer Forest	5177 (7.5)	2484 (3.6)	17,949 (26.1)	33,109 (48.2)	9966 (14.5)	68,684 (0.5)
Aspen Forest and Woodland	107,598 (8.4)	92,004 (7.2)	236,841 (18.5)	500,609 (39.1)	343,511 (26.8)	1,280,563 (8.8)
Barren	52,872 (39.6)	13,289 (10.0)	18,192 (13.6)	26,440 (19.8)	22,601 (16.9)	133,395 (0.9)
Developed	1443 (0.7)	4819 (2.2)	541 (0.2)	42,593 (19.6)	167,541 (77.2)	216,938 (1.5)
Grassland	80,727 (5.6)	95,578 (6.6)	71,477 (5.0)	386,897 (26.8)	807,428 (56.0)	1,442,106 (10.0)
Limber Pine Woodland	4 (0.1)	237 (6.1)	26 (0.7)	2165 (55.2)	1489 (38.0)	3921 (0.0)
Lodgepole Pine Forest	114,905 (13.8)	64,508 (7.8)	137,148 (16.5)	408,600 (49.2)	106,138 (12.8)	831,299 (5.7)

Table 3. Cont.

Southern Rocky Mountains Ecoregion						
Existing Vegetation Type (EVT) Category	GAP ha					Total EVT Category ha
	(%)					
	1	2	2.5	3	4	
Mixed-Conifer Forest	91,210 (7.6)	87,846 (7.3)	154,977 (12.9)	506,968 (42.1)	362,187 (30.1)	1,203,189 (8.3)
Pinyon-Juniper	18,355 (1.9)	50,682 (5.3)	36,605 (3.8)	386,388 (40.4)	463,682 (48.5)	955,712 (6.6)
Ponderosa Pine	35,994 (1.6)	83,489 (3.8)	112,688 (5.1)	842,012 (38.2)	1,130,986 (51.3)	2,205,170 (15.2)
Riparian	21,052 (8.6)	13,503 (5.5)	17,583 (7.2)	80,563 (32.8)	113,188 (46.0)	245,889 (1.7)
Shrubland	67,705 (2.7)	127,211 (5.2)	118,569 (4.8)	904,887 (36.7)	1,250,583 (50.7)	2,468,954 (17.1)
Snow-Ice	41,221 (67.2)	8151 (13.3)	2358 (3.8)	7225 (11.8)	2348 (3.8)	61,304 (0.4)
Sparse	162,830 (54.8)	35,553 (12.0)	39,627 (13.3)	43,009 (14.5)	16,005 (5.4)	297,024 (2.1)
Subalpine Forest	747,527 (30.6)	240,071 (9.8)	405,574 (16.6)	836,305 (34.3)	211,538 (8.7)	2,441,016 (16.9)
Water	3725 (5.9)	5335 (8.5)	1698 (2.7)	21,600 (34.4)	30,441 (48.5)	62,799 (0.4)
Wetland	8111 (6.8)	11,349 (9.5)	4037 (3.4)	25,971 (21.8)	69,883 (58.6)	119,351 (0.8)
Total GAP ha (%)	1,651,170 (11.4)	976,433 (6.7)	1,399,726 (9.7)	5,107,376 (35.3)	5,340,813 (36.9)	14,475,519 (100%)

Table 4. GAP status of Existing Vegetation Type categories (see Table S2 for definition of categories) for the Santa Fe Subregion.

Santa Fe Subregion						
Existing Vegetation Type (EVT) Category	GAP ha					Total EVT Category ha
	(%)					
	1	2	2.5	3	4	
Agricultural	40 (0.1)	455 (1.5)	101 (0.3)	1833 (6.2)	27,075 (91.8)	29,505 (1.3)
Alpine	453 (22.6)	141 (7.0)	25 (1.2)	182 (9.1)	1208 (60.1)	2009 (0.1)
Aspen and Mixed-Conifer Forest	306 (7.9)	371 (9.6)	172 (4.4)	890 (23.0)	2136 (55.1)	3875 (0.2)
Aspen Forest and Woodland	9814 (12.7)	4648 (6.0)	3495 (4.5)	30,877 (39.9)	28,563 (36.9)	77,397 (3.5)
Barren	4045 (46.2)	438 (5.0)	290 (3.3)	799 (9.1)	3185 (36.4)	8757 (0.4)
Developed	223 (0.8)	668 (2.5)	97 (0.4)	4544 (16.8)	21,545 (79.6)	27,077 (1.2)
Grassland	6756 (5.6)	11,666 (9.7)	4544 (3.8)	30,197 (25.0)	67,543 (56.0)	120,706 (5.5)

Table 4. Cont.

Santa Fe Subregion						
Existing Vegetation Type (EVT) Category	GAP ha					Total EVT Category ha
	(%)					
	1	2	2.5	3	4	
Limber Pine Woodland	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Lodgepole Pine Forest	0.1 (4.3)	1 (39.1)	1 (52.2)	0.1 (4.3)	0 (0.0)	2 (0.0)
Mixed-Conifer Forest	40,613 (11.2)	20,745 (5.7)	26,675 (7.4)	159,960 (44.2)	113,726 (31.4)	361,719 (16.5)
Pinyon–Juniper	13,342 (3.5)	8390 (2.2)	20,138 (5.3)	145,166 (37.9)	196,042 (51.2)	383,078 (17.5)
Ponderosa Pine	16,241 (2.5)	17,185 (2.6)	21,711 (3.3)	298,328 (45.1)	308,192 (46.6)	661,657 (30.2)
Riparian	948 (4.8)	1146 (5.8)	495 (2.5)	4920 (24.9)	12,284 (62.1)	19,793 (0.9)
Shrubland	15,066 (5.8)	13,315 (5.2)	10,137 (3.9)	64,256 (24.9)	155,022 (60.1)	257,795 (11.8)
Snow–Ice	9 (43.9)	0 (0.0)	0 (0.0)	0 (0.0)	12 (56.1)	21 (0.0)
Sparse	1206 (35.5)	146 (4.3)	271 (8.0)	650 (19.1)	1122 (33.1)	3395 (0.2)
Subalpine Forest	66,104 (31.1)	8037 (3.8)	12,129 (5.7)	53,830 (25.3)	72,629 (34.1)	212,730 (9.7)
Water	91 (1.9)	351 (7.2)	3 (0.1)	118 (2.4)	4298 (88.4)	4860 (0.2)
Wetland	289 (2.1)	3072 (22.5)	60 (0.4)	1855 (13.6)	8397 (61.4)	13,673 (0.6)
Total GAP ha (%)	175,546 (8.0)	90,775 (4.1)	100,345 (4.6)	798,404 (36.5)	1,022,980 (46.8)	2,188,050 (100.0)

Other EVT categories also have surprisingly low representation in designated protected areas. Only 7.2% and 5.7% of pinyon–juniper forests in the SRME and SFSR, respectively, have GAP 1 or 2 status (Tables 3 and 4). Shrubland habitats account for 17.1% of the SRME, but only 7.9% of these habitat types is within designated protected areas (Table 3). And importantly, only 14.1% and 10.6% of riparian EVTs in the SRME and SFSR, respectively, have a GAP status of 1 or 2 (Tables 3 and 4). With IRAs+, riparian protection would increase to 21.3% and 13.1% in the SRME and SFSR, respectively, which are still well below even the 30 × 30 target.

3.3. Mature and Old-Growth Forest Representation Analysis

The SRME contains some 2,760,948 ha and the SFRS has 601,322 ha of MOG forests (21.8% of the ecoregion MOG), with the rest in structurally younger forest classes (Table 5). Notably, only 21.5% and 16.1% of MOG forests at the ecoregional and subregional scale, respectively, are protected with GAP 1 and 2 status (Table 5). With the inclusion of IRAs+, MOG forest protection levels would rise to 37.9% and 22.9%, respectively, but these are still below most conservation targets.

Table 5. Forest structure classes (based on [25]) and GAP status within the Southern Rocky Mountains Ecoregion and Santa Fe Subregion.

Southern Rocky Mountains Ecoregion						
Forest Structure Class	GAP ha					Total Forest Structure Class ha
	(%)					
	1	2	2.5	3	4	(%)
Young	214,080 (14.1)	110,619 (7.3)	189,426 (12.5)	618,906 (40.9)	381,940 (25.2)	1,514,970 (22.9)
Intermediate	274,961 (11.8)	160,632 (6.9)	302,829 (13.0)	967,726 (41.5)	625,263 (26.8)	2,331,411 (35.3)
Mature	387,317 (14.0)	206,024 (7.5)	438,769 (15.9)	1,078,196 (39.1)	650,641 (23.6)	2,760,947 (41.8)
Total GAP ha	876,358 (13.3)	477,275 (7.2)	931,024 (14.1)	2,664,829 (40.3)	1,657,843 (25.1)	6,607,329 (100.0)
Santa Fe Subregion						
Forest Structure Class	GAP ha					Total Forest Structure Class ha
	(%)					
	1	2	2.5	3	4	(%)
Young	16,957 (8.8)	10,126 (5.2)	9021 (4.7)	78,272 (40.5)	78,996 (40.9)	193,372 (15.9)
Intermediate	33,504 (7.9)	18,373 (4.4)	19,557 (4.6)	182,556 (43.3)	167,959 (39.8)	421,949 (34.7)
Mature	74,385 (12.4)	22,007 (3.7)	41,420 (6.9)	275,932 (45.9)	187,588 (31.2)	601,332 (49.4)
Total GAP ha	124,846 (10.3)	50,505 (4.2)	69,999 (5.8)	536,760 (44.1)	434,542 (35.7)	1,216,653 (100.0)

3.4. Focal Species Distributions and GAP Status

3.4.1. Wolverine

Wolverine habitat connectivity spans the SRME, providing potentially suitable north–south and east–west linkage zones to varying degrees (Figure 3). The highest connectivity scores are clustered in the center of the SRME (around Gunnison, Colorado, dark purple area) and along northwest portions of the SRME southwest of Laramie, Wyoming (Figure 3), as well as within the southeastern section of the SFSR (Figure 3 inset).

Areas in the upper tiers of connectivity scores across the SRME are meeting the 30% but not the 50% targets (32.2% and 31% of areas with 90th percentile and 95th percentile of connectivity scores, respectively; Table 6). With the inclusion of IRAs+, approximately 49% of each tier would be protected, which nearly meets the 50% target. For the SFSR, only 14.7% and 26.5% of the 90th percentile and 95th percentile connectivity tiers, respectively, are protected. With the inclusion of IRAs+, 16.7% and 28.6% of each tier, respectively, would be protected, which are below the 30% target (Table 6).

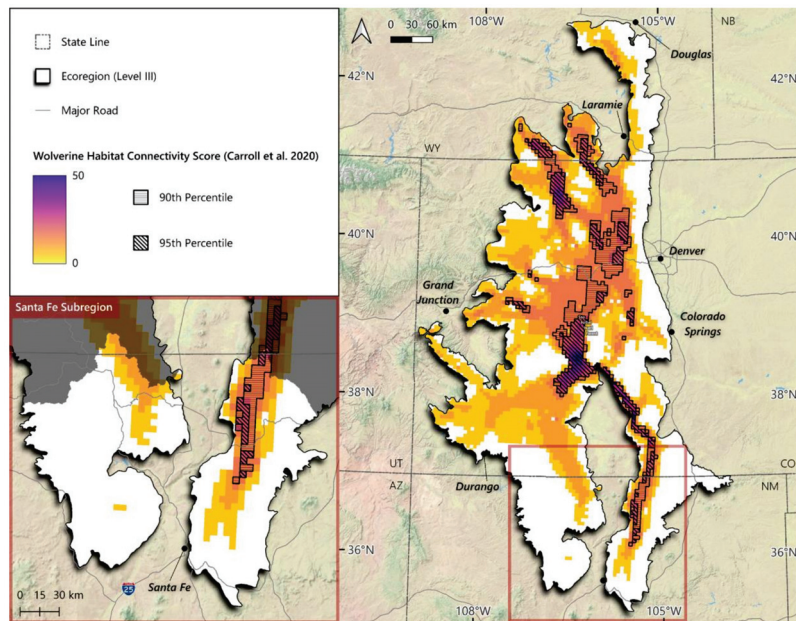


Figure 3. Wolverine connectivity scores for the Southern Rockies Ecoregion and Santa Fe Subregion based on Carroll et al. [26]. Note the clustering of dark colors that may act as important linkage zones for connectivity and dispersal of wolverine across the ecoregion.

Table 6. GAP status of upper tiers of wolverine habitat connectivity across the Southern Rocky Mountains Ecoregion and Santa Fe Subregion.

Southern Rocky Mountains Ecoregion						
Wolverine Habitat Connectivity Tier	GAP ha					Wolverine Habitat Connectivity Tier ha
	(%)					
	1	2	2.5	3	4	
90th Percentile	370,568 (23.2)	142,632 (8.9)	259,856 (16.3)	565,749 (35.5)	255,199 (16.0)	1,594,004 (66.7)
95th Percentile	186,999 (23.5)	59,476 (7.5)	145,152 (18.3)	299,470 (37.7)	104,002 (13.1)	795,099 (33.3)
Total GAP ha	557,567 (23.3)	202,108 (8.5)	405,008 (17.0)	865,219 (36.2)	359,201 (15.0)	2,389,103
Santa Fe Subregion						
Wolverine Habitat Connectivity Tier	GAP ha					Wolverine Habitat Connectivity Tier ha
	(%)					
	1	2	2.5	3	4	
90th Percentile	16,567 (14.7)	4 (0.0)	2224 (2.0)	45,033 (39.9)	49,005 (43.4)	112,833 (73.9)
95th Percentile	10,559 (26.5)	2 (0.0)	809 (2.0)	13,624 (34.2)	14,807 (37.2)	39,801 (26.1)
Total GAP ha	27,126 (17.8)	6 (0.0)	3033 (2.0)	58,657 (38.4)	63,812 (41.8)	152,634

3.4.2. Mexican Spotted Owl and Northern Goshawk Representation Analysis

Both the Mexican spotted owl and northern goshawk overlap in old forest habitats across the SRME, with the goshawk using mature forests for both the summer and winter range and the Mexican spotted owl more limited in its distribution (Figure 4). Thus, we combined the analyses of representation on the same figure for these two forest raptors.

For the Mexican spotted owl, the SRME contains 344,789 ha of suitable habitat, while the SFRS contains 193,419 ha (56% of the total) (Table 7). Levels of protection range from

5.8% in the SFSR to 7.4% in the SRME. The addition of IRAs+ would approximately double their protection levels (12 and 17% in the SFSR and SRME, respectively), but these would still be well below the conservation targets.

Table 7. Suitable habitat for Mexican spotted owl, northern goshawk, and Canada lynx, along with their GAP status within the Southern Rocky Mountains Ecoregion and Santa Fe Subregion.

Southern Rocky Mountains Ecoregion						
Focal Species	GAP ha					Total Focal Species Suitable Habitat ha
	($\%$)					
	1	2	2.5	3	4	
Mexican Spotted Owl	7912 (2.3)	17,767 (5.2)	32,989 (9.6)	181,424 (52.6)	104,697 (30.4)	344,789 (2.7)
Northern Goshawk	995,417 (10.3)	637,456 (6.6)	1,041,847 (10.7)	3,732,433 (38.5)	3,299,723 (34.0)	9,706,876 (75.2)
Canada Lynx	558,604 (19.6)	258,103 (9.0)	520,036 (18.2)	1,163,796 (40.7)	356,529 (12.5)	2,857,068 (22.1)
Total GAP ha	1,561,934 (12.1)	913,326 (7.1)	1,594,872 (12.4)	5,077,653 (39.3)	3,760,949 (29.1)	12,908,733
Santa Fe Subregion						
Focal Species	GAP ha					Total Focal Species Suitable Habitat ha
	($\%$)					
	1	2	2.5	3	4	
Mexican Spotted Owl	7218 (3.7)	4054 (2.1)	11,312 (5.8)	112,238 (58.0)	58,596 (30.3)	193,419 (9.9)
Northern Goshawk	130,313 (7.4)	65,243 (3.7)	83,743 (4.7)	684,744 (38.8)	800,875 (45.4)	1,764,918 (90.1)
Canada Lynx	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Total GAP ha	137,531 (7.0)	69,297 (3.5)	95,056 (4.9)	796,982 (40.7)	859,471 (43.9)	1,958,337

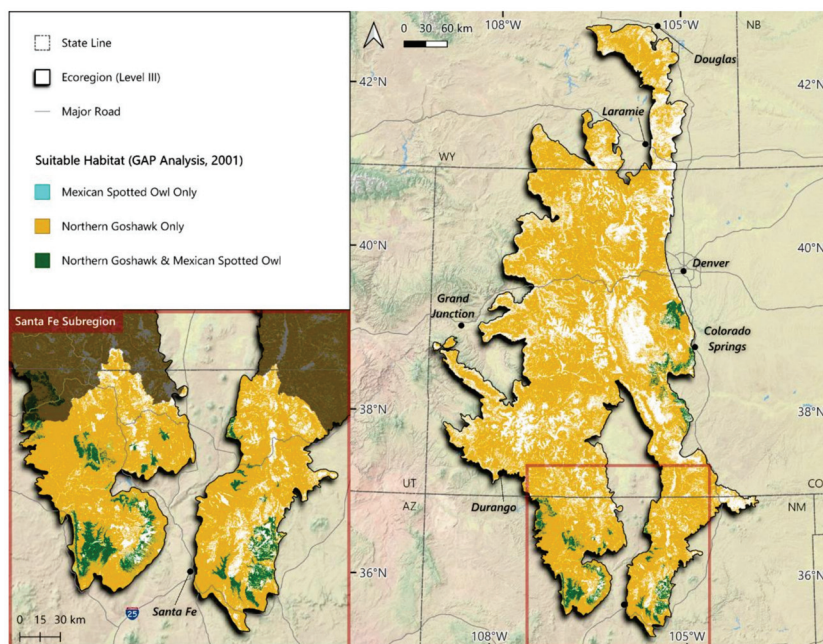


Figure 4. Suitable habitat for both the Mexican spotted owl and northern goshawk in the Southern Rocky Mountains Ecoregion and Santa Fe Subregion.

3.4.3. Canada Lynx Representation Analysis

The SRME contains ~2.9 M ha for Canada lynx habitat with no existing habitat identified in the SFSR (Table 7). Nearly 29% of suitable lynx habitat is protected, and IRAs+ would increase that to 46.8%, which is near the 50×50 target. While the historic range of the lynx includes northern New Mexico according to Thornton and Murray [36], no extant habitat was identified in the SFRS according to the 2001 GAP Analysis data (see Section 4).

3.5. WUI, Wildfires, and Forest Thinning

From 1984 to 2022, ~1.27 M ha (8.8%) of the SRME and 366,839 ha (16.8%) of the SFRS experienced a wildfire, with a substantially lower proportion of the total wildfire footprint intersecting the WUI within the SRME (2.3%) and the WUI in the SFRS (1.5%) (Figure 5, Table 8). Most of the WUI in the SRME is considered low-density intermix (75.6%) and medium-density intermix (12.7%). The same general pattern was observed within the SFSR, with 77% and 11.1% of the WUI being considered low-density and medium-density intermixes, respectively. Of the WUI that intersected the total fire footprint, 88.5% and 90.9% were a low-density intermix in the SRME and SFSR, respectively (Table 8).

Table 8. Wildland–Urban Interface/Intermix class distribution across the SRME and SFSR and the relative proportions that were intersected by at least one fire between 1984 and 2022.

Wildland–Urban Interface/Intermix (2020) Class	Southern Rocky Mountains Ecoregion		Santa Fe Subregion	
	All ha	Burned ha	All ha	Burned ha
	(%)	(%)	(%)	(%)
Low-Density Intermix	410,361 (75.6)	25,685 (88.5)	51,441 (77.0)	4909 (90.9)
Medium-Density Intermix	69,114 (12.7)	1442 (5.0)	7392 (11.1)	166 (3.1)
High-Density Intermix	237 (0.0)	2 (0.0)	26 (0.0)	1 (0.0)
Low-Density Interface	25,640 (4.7)	1536 (5.3)	5086 (7.6)	165 (3.1)
Medium-Density Interface	31,149 (5.7)	295 (1.0)	2495 (3.7)	113 (2.1)
High-Density Interface	6097 (1.1)	78 (0.3)	357 (0.5)	48 (0.9)
Total ha (%) ¹	542,599 (3.8)	29,037 (2.3)	66,797 (3.1)	5402 (1.5)

¹ The first and third columns are the percentages of the SRME and SFSR, respectively. The second and fourth columns are the percentages of the total burned area within the SRME (1,270,603 ha) and SFSR (366,839 ha), respectively.

We also found that 12.6% (160,046 ha) of the total fire footprint in the SRME overlapped existing wilderness, with 11.4% (41,844 ha) overlapping in the SFSR. Upper-tier IRAs in Colorado represented only about 3.4% (43,244 ha) of the total fire footprint in the SRME. Non-upper tier-IRAs in Colorado and IRAs in Wyoming and New Mexico represented 14% (177,324 ha) and 8% (29,507 ha) of the total fire footprint in the SRME and SFSR, respectively.

Notably, 73.5% of the total area thinned by the USDA Forest Service between 2014 and 2023 in the SRME (47,174 ha) and 79.7 of the total area thinned in the SFSR (16,874 ha) were >1 km away from the WUI. Only 8.1% of the thinned area in the SRME (2813 ha) and 4.4% in the SFSR (746 ha) were within 250 m of a WUI area.

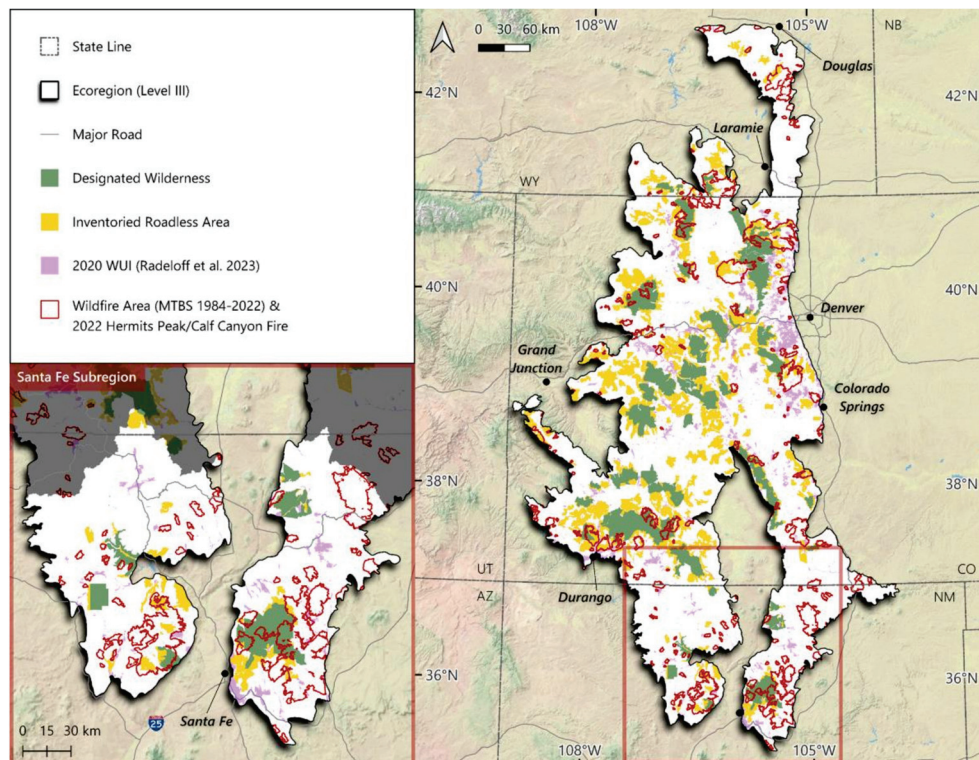


Figure 5. Wildfires within the Southern Rocky Mountains Ecoregion and Santa Fe Subregion (1984–2022) in the Wildland–Urban Interface [31], wilderness, and Inventoried Roadless Areas. IRAs and designated wilderness are shown.

3.6. Climate Change

3.6.1. Historical Trends

From 1979 to 2023, the average temperature across the study area increased by 1.2 °C, as obtained from the Climate Toolbox (Table 9). The minimum temperature increased by 1.5 °C, while the maximum temperature increased by 0.8 °C, on average. Additional historical changes have included a longer frost-free season, declining average annual precipitation, more drought, and reduced snowpack (Table 9).

Table 9. Historical (1979–2023) climate changes for the Southern Rocky Mountains Ecoregion ¹.

Average Annual Temperature	+1.2 °C
Maximum Temperature	+0.8 °C
Minimum Temperature	+1.5 °C
Frost-Free Season	+29 days longer frost-free season
Annual Precipitation	−15%
Drought ²	Increasing frequency
Snowpack ³	<20% at most sites

¹ GridMET gridded surface meteorological dataset accessed from <https://climatetoolbox.org>; accessed on 4 April 2024. ² Palmer Drought Severity Index (PDSI) accessed from <https://climatetoolbox.org>; accessed on 4 April 2024. ³ EPA 2023. <https://www.epa.gov/climate-indicators/climate-change-indicators-snowpack> (accessed on 10 May 2024) [37].

3.6.2. Future Projections under Two Emission Scenarios

Temperature Projections. The lower-emissions trajectory (RCP4.5) indicates that average warming in the SRME could be limited to 3.0 °C (range from 1.7° to 4.3 °C) by the end of the century (Figure 6). The higher-emissions trajectory (RCP8.5) indicates a more

extreme average annual temperature increase of 5.2 °C (range from 3.5° to 7.2 °C) by the end of the century when compared to the historical average from 1951 to 1980 (Figure 6).

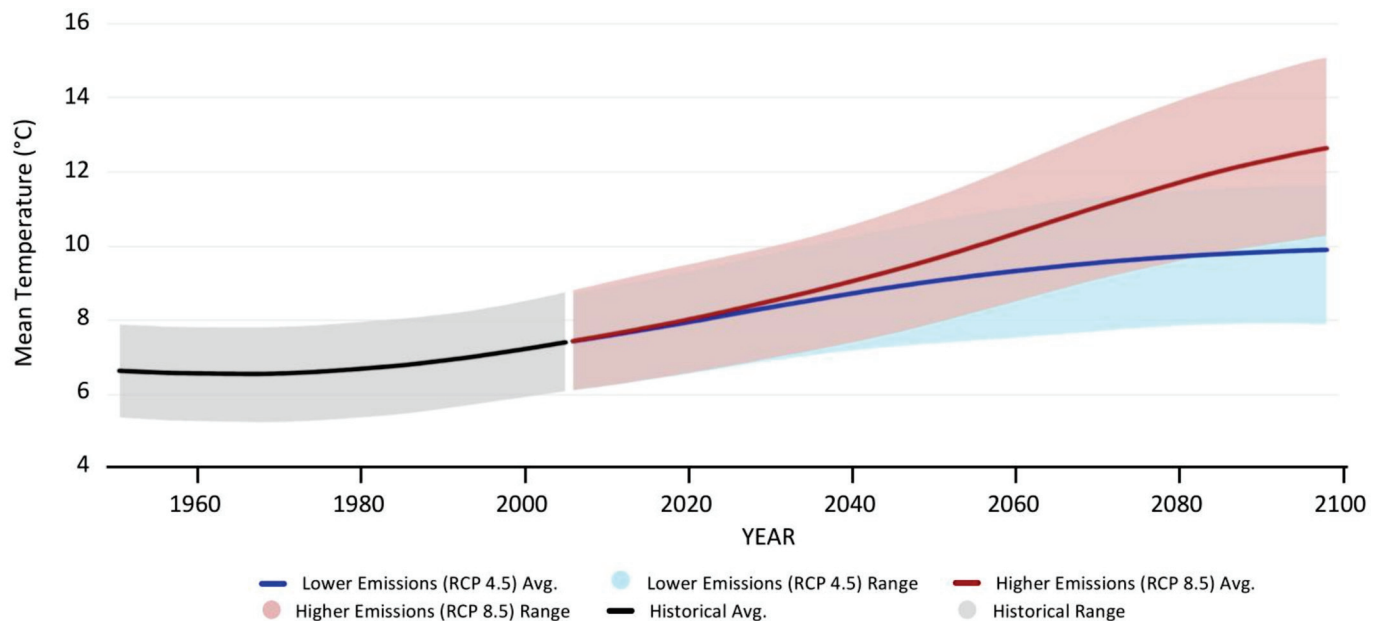


Figure 6. Mean temperature across the study area from 1950 to 2100 under the lower (blue) and higher (pink) emissions scenarios. Graph created with Climate Toolbox Future Time Series web tool [38].

Heat Wave Projections. More frequent days of high heat are expected in the SRME as climate change intensifies over the century (Table 10). An additional 40 days/yr with extreme heat >32 °C are projected by the end of the century if emissions continue unabated (RCP8.5). However, if emissions are reduced, additional severe heat days could be limited to approximately 15 days/yr, on average, by the end of the century.

Table 10. Estimated number of additional days per year over 32 °C, 38 °C, and 41 °C across the Southern Rocky Mountains Ecoregion based on continued high emission (RCP8.5) vs. low emission (RCP4.5) scenarios for two time periods (2040–2069, 2070–2099). Data accessed from Climate Toolbox Future Box Plots web tool [38].

Years	RCP8.5			RCP4.5		
	>32 °C	>38 °C	>41 °C	>32 °C	>38 °C	>41 °C
2040–2069	+19.6	+1.3	+0.1	+12.3	+0.4	+0.0
2070–2099	+39.3	+6.4	+1.1	+15.2	+0.7	+0.0

Precipitation Projections. High year-to-year variation in annual precipitation (Figure S1) makes long-term trends more difficult to assess (Figure S2), and thus we have placed these results in the Online Supplementary Material. The study area could experience a range of future precipitation trends, from a potential increase of ~26% to a decline of ~20% (Figure S2). Average precipitation change is projected at +6%, while uncertainty in the precipitation projections is quite high. However, both evapotranspiration and the Climatic Water Deficit (CWD), a measure of water stress based on the evaporative demand in plants, are expected to increase (Figures S3 and S4). Thus, even if annual precipitation increases, the hotter temperatures mean that more plant stress and evaporative losses would occur. Further, as warming of the SRME intensifies, precipitation is expected to increasingly fall as rain instead of snow, leading to continued declines of 40–92% in snowpack if emissions continue unabated and 22–72% if emissions are reduced (Figures S5 and S6).

Streamflow Projections. Streamflow in the Southern Rockies generally peaks in June when the snowpack recedes. Gradual snowmelt at higher elevations continues through the summer months, feeding summer streamflow. Continued warming is expected to reduce snowpack and cause faster runoff from rainfall in the winter, leading to earlier peak flows (Figure S7). With less snow, lower summer flows and more extreme conditions are expected.

Vegetation Projections. As climate change intensifies, dominant vegetation types are expected to shift, affecting wildlife habitat suitability and wildfire behavior. Uncertainties in vegetation response to changes in climate are related to many factors, including insect outbreaks, wildfires, drought response, plant dispersal mechanisms, plant establishment, and species competition. Results from the functional vegetation model indicate that the distribution of conifer forests may constrict while woodland and shrubland distributions expand (Figure S8) (MC2 model) [33,34].

4. Discussion

4.1. Representation and Importance of Protected Areas

Our ECA builds on prior conservation plans for the SRME and SFSR that are over two decades old with little success toward initial target setting [1,3]. One of the interesting findings of our ECA is that while landownership patterns were very similar between the two scales (e.g., USDA Forest Service manages 46%–48% of the area in both cases), there were striking differences in protection levels between the ecoregion and subregion. In nearly all of the representation analyses, the SFSR underperformed not only in the 30×30 and 50×50 targets but also in comparison with the SRME. This underscores the contextual importance of the subregion relative to its larger surroundings, and it highlights the need for greater conservation attention to begin closing the noted gaps in protection. Current wilderness proposals (which are concentrated in the Colorado portion of the SRME), while important, are not enough to increase relative protection levels. This is because most of the total area proposed for wilderness is already GAP 2 or 2.5. Our analysis also highlights the need for policymakers and land-management agencies to explore additional ways to increase the protection level for GAP 3 or 4 lands across the ecoregion.

Additionally, the protected-area network was highly skewed toward upper-elevation EVTs (alpine, barren, sparse, rock, and ice), which is no surprise given this had also been previously reported [1]. In contrast, montane forest, woodland, pinyon–juniper, and riparian areas where wildlife concentrates, including three of our focal species (goshawk, Mexican spotted owl, Canada lynx), were poorly represented. Ponderosa pine forests, particularly, have low levels of protection across both the SRME and SFSR despite accounting for a large proportion of the EVT area. This forest type is also heavily targeted for fuel reduction, involving intensive thinning projects in both the SRME and SFSR. Importantly, there is some evidence suggesting that the white pine–limber pine hybrid zone is moving north in response to climate disruption [39,40]. Nutritious white pine seeds are eaten by a wide diversity of wildlife and have coevolved a mutualistic relationship with Clark’s nutcrackers (*Nucifraga columbiana*) to disperse their large, wingless seeds. A high level of genetic resistance to the exotic white pine blister rust *Cronartium ribicola*, a significant stressor to white pines throughout the West, is found within the SFSR [41]. However, despite the need to preserve uniquely resistant populations, the Santa Fe and Carson national forest management plans provide no protection for white pines that are vulnerable when clearing vegetation for fuel reduction.

4.2. Focal Species Conservation

We identified the important habitats for four focal species (Canada lynx, northern goshawk, Mexican spotted owl, and wolverine) at both spatial scales. Other than the wolverine, protection levels for the three other focal species underperformed, and were improved by the addition of IRAs+, but still remained below the conservation targets. Three of the four (all but wolverine) focal species use dense forests—mostly MOG forests—although

Canada lynx forage on snowshoe hares using forest openings [27]. The MOG forest' protection's underperformance was striking for the SFSR, where MOG was concentrated but poorly represented in protected areas. For northern goshawks and Mexican spotted owls, their dependence on older forests may put them in conflict with much of the USDA Forest Service's fuel reduction projects that, at least for the spotted owl, can degrade habitat [42], although this is currently debated among researchers [43]. Interestingly, the GAP Analysis 2001 habitat suitability dataset did not delineate any Canada lynx habitat within the SFSR. This may have been due to assumptions at the time about the species' historical range. Thornton and Murray [36], however, found that the Canada lynx was historically more widespread than typically thought, with a significant amount of suitable habitat located in the higher elevations of the SFSR. That study also found that Canada lynx suitable habitat across the region will diminish by 2050 and 2070 under a moderate-emissions scenario [36]. Such habitat changes will need to be accounted for when determining where Canada lynx should be reintroduced in the SRME, and our results show that even this relatively high-elevation species would still benefit from increased protection levels.

The situation for wolverines is better overall in terms of habitat protection; however, even high-elevation areas are experiencing recreation pressures [44]. Based on the wolverine connectivity score [26], we identified several linkage zones that may connect portions of the wolverine range, potentially allowing for movements in relation to climate shifts and expansion of wolverine into the southern trailing edge. These include linkage zones around Gunnison, Colorado (central portion of the region), just southwest of Laramie, Wyoming (northern edge), along the spine of the Rockies, and on the eastern flanks of the Santa Fe National Forest (again poorly represented). Additionally, although not modeled here, at mid-elevations, linkage zones are also known to be important for the movements of lynx from their northern to southern range in the Rockies [27].

4.3. Wildfires, Wilderness, and the Wildland–Urban Interface

Fire regimes of the SRME have been described as moderate–high frequency and low–mixed severity at lower elevations (e.g., foothills) with infrequent, high-severity fires in upper montane areas [45–48]. Wildfires tend to peak prior to the arrival of midsummer monsoons in the SFSR. Historically, there have been very large fires (hundreds of thousands to millions of hectares) during drought years in Colorado [47] and New Mexico [48]. Variability in fire regimes throughout the SRME creates the conditions for a mixture of open and closed canopy forests; however, forest densities have been affected by fire suppression (mostly foothills) [47], and logging and livestock grazing in places. Notably, wildfire regimes in large, protected areas across the Rockies seem to be operating within historic bounds [47], possibly due to their highly skewed upper-elevation locations that are difficult to access for fire suppression and vegetation treatments and differences in vegetation types at higher elevations [1]. This is in contrast to areas with less protection and more exposure to logging, which tend to burn more severely [49]. Additionally, outbreaks of bark beetles (*Scolytinae*) and western spruce budworm (*Choristoneura freemani*) have been widespread since the 1990s [50] and linked to global overheating, especially during the winter [51]. Importantly, outbreaks can lower forest canopy fuel profiles, rendering affected areas less prone to subsequent fires [50,52–55]. Outbreaks also tend to be highly concentrated in areas where extensive monoculture forestry has reduced host-tree species variability, simplified structural complexity (e.g., older forest age classes, large trees, snags), and degraded habitat for insectivorous species [56].

Approximately 1.27 M ha of the SRME and 366,839 ha of the SFSR experienced wildfires at least once over the four decades for which we have fire data. Interestingly, existing wilderness and IRAs represented 19.5% to 30% of the total fire footprint in the SFSR and SRME, respectively, despite these designations accounting for 12.8% (281,110 ha) to 24.3% (3,523,888 ha) of the total area in each region. While IRAs were not designated until at least 2001, the disproportionate occurrence of fire in the wilderness and IRAs is still worth noting and may be due to a number of factors. Wilderness areas in the SRME

skew toward upper-elevation areas (the average elevation of the wilderness in the SRME is 3249 m) where subalpine and lodgepole forests dominate, both of which have fire regimes characterized by long fire rotations and large stand-replacing fires. For example, 13.4% (21,414 ha) of the wilderness that burned in the SRME was due to the 2020 Cameron Peak Fire alone. Existing wilderness represents 11.1% of the total land area in the SRME and 12.6% of the total fire footprint, indicating that fire occurrence was also disproportionate in IRAs. These areas tend to be located at lower elevations (the average elevation of upper-tier and non-upper-tier IRAs is 3126 m and 2893 m, respectively) compared to the existing wilderness, and therefore have a greater proportion of forest types with shorter fire rotations such as mixed-conifer and ponderosa pine forests. While we did not conduct an analysis of fire severity distributions, the greater occurrence of fire in IRAs may represent a restorative trajectory toward pre-suppression historical conditions.

The WUI, in particular, represented 2.3% and 1.5% of the total area burned in the ecoregion and subregion, respectively. Most of the wildfire area that intersected the WUI occurred in the low-density intermix class (~90% of the total WUI area burned between 1984 and 2022). This class is also the most abundant WUI type across both the SRME and SFSR. Interestingly, 73.5% to 79.7% of the total area thinned in the SRME and SFSR, respectively, was >1 km away from the WUI. That is, despite the wide distribution of the WUI (542,599 ha across the ecoregion), the vast majority of thinning activities on USDA Forest Service land are occurring at substantial distances from at-risk communities.

Additionally, while the U.S. Forest Service has conducted hundreds of prescribed burns over the past few decades, there have been four controversial prescribed burns since 2000 that escaped containment and destroyed dozens of homes, including the Cerro Grande Fire, the Cerro Pelado Fire, the Hermits Peak, and the Calf Canyon Fire, within the subregion. Based on an analysis of the USDA Forest Service's Fire History Occurrences and Perimeters dataset for Region 3, Hyden [20] estimated that the total area burned since 2014 in the Santa Fe National Forest area by escaped prescribed fires was ~154,830 ha, about 94% of all wildfires. While prescribed burning along with cultural burning practices have many ecological benefits, the substantially large relative area impacted by escaped prescribed fires that do so under extreme fire weather could be a limiting factor in forest recruitment in a changing climate, especially for important habitat types such as MOG forests. Even one escaped burn can shelf all prescribed fires at least temporarily due to controversy with the affected communities and human health issues regarding smoke inhalation (<https://www.fs.usda.gov/about-agency/newsroom/releases/usda-forest-service-chief-randy-moores-statement-announcing-actions> (accessed on 10 May 2024)).

4.4. Climate Change

The Southern Rocky Mountains Ecoregion has already experienced elevated temperatures, increased drought, and reduced snowpack. The velocity of climate change across the ecoregion will depend on the particular emission pathway (RCP4.5 vs. RCP 8.5); however, the current trajectory more closely follows RCP8.5, as emissions continue to rise to unprecedented levels [57]. Climate change may also interact with land use (although not modeled here) to limit the adaptive capacity of focal species and important habitat types. Most notably, projected increases in wildfires would reset forest succession from MOG to complex early seral forests [58], resulting in broad shifts in species assemblages. Further, MC2 model projections indicate that conifer distribution may shrink while woodlands expand and this may affect at least the three focal species using conifer forests in our study area (lynx, spotted owl, goshawk). Continued reductions in snowpack will affect stream flows, with impacts to aquatic species and riparian obligates (e.g., beaver, *Castor canadensis*). At higher elevations, wolverines will be affected due to their propensity to den in snowfields [44].

5. Conclusions and Conservation Recommendations

The biodiversity of the SRME varies across topo-edaphic gradients (e.g., life zones) and is particularly vulnerable to unprecedented land uses and climate change. The protected-areas network, while important in potentially slowing climate change effects [9], poorly represents most EVTs, MOG forests, and suitable habitats for focal species, especially along the trailing edge within the SFRS that might be more vulnerable to higher climate velocities.

We reaffirmed the conservation value of IRAs [1], especially if bumped up in protection status from GAP 2.5 to GAP 2, in helping to meet 30×30 and 50×50 targets. IRAs could be upgraded to IRAs+ by adopting enhanced protective measures (“upper-tier roadless”) of the 1.7 M ha Colorado Roadless Rule applied throughout the ecoregion. IRAs+ could also be advanced to wilderness protection through congressional legislation as proposed in Colorado (e.g., H.R. 803) and New Mexico (Pecos Wilderness Protection Act (not analyzed here, S. 3033, due to lack of spatial data). President Biden’s Executive Order 14,008 pertains to 30×30 [59] and representation targets in this ecoregion could help inform the nation’s overall 30×30 efforts. Notably, all 128 national forest plans are proposed for revision in relation to a nationwide MOG forest draft environmental impact statement in response to President Biden’s Executive Order 14,008 [60]. Our target-setting for MOG forests helps inform the importance of this process underway and the need for strict protections from logging [26] given their pivotal conservation importance.

Our ECA provides an integrated approach to conservation, wildfire risk reduction, and climate change planning in reaffirming the importance of broad conservation targets [1,3,21] and integrating them with effective wildfire risk reductions aimed at the built environment. Most notably, the Forest Service is conducting controversial forest management and fuel-reduction treatments >1 km from the nearest structures, while at least some scientists are calling for wildfire risk reduction targeting the home ignition zone [18,19,61]. A more targeted use of fuel-reduction treatments [61] might allow protected area proposals to advance in association with climate change planning for more fires. Additionally, increased habitat protection for three of the four focal species in our study area (Canada lynx, Mexican spotted owl, and northern goshawk) that utilize forests might improve their chances of surviving climate change and land-use stressors, while additional restrictions are needed on recreation access in high elevation areas to protect wolverines and allow them and lynx to reoccupy the trailing edges of their historic range in search of climate refugia. Intact areas protected from development have the best chance of serving as climate refugia and important linkage zones [8]. Moreover, effective road closures and road obliterations would help in rewilding efforts across the region [62], reduce fragmentation of linkage zones, and lower unwanted human-caused wildfire ignitions [63].

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/land13091432/s1>. Figure S1. Annual precipitation (mm) across the study area, from 1979–2023, showing precipitation lower than the overall mean (441 mm) in red and higher than the mean in blue. The trendline shows an overall decline in precipitation of -16mm/decade ($r = -0.36$, $p = 0.02$). Graph created with gridMET data from Climate Toolbox Historical Climate Tracker web tool (Hegewisch and Abatzoglou, 2023) [38]. Figure S2. Projected future mean precipitation for the study area varies substantially compared to the historical average (1950–2005). Graph created with Climate Toolbox Future Time Series web tool based on MACAv2-METDATA CMIP5 model ensemble (Hegewisch and Abatzoglou, 2023) [38]. Figure S3. Evapotranspiration is projected to increase by 17–37% with higher emissions (RCP8.5) and by 8–23% with lower emissions (RCP4.5). Graph created with Climate Toolbox Future Time Series web tool based on MACAv2-METDATA CMIP5 model ensemble (Hegewisch and Abatzoglou 2024, 2023) [38]. Figure S4. Increasing Climatic Water Deficit (mm), based on continued higher emissions (RCP8.5). Data from 20 GCMs shown, including median (blue line), 5th and 95th percentiles (box), and highest/lowest values (green lines or “whiskers”). Graph downloaded from Climate Toolbox Future Box Plots web tool (Hegewisch and Abatzoglou, 2023) [38]. Figure S5. Winter (Dec-Feb) snow water equivalent (mm) across the study area is projected to decline by 40–92%, as compared to the historical period, by the end of the century. Graph downloaded from Climate Toolbox Future Box Plots web

tool (Hegewisch and Abatzoglou, 2023) [38]. Figure S6. Observed changes in April snowpack across the Western U.S. from 1955–2020. Map by NOAA Climate.gov based on USDA Natural Resources Conservation Snow Data (EPA 2023). Figure S7. MC2 vegetation model results compare modeled 1971–2000 vegetation types (left) to projected vegetation types in 2070–2099 (right) based on ensemble average across 20 GCMs and continued higher emissions (RCP8.5). Limited shifts in dominant vegetation type are expected across the study area by the end of the century, primarily as a loss of subalpine forest, and expansion of shrublands. Graphic downloaded from Climate Toolbox Future Vegetation web tool using MC2-MACAv2-Prism, without fire suppression. Figure S8. Projected streamflow (m^3/s) on the Colorado River at the Glenwood Springs Gauge Station from 2070–2099, as compared to historical flows (1950–2005). Historical flows (dark blue) show a peak in June and lowest flows during winter, while future. Table S1. The 10 southernmost watersheds (8-digit Hydrologic Unit Code) of the Southern Rocky Mountains Ecoregion (SRME), which we used to delineate the Santa Fe Subregion (SFSR). Table S2. Existing Vegetation Types (EVT) as defined by LANDFIRE 2022 within the SRME and the broader categories we created from them. References [37,38] are cited in the Supplementary Materials.

Author Contributions: D.A.D. was the project manager, overseeing all phases of this project, including conceptualization, methods, analysis, and writing. K.A. was involved in workshop organization, data compilation and uploads, manuscript upload, and writing. B.C.B. conducted all GIS analyses and associated writing. M.K. conducted the climate change analysis and associated writing. All authors have read and agreed to the published version of the manuscript.

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Article

The Interconnectivity and Spatio-Temporal Evolution of Rail Transit Network Based on Multi-Element Flows: A Case Study of Beijing-Tianjin-Hebei Urban Agglomeration, China

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Abstract: For intercity transportation within urban agglomerations, rail transit interconnectivity not only stimulates city-to-city interactions but also facilitates the networking of urban spaces. Crucially, comprehending the spatial network of urban agglomerations needs a focus on rail transit interconnectivity. Drawing on the space of flows theory, this study establishes a framework to evaluate rail transit interconnectivity and the spatial structure of urban agglomerations, utilizing the Beijing-Tianjin-Hebei urban agglomeration as a case study. The objective of this study is to explore the impact of rail transit interconnectivity on the spatial structure in the urban agglomeration. Firstly, it establishes a coupled concept of urban quality and line quality to elucidate the interaction between rail transits and urban development. Secondly, it employs the AHP-CRITIC-TOPSIS and modified gravity model to evaluate the interconnectivity degree of rail transits and visualize the network. Thirdly, based on the multi-element flows facilitated by rail transit interconnectivity, the evolution of the spatial structure within the urban agglomeration is quantified using social network analysis. The study findings are as follows: (1) From 2010 to 2021, the interconnectivity degree of rail transit in the Beijing-Tianjin-Hebei urban agglomeration experienced substantial growth, emphasizing the correlation between interconnectivity and the city hierarchy within the urban agglomeration. (2) The interconnectivity degree of the Beijing-Tianjin-Hebei urban agglomeration shows an uneven pattern of “three cores and numerous weak links,” characterized by spatial polarization. (3) Rail transit interconnectivity contributes to shaping the spatial structure of urban agglomerations in terms of interconnectivity, polycentricity, and integration, although the enhancement of polycentricity is limited. The framework developed in this study can be extensively employed to investigate the interplay between rail transit interconnectivity and the spatial structure of urban agglomerations, thereby promoting the sustainability of regional planning.

Keywords: rail transit; urban agglomeration; transport interconnectivity; urban spatial structure; spatio-temporal evolution

1. Introduction

With the accelerated process of urbanization and globalization, urban agglomerations have become a crucial strategy for national development and competition [1]. The increasing demand for enhanced interconnectivity and cooperation among cities in urban agglomerations continues to grow [2]. However, challenges persist within the intercity transportation system, including insufficient interconnectivity, inefficient transportation, and transport pollution [3]. The incoherence between the transportation subsystem and

other urban subsystems has become a significant factor hindering the development of urban agglomerations. In this condition, regional rail transits are regarded as the preferred mode of green transportation for addressing these challenges of intercity transportation, with the advantages of large capacity, high punctuality, fast speed, and low pollution [4,5]. The five megacities, including New York, London, Tokyo, Paris, and the North American Great Lakes region, all alleviated a significant portion of their passenger traffic by developing advanced intercity rail transit systems, which are integrated and coordinated with other modes of transportation [6]. Hence, constructing an interconnected rail transit system that aligns with social needs and urban planning is crucial for promoting the sustainable development of urban agglomerations.

Rail transit not only functions as a carrier for intercity transportation but also plays a guiding role in the spatial structures of urban agglomerations through its interconnectivity [7]. As a transport carrier, rail transits facilitate the physical interconnectivity of urban agglomerations. Cities can foster the exchange, cooperation, and shared utilization of flows, including people, goods, information, energy, and financial resources. The space of flows theory indicates that the high-speed characteristics of multi-element flows enhance the convenience and efficiency of spatial circulation, significantly reducing distances among cities and propelling the networking of the urban spatial structure [8]. At present, the spatial structure of regional systems has been established on the logical foundation of networks, flows, and nodes. As a key aspect of the space of flows theory, the multi-element flows generated by rail transit interconnectivity can reflect variations among cities in terms of connection density, connection strength, and urban hierarchical structure [9]. Therefore, the specific objective of this study is to explore the interaction between rail transit interconnectivity and the spatial structure of the urban agglomeration to guide the networking of spatial structure and optimize spatial order in urban agglomerations.

More existing studies have focused on the interaction between transportation systems and spatial planning at the urban scale, investigating the accessibility of air traffic, railways, and highways, and their impact on urban space [9,10]. The research methodologies evolved from qualitative analysis to quantitative indicator evaluations, and later incorporated techniques such as data mining and Geographic Information Systems (GIS) [11,12], currently being in a phase of integrated development across multiple disciplines. However, regional spatial development is moving towards integration and networking, which can accelerate the movement of elements among cities unrestricted by administrative boundaries. Hence, this study agrees that there is a need to enrich the studies at the urban agglomerations scale, considering the complexity of the spatial planning and formulation of refined policies. For modern intercity transportation systems, interconnectivity is no longer confined to the physical single dimension, presenting a limitation in many existing studies. This study regards it as representing dimensional interactions on the virtual space with multi-element flows. Furthermore, existing studies almost evaluate the rail transit interconnectivity with indicators in terms of line and network attributes and overlook the interaction between rail transit and urban development. Therefore, establishing a scientific evaluation model remains an effective approach to address the current issues of one-sided and singular evaluation indicators that fail to reflect the actual development situation.

Against this background, this study aims to establish a comprehensive framework for evaluating rail transit interconnectivity and examining its role in shaping the spatial structure network at the urban agglomeration scale. The novelty and originality of the evaluation framework can be highlighted as follows. Drawing on the space of flows theory, this study concentrates on the intricate spatial network system of urban agglomerations. It introduces the concept of coupling urban quality with line quality, revealing the interaction mechanisms between rail transit and urban development. Interconnectivity is defined here as the interaction of multi-element flows. Building on this foundation, we first evaluate rail transit interconnectivity and then delve into the spatio-temporal evolution of its network's spatial structure within the urban agglomeration, which can systematically investigate the evolutionary structure, spatial attributes, and specific characteristics of the network. The

evaluation framework streamlines the effective integration of multi-element flows resulting from rail transit interconnectivity within an urban agglomeration. This study enhances the theoretical aspects of rail transit interconnectivity, broadens the utilization of the space of flows theory in urban agglomeration development, and complements research on the coordinated development of rail transit systems and spatial planning.

To fulfill the study objective, we take the Beijing-Tianjin-Hebei (BTH) urban agglomeration as a case study and describe how we combined the AHP-CRITIC-TOPSIS method with the gravity model and social network analysis (SNA) method to create an evaluating framework that leverages the advantages of all models. First, an evaluation indicator system is developed, rooted in the frameworks of urban quality and line quality. Second, we employ the AHP-CRITIC-TOPSIS method to calculate the indicator system, deriving the urban integrated quality, which serves as the basis for modifying the gravity model. Third, this study refines the parameters of the gravity model to evaluate the interconnectivity degree of rail transits. Finally, the SNA method is employed to analyze the spatio-temporal evolution of the BTH rail transit network (BTHRTN), revealing the impact of rail transit interconnectivity on the spatial structure of the BTH urban agglomeration. The study results may help reveal the underlying mechanisms governing the development and evolution of rail transit interconnectivity networks, playing a crucial role in optimizing and establishing a rational urban spatial network plan dominated by rail transit.

2. Literature Review

2.1. Rail Transit and Urban Spatial Networking

With the globalization trend, cities no longer function as independent entities; instead, they engage in the exchange of materials and energy with the external environment. In this dynamic process, intercity relations become integral components within the network space of the urban agglomeration. Many scholars consider that the pattern of urban growth and form is characterized by a strong link with the interaction of multi-flows in urban networks [13]. Guided by the space of flows theory, urban studies based on flow data has evolved into a novel research paradigm in urban network science [14]. The studies utilize geographic methods such as spatial interaction models and accessibility models to conduct research related to the spatial pattern and interconnectivity of urban networks [15,16]. Transportation serves as the physical foundation of the regional connection, and its interconnectivity offers a method to evaluate the regional spatial interaction. The interaction between transport interconnectivity and the urban spatial structure has become a hot topic [17].

Rail transit serves a foundational role in intercity operations, making flows central elements for characterizing regional connections [18]. Most studies concentrate on the urban or national scale, exploring the interaction between regional spatial networking and rail transit systems in terms of evolution and optimization [19]. The results have found that the primary impact of rail transit on the regional spatial planning lies in accessibility and polycentricity [9]. However, few studies have explored the urban agglomeration space from a network perspective based on flows developed by rail transit interconnectivity. Exploring spatial interaction is an important path to study regional relations, regional connection, and regional spatial structure. By evaluating the interconnectivity degree of the rail transit in the urban agglomeration, we can deeply understand its role in shaping the spatial structure network.

Regarding data sources and methods, analysts frequently examined pertinent data (e.g., GDP, population, passenger and freight volume) [20,21] using approaches such as the gravity model, field strength model, breaking point analysis, exploratory spatial data analysis (ESDA), and SNA to gauge relative advantages or connections among cities in the regional spatial network [22,23]. Due to coordinated development, the exchange of flows among cities has become more diverse and interactive, an aspect not fully considered in previous research on sustainable regional development. The DPSIR framework can tackle this challenge by enabling users to model feedback processes and identify the

parameters driving them. It provides a holistic perspective on the effects of changes within the rail transit system and the system's response to many changes [24]. However, when using DPSIR in research, it does not comprehensively depict the system's structure and functionality. Thus, combining DPSIR with other models for enhancing its utility is necessary [25].

Considering the comprehensive use of methods, we discovered that traditional approaches such as ESDA and spatial econometrics have limitations because they depend on measuring proximity or distance relationships among geographical regions. This limitation makes it challenging to dynamically grasp the structural characteristics of spatial associations in the overall context of rail transit interconnectivity. As inter-regional flow and interconnectivity trends become more prominent in the rail transit system, spatial associations demonstrate a multi-threaded and complex network structure [26]. The SNA method provides a breakthrough in overcoming the limitations of analyzing attribute data, focusing on effectively analyzing the network characteristics of relationship data [27]. In conclusion, this study emphasizes the necessity of exploring the spatial networking of urban agglomerations, particularly focusing on element flows generated by rail transit interconnectivity using the SNA method and similar approaches.

2.2. The Evaluation of Rail Transit Interconnectivity

At present, the top priority for urban agglomeration development is still the issue of interconnectivity [28]. Measuring the intensity and structure of network interconnectivity and determining a city's status in the regional network can significantly support the development of regional spatial planning [29]. Reasonable evaluation of interconnectivity is the basis for making scientific policies to promote sustainable urban development [10].

In terms of the selection of evaluation indicators, existing studies focus on selecting a smaller quantity of representative indicators in the aspects of the economy, population, and physical indicators of lines and networks, such as line length, number of nodes, network density, and toll costs [30,31]. In the context of modernization and informatization, the element flows carried by rail transit interconnectivity are diverse, including people, goods, information, funds, energy, and more. A limited number of indicators cannot fully capture the complexity of the element flow. Furthermore, there exists a complex interaction relationship between rail transits and urban development. A very substantial amount of research effort has already been devoted to analyzing the interaction between rail transit (i.e., accessibility, station, and passenger capacity) and urban form (i.e., land use, spatial distribution, and accessibility) [7,9]. However, existing studies evaluating rail transit interconnectivity fail to reflect that the capacity of a rail transit service in urban agglomerations not only depends on its own construction but also is impacted by the multi-urban agglomeration attributes [32]. Therefore, this study constructs a framework for coupling urban quality and line quality, which can reveal the interaction between rail transits and regional development.

In terms of evaluation methods, the entropy weight method, TOPSIS method [11], gravity model [23], and informatization methods such as GIS [12] have been used in conjunction. Among them, the traditional gravity model is widely employed in the domains of geographic distance attenuation and spatial interaction [33]. It takes into account both the size and attributes of the study area, especially showing the direction of material flows within networks. However, existing gravity models often use a limited set of indicators, such as GDP and population, to explain complex network systems. In fact, rail transit networks are complex and influenced by multiple factors, including social, economic, cultural, and geographical aspects. Hence, in this study, the model parameters were modified to better reflect the urban spatial interactions affected by rail transit interconnectivity.

In summary, existing literature about rail transit interconnectivity in the regional spatial space focuses more on the urban scale and less on the networking of the spatial structure in urban agglomerations based on the space of flows theory. In the evaluation of interconnectivity, the selection of evaluation indicators mostly focuses on the rail transit

attributes and neglects the flow interaction between rail transit and urban development. The DPSRI model can systematically translate the interaction of multi-element flows, and when combined with SNA, it can compensate for its inability to explore the structure of network systems. Evaluation methods are diverse; among them, the gravity model can capture interactions between cities and also visualize the directional interconnectivity network. However, the modified gravity model is constrained by limitations in indicator selection. Therefore, academics are still at the stage of exploring the indicator selection and the evaluation methods and lack a comprehensive framework to evaluate rail transit interconnectivity and its impact on regional spatial planning.

3. Materials and Methods

3.1. Study Area

The BTH urban agglomeration is situated at the nexus connecting three major regions: North China, Northeast China, and East China, as shown in Figure 1. Covering an expansive 216,800 km², it includes 16 cities, comprising the municipalities of Beijing and Tianjin, and 13 cities within Hebei Province: Zhangjiakou, Chengde, Qinhuangdao, Tangshan, Cangzhou, Hengshui, Langfang, Baoding, Shijiazhuang, Xingtai, Handan, Dingzhou, Xinji, and Anyang in Henan Province. As of 2021, the BTH urban agglomeration had a population of 113 million and a gross domestic product (GDP) of 96,356 million yuan, marking a 2.2-fold increase from 2014. However, cities within the BTH urban agglomeration exhibit significant spatial disparities in socioeconomic development levels [9]. Specifically, a notable economic gap existed between Beijing and Hebei in 2021, with Beijing's GDP per capita soaring to 183,980 yuan, in stark contrast to Hebei's meager 54,172 yuan.

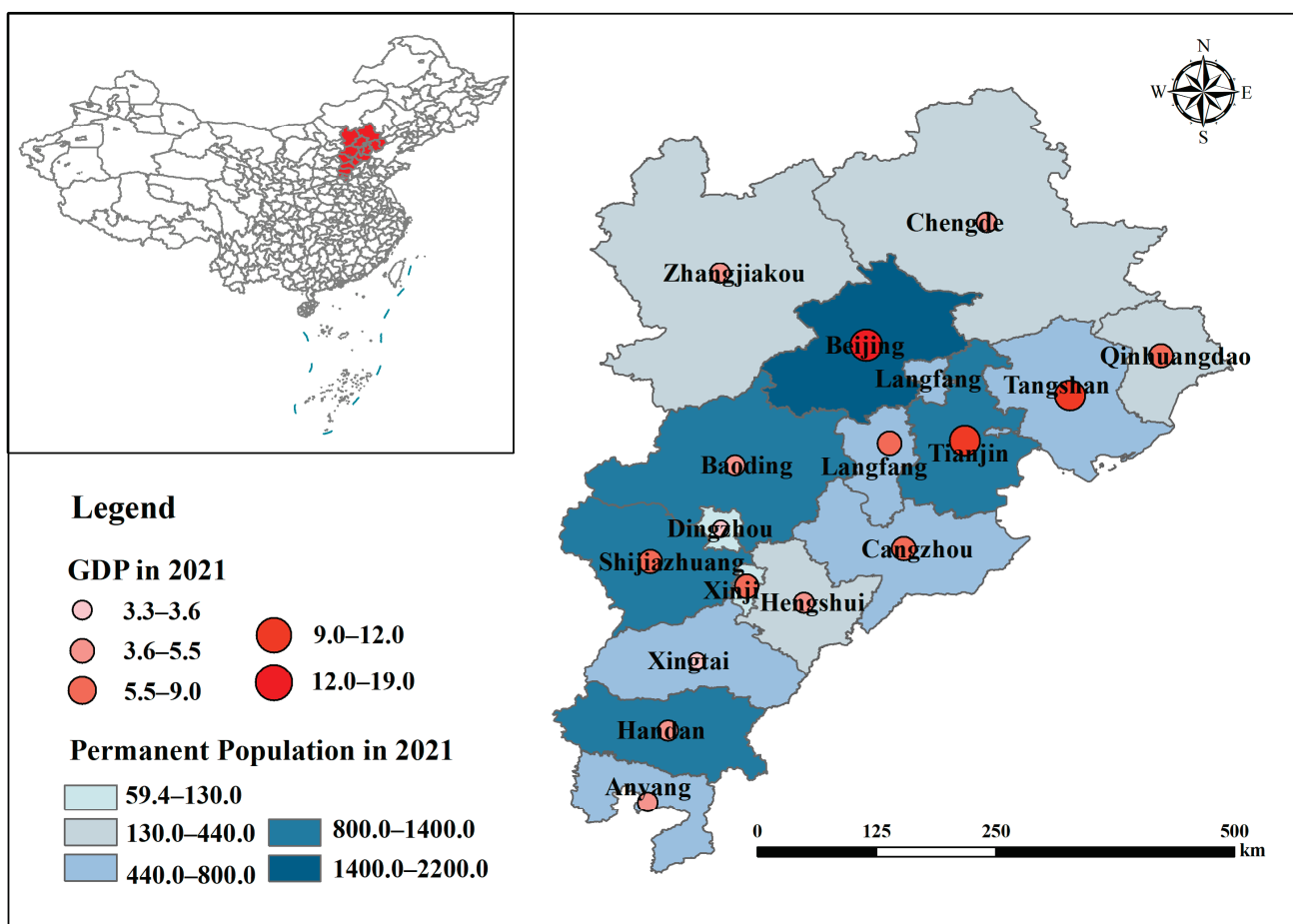


Figure 1. The location of the BTH urban agglomeration in China.

China initiated the strategy of coordinating the development of the national capital of Beijing and the neighboring Tianjin Municipality and Hebei Province in early 2014. Intercity transportation forms the cornerstone for enhancing connections and mitigating regional disparities. In 2015, China introduced the concept of constructing “BTH on the track” for coordinated development, with plans to realize this vision by 2025. Driven by continuous policies and social demands in China, the BTHRTN has expanded rapidly, and a myriad of transportation problems are receiving much attention from multi-disciplinary researchers, including the over-concentration of transport functions in the capital and an uneven regional transport layout [27]. Urgent measures are necessary to revamp the intercity transport network, striving for a networked spatial pattern in regional spatial planning [34]. Accordingly, the BTH urban agglomeration serves as a valuable case study, probing the impact of the rail transit network’s interconnectivity on shaping the networked spatial structure within the urban agglomeration. A pressing concern is the definition of the interconnectivity degree of the BTHRTN and the analysis of the evolution characteristics of its spatial structure.

3.2. Data Source

This study utilizes the panel data of the BTH urban agglomeration from 2010 to 2021 as the main data source for analysis. And the years 2010, 2014, 2018, and 2021 are selected as the cross-sectional data sources in the social network analysis. The study data are mainly obtained from the following sources: (1) To guarantee the scientific and accuracy of the data, most of the raw data come from the China Statistical Yearbook, China Urban Statistical Yearbook, China Transportation Statistical Yearbook, China Environmental Statistical Yearbook, Beijing Statistical Yearbook, Tianjin Statistical Yearbook, Hebei Statistical Yearbook, and Henan Statistical Yearbook for the years 2010–2021. (2) The map of the study area comes from the 1:1 million topographic databases of the National Geographic Information Resource Catalog Service System (NGIRCS). (3) Rail transit network data come from the Open Street Map. (4) Per capita carbon emission data come from the MEIC database. (5) The data on rail transit travel time and costs are primarily sourced from the China Railway Network: <https://www.12306.cn/index/> (accessed on 21 October 2022) and other research collections. For the missing data, this study uses the linear interpolation method to supplement. The standardization of positive and negative indicators is selected to address the disparity in the nature and scale of indicators.

3.3. Research Framework

This study constructs a research framework that mainly includes the following aspects (Figure 2). First, clarifying the relationship among rail transit, interconnectivity, and urban agglomeration is the foundation to evaluate the interconnectivity of rail transit in the urban agglomeration. Second, establishing the indicator system in the aspects of urban quality and line quality to obtain the urban integrated quality, can reveal the complex mechanism of rail transit systems. Third, the gravity model is modified to evaluate the interconnectivity degree of rail transits in the urban agglomeration, demonstrating the urban attributes and visualizing the directional network. Fourth, the gravity matrix is used as the basic data for social network analysis to investigate the spatio-temporal impact of rail transit networks on the spatial structure in the urban agglomeration. Finally, based on the above, a case study of the BTH urban agglomeration is conducted and options proposed to improve the interconnectivity, polynetrality, and tailored policies in the urban agglomeration development based on the evaluation results.

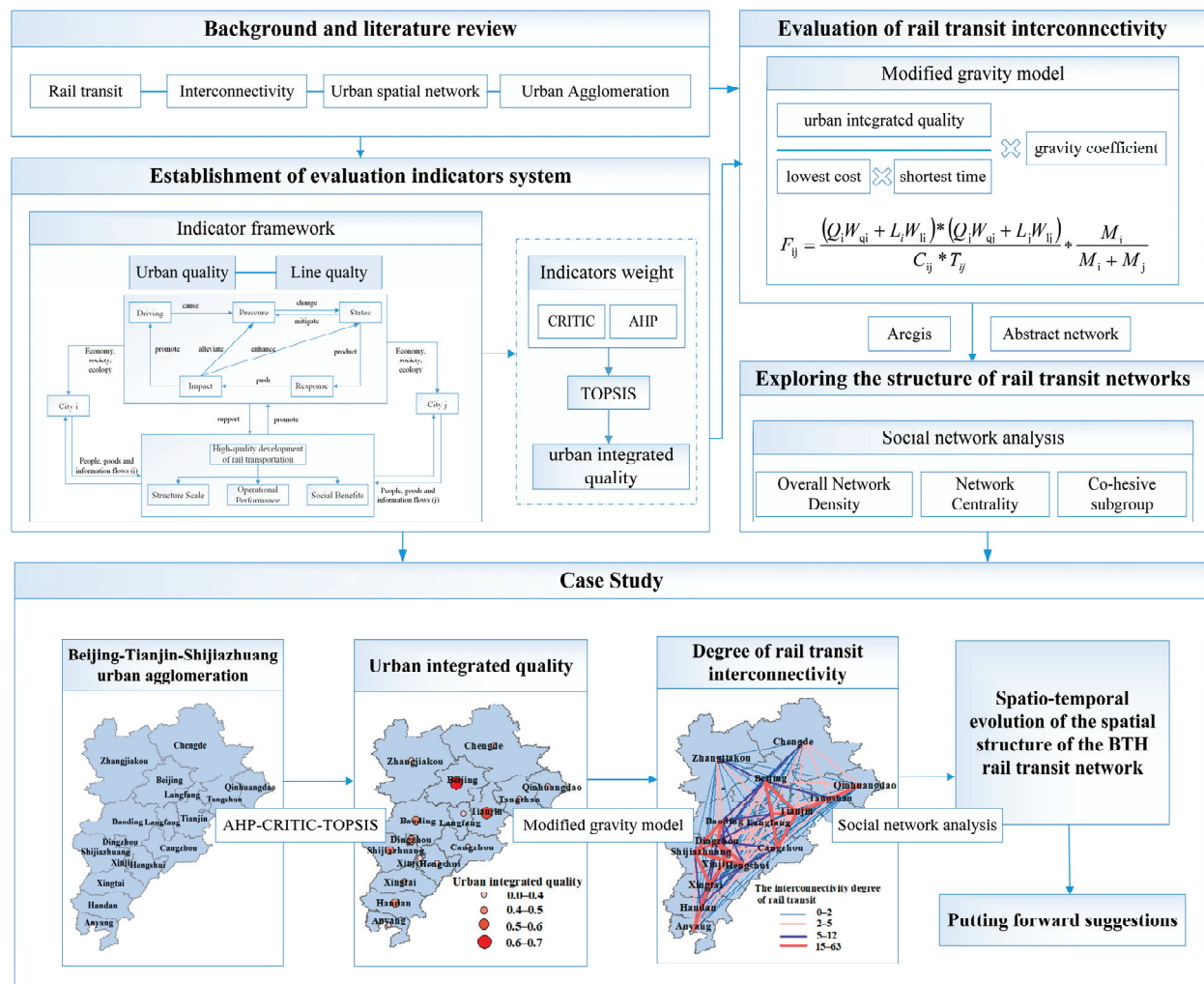


Figure 2. Research framework.

3.4. Establishment of Evaluation Indicator System

3.4.1. Indicator System Framework

The development of rail transit interconnectivity can enhance accessibility, alleviate traffic congestion, optimize spatial utilization efficiency, foster regional integration, and then prompt the urban spatial structures. Its interconnectivity degree can indicate the spatial interaction in the urban agglomeration, which offer a path for exploring the regional spatial structure. The top priority for evaluating the interconnectivity degree is to establish a scientific evaluation indicator system. Considering the intricate and interactive relationship between rail transit and urban development, this study establishes an indicator system within the framework of coupling urban quality and line quality. Urban quality indicators gauge the extent of urban functionality, encompassing evaluations of economic, social, and ecological operations. Line quality indicators pertain to the physical attributes of rail transit that influence its interconnectivity. Urban quality influences the demand for multi-element flows within the urban agglomeration, whereas line quality determines the efficiency of multi-element flows transmission.

Urban development is a multi-level open system, covering dynamic flows on economy, society, and ecology. In particular, sustainability and livability are often acknowledged as the main final objectives of urban development. Against this, the DPSIR framework is a conceptual model for understanding complex interactions between social, economic, and ecological systems [35]. In the DPSIR framework (Figure 3), human and natural drivers exert pressure on the urban systems, leading to state changes and a series of impacts

that may require a policy response. The human response can simultaneously produce feedback to the drivers, reduce pressures, improve states, and reduce negative impacts, thus creating a feedback loop of Driver-Pressure-State-Impact-Response [36]. For effective management towards sustainable urban agglomerations, integrating the DPSIR framework into urban development can conceptualize the interaction of energy and material flows between humans and environmental systems. The literature shows that natural, economic, and social factors are the basic elements of urban ecosystems. So, the principal indicators of sustainable urban development in this day are derived from these factors.

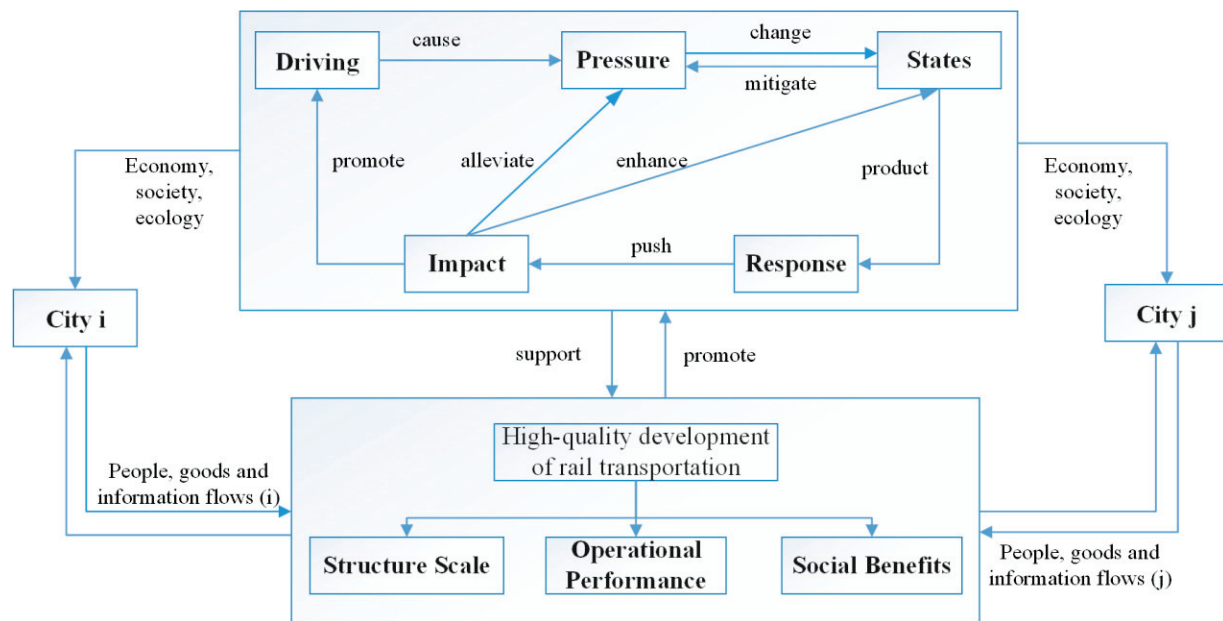


Figure 3. The indicator system framework of urban quality–line quality.

The primary objective of urban rail transit systems is to deliver high-quality services [37]. Rail transits facilitate the swift exchange and utilization of people, logistics, and information flow within urban agglomerations. This enhances accessibility, reduces time-space distances for residents traveling within urban agglomerations, fosters regional synergy, and bolsters overall competitiveness [38]. To achieve these goals, the line quality evaluation indicator system is constructed, considering aspects like line network structure and scale, operational performance, and social benefits.

The framework of the urban quality–line quality evaluation system is shown in Figure 3.

3.4.2. Evaluation Indicator System Construction

In Section 3.4.1, the study establishes the urban quality–line quality framework. Adhering to the principles of independence, scientific rigor, and operational feasibility, the research ultimately chooses 25 indicators (refer to Tables 1 and 2) to evaluate the interconnectivity degree of rail transits within the urban agglomeration.

(1) The selection of urban quality indicators

In the evaluation indicators of urban quality, the overall indicators need to form a logically closed loop under the DPSIR, reflecting the intrinsic mechanism of sustainable urban development oriented by rail transit [39]. The indicators of DPSIR are defined as follows:

“Driving force” is the fundamental and potential power of urban development. A high per capita GDP reflects strong economic capacity, enabling urban areas to invest in and strengthen rail transit networks. The increasing urbanization rate concentrates populations in cities, leading to more frequent movements within and between urban agglomerations, thus boosting the demand for rail transits. With growing awareness

of sustainable development and environmental concerns, urban areas allocate budget resources to enhance energy conservation and environmental protection, supporting rail transit development.

“Pressure” is the load of accelerated urban development developed by the driving force. GDP growth year-on-year reflects economic expansion, driving increased transportation needs. Population density indicates a concentrated population, leading to heightened transit demands. Energy efficiency of GDP growth emphasizes the importance of energy-efficient transit solutions for sustainable development.

“State” is the comprehensive performance of urban development. With urbanization and rail transit development, the city and transportation demonstrate stability. Disposable income influences individual transportation choices. Road area underscores the need for efficient alternatives like rail transit systems. Carbon emissions highlight environmental impact, emphasizing sustainable modes such as rail transit.

“Impact” refers to the impact of the state of the system in economic, social, and ecological aspects. The robust growth of urban areas and transportation systems will influence the proportion of the tertiary sector. This reflects the city’s economic structure, and modifications may affect the demand and scale of rail transport. The extensive advancement of rail transits can impact the adjustment of the average noise level of transportation arteries, thereby enhancing the residents’ quality of life index. Additionally, the implementation of green transportation in urban areas will decrease the average annual concentration of PM_{2.5}, thus improving the overall environmental quality of the city.

“Response” indicates the countermeasures taken by human beings to stabilize and maintain the state of the urban systems. The share of science and technology expenditure reflects the investment level in technological innovation resulting from urban and transportation development. An increasing proportion indicates the adoption of more advanced technologies, fostering industrial upgrading and economic innovation. With the expansion of the transportation industry, employment opportunities increase, contributing to the enhancement of urban economic vitality and social development. Additionally, the urban greening coverage rate mirrors the urban ecological environmental condition. Increasing urban greening coverage can improve air quality, mitigate the urban heat island effect, and promote ecological balance and sustainable development.

(2) The selection of line quality indicators

In the evaluation indicators of line quality, they are influenced not only by the number of lines and network density, but also by the capacity for people, logistics, and information flow [40].

The number of lines, line density, and number of connected cities serve as representative indicators reflecting the scale of the rail transit structure. The number of lines offers an intuitive demonstration of the rail transit system’s scale, depicting the scope of public transportation infrastructure expansion. Line density evaluates the concentration of rail transit lines within a specific geographical area, with higher density typically correlating with increased interconnectivity and accessibility. The number of connected cities indicates the quantity of urban centers served by the rail transit system, highlighting its role in geographical coverage and regional integration.

Total passenger transportation, cargo turnover, and operating mileage serve as representative indicators reflecting the operational performance of the rail transit system. The total passenger transportation metric reveals fluctuations in passenger demand, playing a crucial role in assessing the system’s busyness and efficiency. Cargo turnover measures the system’s contribution to urban and regional freight transport, providing insights into its capacity and involvement in commercial activities. Operating mileage represents the distance covered by the system, and an increase in this metric typically signals an expanded service range, which is crucial for evaluating geographical coverage and interconnectivity.

The rate of growth in passenger numbers and smart payment system utilization rate are representative indicators of the social benefits associated with urban agglomeration interconnectivity. The growth in passenger numbers within the urban agglomeration

rail transit system brings about positive impacts, including reduced traffic congestion, improved traffic safety, and decreased air pollution, leading to societal benefits. The increasing passenger numbers indicate a rising preference for sustainable rail transit, diminishing the demand for individual cars and contributing to the enhancement of urban traffic conditions. Concurrently, the widespread use of smart payment systems enhances payment efficiency, mitigates the impact of cash transactions on system operations, and improves the overall travel experience.

Based on the above, this study constructs the urban quality and line quality evaluation indicator systems as shown in Tables 1 and 2.

Table 1. Evaluation indicators of urban quality.

Aspect	Dimension	Indicators	Supporting References	AHP Weights	CRITIC Weights	Indicator Weights
Driving	Economic Driving	GDP per capita	Wang et al. (2022) [20]	9.01	4.79	6.90
	Social Driving	Urbanization rate	Mu et al. (2022) [41]	13.28	6.60	9.94
	Ecology Driving	Energy saving and environmental protection budget expenditure	Chen et al. (2021) [42]	3.55	4.09	3.82
Pressure	Economic Pressure	GDP growth year-on-year	Liu et al. (2020) [43]	3.51	8.73	6.12
	Social Pressure	Population Density	Zhao et al. (2021) [36]	4.32	7.72	6.02
	Ecology Pressure	Energy consumption per unit of GDP growth rate	Li et al. (2020) [44]	7.32	5.42	6.37
States	Economic States	Disposable income per capita	Chen and Whalley (2012) [3]	3.25	4.56	3.91
	Social States	Road area per capita	Sun et al. (2016) [45]	2.60	9.37	5.99
	Ecology States	Carbon emissions per capita	Lugaric and Krajcar(2016) [46]	11.00	7.12	9.06
Impact	Economic Impact	Share of tertiary industry	Chan et al. (2002) [47]	5.89	5.56	5.73
	Social Impact	Average noise value of transportation arteries	Peng et al. (2021) [48]	3.08	8.50	5.79
	Ecology Impact	Average annual concentration of PM2.5	Qiu et al. (2020) [49]	4.74	7.21	5.98
Response	Economic Response	Share of science and technology expenditure	Handy and Susan (2005) [50]	8.97	6.02	7.50
	Social Response	Number of employed persons in the transportation industry	Zhang et al. (2019) [51]	9.43	6.50	7.97
	Ecology Response	Urban greening coverage rate	Tirachini et al. (2013) [52]	10.05	7.82	8.94

Table 2. Evaluation indicators of line quality.

Aspect	Dimension	Indicators	Supporting References	AHP Weights	CRITIC Weights	Combined Weights
High-quality development of rail transit	Structure Scale	Number of lines	Chen et al. (2014) [53]	15.18	11.43	13.31
		Line density	Sekar et al. (2016) [54]	19.23	11.64	15.44
		Number of connected cities	Experts' suggestion	15.02	11.43	13.23
	Operational Performance	Total passenger transportation	Pan et al. (2017) [21]	9.29	9.40	9.34
		Cargo turnover	Gao et al. (2020) [55]	8.26	11.17	9.72
		Operating mileage	Hu et al. (2017) [56]	10.13	10.16	10.14
	Social Benefits	Rate of growth in passenger numbers	Chalumuri et al. (2017) [57]	7.40	18.86	13.13
		Smart payment system utilization rate	Experts' suggestion	15.49	15.91	15.70

3.4.3. Indicators Weight

The rationality of indicator weights plays a pivotal role in directly influencing the reliability and validity of evaluation results. Indicator weights can be determined using three categories of calculating methods: subjective weighting, objective weighting, and a combination of subjective–objective weighting [58]. To enhance the accuracy of indicator weights, this study employs the combined assignment method (AHP-modified CRITIC) [59]. The AHP-CRITIC method provides numerous advantages. The comprehensiveness of the assessment is bolstered by considering various factors, including expert judgments and overall system consistency. By effectively balancing subjective judgments with system objectivity, the method mitigates subjectivity and adeptly handles uncertainty. Furthermore, employing CRITIC to address potential inconsistencies in AHP results in reduced errors, improved consistency, and reliability of the entire assessment system. This demonstrates enhanced stability and trustworthiness in complex decision environments.

The steps of the hierarchical analysis method are shown below: (1) establish a hierarchical model, and decompose the relevant factors into multiple levels from top to bottom according to different attributes; (2) construct a judgment matrix, and score it using Saaty's 1–9 scale method; (3) solve the matrix eigenvectors, and calculate the approximation value of the matrix eigenvectors by the square-root method; (4) test the consistency of the judgment matrix, and in this study, $CR = CI/RI = 0.044 < 0.1$, passing the one-time test.

The CRITIC method integrates the strengths of the evaluation indicators and conflicts between indicators to provide a comprehensive measure of objective indicator weights [60]. The steps for its determination are shown below: (1) Using the normalized data, the first step is to carry out the calculation of indicator variability, which is expressed in the form of standard deviation, and S_j represents the standard deviation of the j th indicator, as shown in Equation (3). (2) The second step is calculating the ability of indicators' conflict, expressed in the form of the correlation coefficient, R_j denotes the correlation coefficient between evaluation indicators i and j , as shown in Equation (3). (3) The third step is to calculate the amount of information, as shown in Equation (4), the larger the C_j is, the greater the role of the j th evaluation indicator in the indicator system, and the higher the weight of the indicator. Based on the above, the objective weight w_j of the j th indicator is determined, as shown in Equation (5).

$$\bar{x}_j = \frac{1}{n} \sum_{i=1}^n x_{ij} \quad (1)$$

$$S_j = \sqrt{\frac{\sum_{i=1}^n (x_{ij} - \bar{x}_j)^2}{n-1}} \quad (2)$$

$$R_j = \sum_{i=1}^p (1 - r_{ij}) \quad (3)$$

$$C_j = S_j \sum_{i=1}^p (1 - r_{ij}) = S_j \times R_j \quad (4)$$

$$w_j = \frac{C_j}{\sum_{j=1}^p C_j} \quad (5)$$

Integrated weighting method: the subjective and objective weights are $W_1 = (w_1^\alpha, w_2^\alpha, \dots, w_m^\alpha)^T$ and $W_1 = (w_1^\beta, w_2^\beta, \dots, w_m^\beta)^T$ respectively, then the linear weightings are derived from the combined indicator weight $W = (w_1, w_2, \dots, w_m)^T$, and the combined weight of the j th indicator $W_j = \alpha w_j^\alpha + \beta w_j^\beta$, where $j = 1, 2, \dots, n$; $\alpha + \beta = 1$, and this study takes $\alpha = \beta = 0.5$, from which the combined weight of each indicator can be calculated.

3.4.4. Calculation of the Values of Urban Quality and Line Quality

Based on indicator weights determined by the AHP-CRITIC method, this study selects the TOPSIS method to score the urban quality and line quality separately to obtain the Q_i and L_i values, which is the foundation of evaluating the interconnectivity degree of the rail transits. The TOPSIS is a technique for ranking a finite set of evaluation objects based on their proximity to an idealized target [61]. It serves as a method for assessing the relative merits and demerits among existing alternatives by considering the degree of closeness between the evaluated objects and an idealized goal [62]. The key computational steps are as follows: (1) Create the evaluation matrix D , as shown in Equation (6) below; (2) Multiply the decision matrix D obtained above by each indicator weight w_j derived in the previous context to obtain the weighted decision matrix D_2 , as shown in Equation (8) below; (3) Obtain the positive and negative ideal solutions by incorporating the aforementioned into the weighted decision matrix, i.e., identify the maximum and minimum values for each matrix column. Here, t_j^+ denotes the optimal solution for the j -th indicator, and t_j^- denotes the worst solution for the j -th indicator, as shown in Equations (9) and (10) below; (4) Compute the euclidean distance between each indicator and the optimal/worst solutions, as shown in Equations (11) and (12) below; (5) Combine the distances from optimal and worst points for each evaluation indicator, calculate the final scores, thus obtaining values for both urban quality Q_i and line quality L_i as shown in Equations (13) and (14) below

$$D = \begin{bmatrix} r_{11} & \dots & r_{1n} \\ \dots & \dots & \dots \\ r_{m1} & \dots & r_{mn} \end{bmatrix} \quad (6)$$

$$t_{ij} = w_j \cdot r_{ij} \quad (7)$$

$$D_2 = \begin{bmatrix} w_1 r_{11} & \dots & w_1 r_{1n} \\ \dots & \dots & \dots \\ w_m r_{m1} & \dots & w_m r_{mn} \end{bmatrix} \quad (8)$$

$$t_j^+ = \max\{w_j r_{1j}, \dots, w_j r_{mj}\} \quad (9)$$

$$t_j^- = \min\{w_j r_{1j}, \dots, w_j r_{mj}\} \quad (10)$$

$$S_i^+ = \sqrt{\sum_{j=1}^n (t_{ij} - t_j^+)^2} \quad (11)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (t_{ij} - t_j^-)^2} \quad (12)$$

$$Q_i = \frac{s_i^-}{s_i^+ + s_i^-} \quad (13)$$

$$L_i = \frac{s_i^-}{s_i^+ + s_i^-} \quad (14)$$

3.5. Evaluation of the Interconnectivity Degree of Rail Transits

In this study, the gravity model is modified guided by the space of flow theory and used to evaluate the interconnectivity degree of rail transits. The traditional quality is adjusted to the urban integrated quality M_i [3]. It refers to the capacity of individual cities to implement rail transit interconnectivity and is determined by the the combination of urban quality and line quality, as shown in Equation (15) below.

$$M_i = Q_i W_{qi} * L_i W_{li} \quad (15)$$

The transportation distance R_{ij} is adjusted to the geometric mean of the shortest time T_{ij} and lowest cost C_{ij} of rail transit, as shown in Equation (16) below:

$$R_{ij} = \sqrt{C_{ij} \times T_{ij}} \quad (16)$$

The spatial attractiveness and interconnections between districts are directional, and districts with a high comprehensive quality tend to be more attractive. This study adjusts the gravity coefficient by the urban integrated quality, as shown in Equation (17) below:

$$G_i = \frac{M_i}{M_i + M_j} \quad (17)$$

In summary, the modified gravity model is shown in Equation (18) below:

$$F_{ij} = \frac{(Q_i W_{qi} + L_i W_{li}) \times (Q_j W_{qj} + L_j W_{lj})}{C_{ij} \times T_{ij}} \times \frac{M_i}{M_i + M_j} \quad (18)$$

In Equation (18), F_{ij} is the interconnectivity degree of rail transit between city i and city j ; M_i is the the urban integrated quality of city i ; Q_i is the urban quality of city i ; L_i is the line quality of city i ; W_{qi} and W_{li} are the weights of the city's urban quality and line quality, which are 0.6 and 0.4; C_{ij} and T_{ij} is the lowest cost and time of traveling between cities i and j . between city i and city j .

3.6. Exploration of the Spatial Structure of the Rail Transit Network

The SNA method is an important research method for exploring the formation of multiple relationships between cities. It views the relationships between nodes as the basic unit of analysis and the structure as the pattern of relationships between cities. The SNA can be divided into two analytical frameworks: egocentric networks and holistic networks, which can reflect both the individual's position in the network structure and also reveal the overall network structure characteristics of the whole network. Therefore, the study utilizes the SNA method and Ucinet 6.5 software to explore the spatial structure of the urban agglomeration, which is oriented by the element flows in the process of rail transit interconnectivity. It is measured in terms of density, centrality, and cohesive subgroups.

3.6.1. Overall Network Density

Network density is a fundamental concept in social network analysis, indicating the degree of correlation between nodes in the network, i.e., the probability of connection between nodes. The overall network density can take account of the interconnectivity degree within BTHRTN. The higher the BTHRTN density, the greater interconnectivity and cooperation. Its calculation formula is as follows:

$$D = \frac{m}{n(n-1)} \quad (19)$$

In Equation (19), D represents the network density, m represents the total number of actual interconnections between cities, and n represents the total number of city nodes in the network.

3.6.2. Network Centrality

Centrality analysis aims to explore the urban status and rights in the network. The measurements include three aspects: degree centrality, betweenness centrality, and closeness centrality.

Degree centrality. It is a measure of the nodes' significance in the network, as shown in Equation (20). A higher centrality value indicates that the node city occupies a more central position within BTHRTN.

$$C_D(c_i) = \frac{ID(c_i) + OD(c_i)}{2(n-1)} \quad (20)$$

In Equation (19), $ID(c_i)$ represents the indegree of city i , $OD(c_i)$ represents the outdegree of city i .

Closeness centrality. Closeness centrality, also known as overall centrality, refers to the degree of closeness between cities within BTHRTN, and determines the city's control capacity over other members within BTHRTN, as shown in Equation (20).

$$C_C(c_i) = \frac{\sum_{j \neq i} g_{jk}(c_j) / g_{jk}}{(n-1)(n-2)} \quad (21)$$

In Equation (21), $g_{jk}(c_j)$ represents the ability of city i to control city j .

Betweenness centrality. It is the number of times a node acts as an intermediary between two other nodes within BTHRTN, as shown in Equation (21). A higher betweenness centrality value indicates a closer interconnectivity degree between the core city and non-core cities within BTHRTN.

$$C_B(c_i) = \frac{(n-1)}{\sum_{j=1}^n d_i(c_i, c_j)} \quad (22)$$

In Equation (22), $d_i(c_i, c_j)$ represents the number of lines involved in the connection between city i and city j .

3.6.3. Cohesive Subgroup

Cohesive subgroups refer to the actors in a network that have direct, frequent, strong, and active links or communications. Cohesive subgroup analysis can identify relative groups among cities, i.e., cities with relatively dense relationships and strong ties. Cohesive subgroups in the networks are essential for delineating the internal structure of the urban agglomerations. Based on this method, we can determine the number of these subgroups and their specific members, as well as analyze the relationship and interaction patterns among them. These provide valuable insights into the development dynamics of urban agglomeration networking from a holistic perspective.

4. Results and Analysis

Rail transit, as a key component of the transportation network, has greatly facilitated the integration of transportation within urban agglomerations. It facilitates the unrestricted movement of diverse production factors across urban agglomerations, directing them towards advantageous areas and thereby improving resource allocation efficiency. Given this context, the rapid construction of a rail transit interconnectivity system, aligned with societal demands and regional spatial planning, is vital for promoting the sustainable development of urban agglomerations. To fulfill the research objectives, this study takes the BTH urban agglomeration as a case study and analyzes the spatio-temporal evolution of rail transit interconnectivity in the BTH urban agglomeration in terms of node cities, rail transit lines, and the rail transit network. The results and analysis are shown as follows.

4.1. Node Cities Characteristics within BTHRTN

Utilizing Equation (15), this study computes the urban integrated quality values for the years 2010 to 2021 within the BTH urban agglomeration, as shown in Table 3. This

analysis illustrates the distinctive characteristics of these pivotal urban nodes, which play a foundational role in understanding the cities' roles and influence in the BTHRTN.

Table 3. The values of the urban integrated quality.

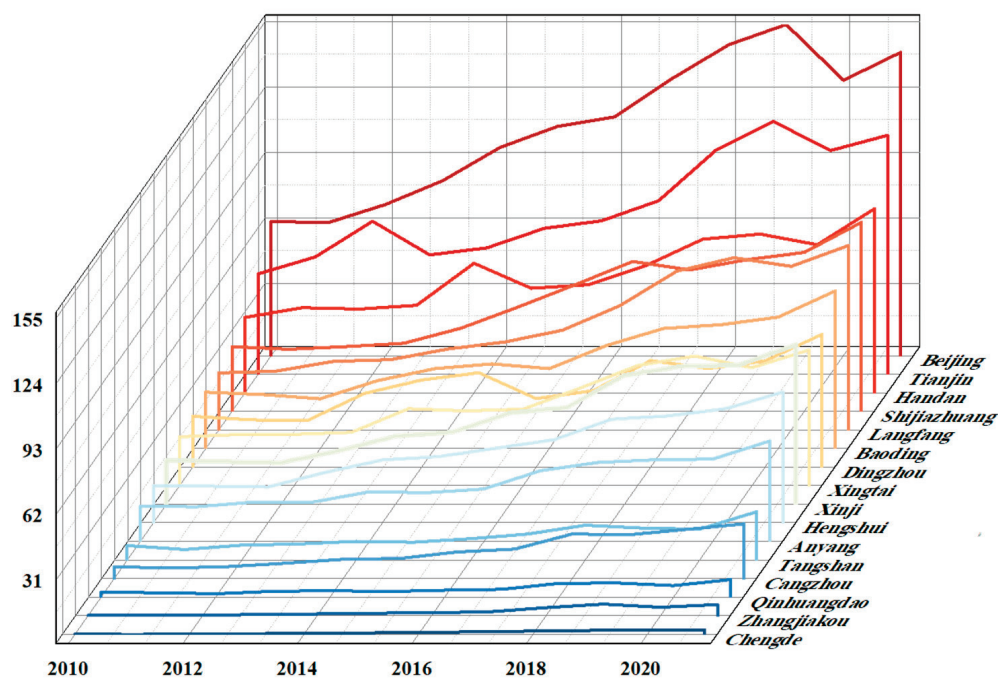
Region	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Mean
Beijing	0.59	0.58	0.61	0.64	0.69	0.71	0.71	0.74	0.76	0.77	0.71	0.73	0.687
Tianjin	0.47	0.49	0.50	0.50	0.50	0.53	0.53	0.55	0.60	0.63	0.60	0.60	0.542
Shijiazhuang	0.41	0.43	0.41	0.41	0.44	0.49	0.53	0.56	0.52	0.54	0.55	0.58	0.489
Zhangjiakou	0.26	0.26	0.27	0.28	0.30	0.32	0.33	0.35	0.41	0.44	0.43	0.44	0.341
Chengde	0.28	0.28	0.29	0.29	0.32	0.32	0.34	0.36	0.39	0.41	0.42	0.43	0.345
Qinhuangdao	0.37	0.36	0.32	0.39	0.40	0.38	0.40	0.41	0.46	0.46	0.44	0.48	0.406
Tangshan	0.37	0.35	0.37	0.37	0.39	0.38	0.41	0.42	0.47	0.46	0.44	0.50	0.412
Cangzhou	0.31	0.29	0.31	0.32	0.34	0.34	0.35	0.37	0.42	0.43	0.44	0.45	0.364
Hengshui	0.32	0.32	0.32	0.35	0.37	0.38	0.39	0.40	0.42	0.42	0.44	0.46	0.381
Langfang	0.35	0.35	0.37	0.37	0.38	0.39	0.42	0.45	0.49	0.50	0.50	0.52	0.424
Baoding	0.40	0.39	0.38	0.40	0.42	0.43	0.43	0.47	0.48	0.49	0.51	0.54	0.445
Xingtai	0.35	0.35	0.35	0.35	0.39	0.39	0.39	0.43	0.47	0.47	0.46	0.48	0.407
Handan	0.41	0.43	0.43	0.43	0.50	0.45	0.45	0.46	0.50	0.50	0.49	0.52	0.463
Dingzhou	0.38	0.37	0.37	0.44	0.46	0.47	0.40	0.41	0.47	0.46	0.46	0.50	0.432
Xinji	0.30	0.29	0.29	0.31	0.33	0.33	0.36	0.37	0.41	0.43	0.42	0.46	0.360
Anyang	0.34	0.33	0.36	0.36	0.37	0.38	0.39	0.43	0.44	0.44	0.45	0.47	0.397
Mean	0.369	0.369	0.372	0.388	0.412	0.417	0.427	0.450	0.481	0.490	0.485	0.511	

From an aggregate viewpoint of the BTH urban agglomeration, the mean values of overall urban integrated quality exhibit a noticeable upward trend, with values of 0.369 (2010), 0.412 (2014), 0.481 (2018), and 0.511 (2021). The largest change in sequential growth rate appeared in 2014 and 2016. This phenomenon may be attributed to the formal proposal of the BTH coordinated development strategy in 2014 and the initial proposal of constructing the “BTH on the track” in December 2015. The mean values for 2018 and 2020 decreased compared to the previous year, corresponding to the global financial crisis in 2018 and the outbreak of the pandemic in December 2019. From the individual perspective of the 16 node cities, the mean values across the period from 2010 to 2021 exhibit notable distinctions. Beijing claims the top position with a mean of 0.69, doubling the value of the last-ranked city, Zhangjiakou (0.341). Tianjin and Shijiazhuang closely trail Beijing and surpass most other cities significantly. This suggests that Beijing, Tianjin, and Shijiazhuang lead as top cities with elevated urban integrated quality in the BTH urban agglomeration, demonstrating enhanced capabilities and attractiveness for interconnection with other cities. In Hebei Province, Qinhuangdao, Tangshan, Langfang, Baoding, Handan, Xingtai, and Dingzhou closely resemble each other with high mean values of urban integrated quality. Particularly noteworthy is Handan's fourth position, leveraging evident geographical advantages as a national railway hub. Positioned strategically within the BTH urban agglomeration and surrounded by the three major economic circles in China, Handan holds a key status across four provinces, manifesting substantial overall influence.

In summary, the figures for BTH urban integrated quality vary at the spatial level but increase at the temporal level. It is characterized by the gradual evolution of the “Beijing-Tianjin double-core” pattern to the “Beijing-Tianjin-Shijiazhuang (weak) triple-core” pattern.

4.2. Interconnectivity Degree of BTHRTN

Utilizing Equation (18), this study calculates the interconnectivity degree of rail transits in the BTH urban agglomeration and constructs gravity matrices for the years 2010 to 2021. The results are uniformly processed. If the processed rail transit interconnectivity values remain below one, it indicates a weak connection, and these values are recorded as zero. Due to space limitations, the calculation results for 2010, 2014, 2018, and 2021 are presented in the supplementary materials. The spatio-temporal change trend of the interconnectivity degree among the 16 node cities within BTHRTN from 2010 to 2021 is illustrated in Figure 4.



*Note: the colorful lines are used to show the change in values for different cities.

Figure 4. The total values of the interconnectivity degree of 16 cities from 2010 to 2021.

To further evaluate rail transit interconnectivity, this study employs the natural breakpoint method in ArcGIS to categorize the results from 2010 to 2021 into four levels (0–5, 6–15, 16–30, 30–72); the urban integrated quality of node cities is categorized into four degrees (0–0.4, 0.4–0.5, 0.5–0.6, and 0.6–0.7). Furthermore, the XY to Line tool in ArcGIS is employed to visually represent the BTHRTN based on the gravity matrix data, as depicted in Figure 5.

The spatio-temporal characteristics of BTHRTN interconnectivity degree are summarized through a combined analysis of Table 4, Figures 3 and 4:

- (1) Between 2010 and 2021, the interconnectivity degree of the BTHRTN displays an uneven pattern characterized by spatial polarization. Figure 4 depicts significant regional discrepancies in the interconnectivity degree within the BTHRTN. Development imbalance continues among Beijing, Tianjin, Shijiazhuang, and other non-core cities, indicating a spatial pattern of “three cores and weak overall” in the BTH urban agglomeration. Using 2021 as an example and referring to Table 4, Beijing occupies an absolute core position in the BTH urban agglomeration. Its mean interconnectivity degree is twice the overall average degree of the BTH agglomeration and 19 times higher than Zhangjiakou, the city with the lowest degree. It is apparent from Figure 5 that the high interconnectivity degrees exist between cities with high urban integrated quality and their neighboring cities. Cities with lower urban integrated quality, such as Zhangjiakou, Chengde, Qinhuangdao, and Hengshui, fail to make strong connections with cities beyond the core cities. Consequently, in the evolution of interconnectivity within the BTHRTN, a small number of node cities bear the majority of the transmission pressure.

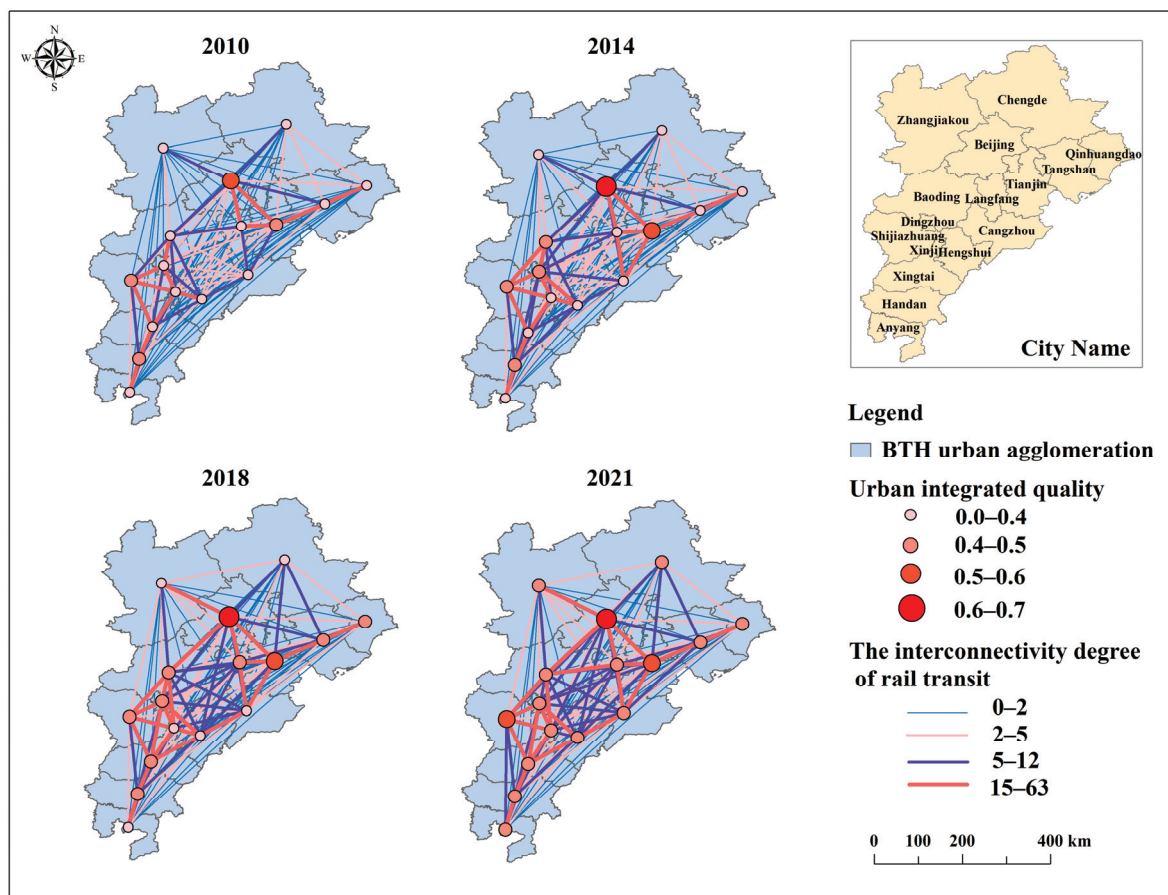


Figure 5. The interconnectivity degree of rail transit in the BTH urban agglomeration.

- (2) Since 2010, the overall interconnectivity degree of the BTHRTN has been increasing, and the growth rates of individual cities are coordinated. Figure 4 provides detailed data on the total values of interconnectivity degree within the BTHRTN over the study period. In the temporal perspective, the overall degree in 2010 is 1.7 times higher than that in 2021, which demonstrates that the interconnectivity degree of the BTHRTN has significantly improved. The five years 2014, 2017, 2018, and 2021 are the fastest growing years with a high growth of 15%. This phenomenon is similar to the evolution of urban integrated quality, which indicates the coordinated development between rail transit and cities. In the spatial perspective, 12 cities have a year-on-year growth rate higher than the average degree of the BTH urban agglomeration. This indicates that the improvement in interconnectivity degree among most cities in the BTH urban agglomeration is a result of collaborative efforts. Beyond that, as shown in Figure 4, all 16 cities experienced varying degrees of fluctuations from 2010 to 2021. Langfang and Chengde are the two cities with the least fluctuations and low interconnectivity degree.
- (3) As of 2021, the foundational spatial structure of the “BTH on the track” has consolidated, with Beijing, Tianjin, and Shijiazhuang functioning as the three core hubs. Figure 5 illustrates the establishment of a rail transit interconnectivity network around these core cities throughout the study period. The changes in node size and line thickness in Figure 5 depict the central role of Beijing, Tianjin, and Shijiazhuang, radiating outward and fostering the interconnectivity of neighboring cities. The interconnectivity degree of Beijing, Zhangjiakou, Chengde, and Tangshan has significantly improved. Likewise, the southern region, centered around Shijiazhuang, has consistently improved in interconnectivity, a change more pronounced than in the region with Beijing and Tianjin at its cores. This change emphasizes the marginal influence

of rail transit conduction. The most intriguing aspect in Figure 5 is the relationship between the advancement of rail transit interconnectivity and the integrated quality of urban areas. When examined in conjunction with the results in Section 4.1, it becomes clear that the advancement in urban integrated quality and the augmentation of rail transit interconnectivity mutually reinforce each other. Essentially, the BTH urban agglomeration exemplifies a pattern of integrated development. This phenomenon emphasizes the importance of researching the coordinated development between transportation and cities, suggesting a fertile area for further exploration.

Table 4. Network density.

	2010	2014	2018	2021
Study area	0.322	0.408	0.523	0.617

4.3. Spatial Structure Evolution of BTHRTN

Based on the gravity matrix data calculated by the modified gravity model, this study selects four-year panel data (2010, 2014, 2018, and 2021), and uses SNA and Ucinet 6.5 software to explore the spatial structure of the BTHRTN in terms of network density, centrality, and cohesive subgroups.

4.3.1. Centrality Analysis

In Table 4, the density of the BTHRTN demonstrates an overall increase trend, which shows that the interconnectivity degree of the BTHRTN generally improves, and its spatial structure becomes closer.

4.3.2. Centrality Analysis

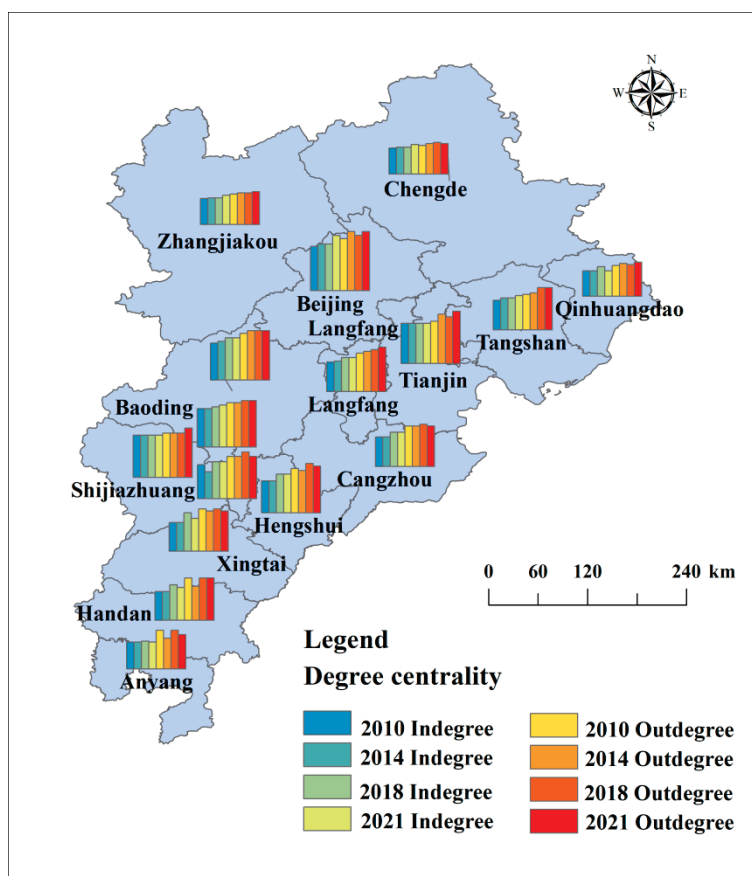
Given that the BTHRTN is directional, the urban centrality is divided into indegree and outdegree for analysis. The indegree indicates how much the city is influenced by other cities, and the outdegree indicates the city's capability to influence other cities.

(1) Degree centrality

The calculation results of degree centrality are shown in Table 5. From the temporal perspective, both the indegree and outdegree show improvement, particularly from 2014 to 2018. When comparing the urban outdegree, Beijing's outdegree surpasses the average value, which indicates Beijing's absolute core position within the BTHRTN. Beijing can make it the primary driving force for overall rail transit interconnectivity. The urban outdegree has increased on average by a factor of 2.02, indicating the growing significance and influence of each city, and their interconnectivity degree has significantly enhanced. In particular, the degree of six cities, namely, Zhangjiakou, Chengde, Cangzhou, Hengshui, Langfang, and Xinji are much higher than the average degree of the BTH urban agglomeration, and their disparities with other cities in the BTHRTN are narrowing. When comparing the urban indegree, cities with high outdegree tend to also possess high indegree (Figure 6). The indegree of Tianjin and Langfang is higher than other cities. The two cities can make full use of the spillover effect from Beijing and are more frequently interconnected with other cities. It is worth noting that Shijiazhuang, the provincial capital of Hebei Province, shows a rising trend year by year. However, it still lags behind Baoding and Handan. This phenomenon indicates its hub position within the BTHRTN has been weakened. When comparing the indegree and outdegree, the outdegree of the five cities, namely Beijing, Tianjin, Shijiazhuang, Langfang, and Handan, is always greater than their indegree (Figure 6). This evidences that the five cities have an obvious diffusion effect, and their influence on other cities surpasses those cities' influence on themselves. The other cities in Hebei Province and Anyang consistently exhibit a phenomenon where the outdegree is lower than the indegree (Figure 6). These cities are more dependent on the interconnectivity radiation from the five cities centered on Beijing and Tianjin.

Table 5. The values of the degree centrality in the BTH agglomeration.

City	2010		2014		2018		2021	
	Indegree	Outdegree	Indegree	Outdegree	Indegree	Outdegree	Indegree	Outdegree
Beijing	41.57	64.65	58.95	99.81	96.93	148.46	104.63	144.78
Tianjin	43.73	48.60	59.07	60.98	97.69	107.27	105.80	114.33
Shijiazhuang	27.57	31.73	37.78	40.50	59.91	68.14	76.27	90.65
Zhangjiakou	2.87	1.27	4.56	2.01	9.45	4.87	9.74	6.37
Chengde	2.27	1.01	3.46	1.60	5.16	2.63	7.20	3.18
Qinhuangdao	3.71	3.30	5.65	4.12	9.06	5.68	10.11	9.45
Tangshan	8.76	7.88	12.21	9.90	21.08	17.54	26.65	24.00
Cangzhou	10.52	6.66	14.62	10.26	29.13	20.63	34.49	26.99
Hengshui	19.38	18.70	32.44	30.89	55.38	48.50	66.90	63.12
Langfang	41.33	28.11	58.26	39.45	99.12	76.27	105.85	88.45
Baoding	28.74	27.84	44.37	38.86	61.57	58.00	75.86	75.81
Xingtai	27.43	24.28	45.08	37.51	61.85	56.17	72.32	65.41
Handan	32.07	36.80	48.31	62.47	70.56	73.92	82.78	88.40
Dingzhou	27.31	25.17	40.36	42.33	56.12	51.58	70.49	64.03
Xinji	28.15	21.99	41.36	33.34	69.58	62.18	88.19	76.80
Anyang	20.35	17.71	32.17	24.55	44.78	38.56	53.15	48.65
Mean	22.86	22.86	33.67	33.66	52.53	52.53	61.90	61.90
Network Centralization (Indegree)	7.07		5.67		6.65		6.46	
Network Centralization (Outdegree)	14.15		14.77		13.75		12.183	

**Figure 6.** Degree centrality map.

Network centralization refers to the overall centrality of the network. The closer the value is to 100%, the more centralized the network becomes. In Table 5, the overall central potential of indegree and outdegree demonstrates a decreasing trend, indicating that there are imbalances and asymmetries of interconnectivity within the BTHRTN. In summary, Beijing, Tianjin, and Langfang occupy the central positions of the BTHRTN, along with obvious regional differences.

(2) Closeness centrality

The calculation results of closeness centrality are shown in Table 6. The higher values represent the closer connections between cities within the BTHRTN, and the less possibility to be controlled by other cities in the interconnectivity process. From Table 6, the mean values of both incloseness and outcloseness demonstrate an overall increase trend, which indicates that the interconnectivity degree of the BTHRTN is getting higher and the flow of people, logistics, and information is rapidly accelerating. From the node cities' perspective (Figure 7), the discrimination between incloseness and outcloseness of each city demonstrates an overall decrease trend, indicating that the distribution of closeness centrality between cities tends to be balanced over time, and the overall interconnectivity degree within the BTHRTN is gradually increasing. Before 2014, Beijing, Tianjin, and Shijiazhuang consistently wielded substantial influence over other cities. After 2014, the interconnectivity degree of Hengshui, Langfang, Baoding, Xingtai, and Handan has experienced a notable increase. On the other hand, Zhangjiakou, Chengde, and Qinhuangdao are always in the stage of lower connection and are easily controlled by the core cities.

Table 6. The values of the closeness centrality.

City	2010		2014		2018		2021	
	Incloseness	Outcloseness	Incloseness	Outcloseness	Incloseness	Outcloseness	Incloseness	Outcloseness
Beijing	75.00	78.95	78.95	93.75	88.24	100.00	93.75	100.00
Tianjin	68.18	68.18	68.18	68.18	71.43	83.33	78.95	88.24
Shijiazhuang	71.43	71.43	71.43	71.43	75.00	75.00	75.00	83.33
Zhangjiakou	44.12	45.46	45.46	50.00	51.72	53.57	53.57	55.56
Chengde	44.12	45.46	45.46	50.00	48.39	51.72	53.57	51.72
Qinhuangdao	42.86	42.86	50.00	42.86	51.72	55.56	53.57	57.69
Tangshan	50.00	53.57	53.57	57.69	60.00	62.50	71.43	71.43
Cangzhou	50.00	50.00	57.69	57.69	68.18	68.18	71.43	68.18
Hengshui	53.57	53.57	65.22	65.22	75.00	71.43	83.33	78.95
Langfang	50.00	51.72	57.69	57.69	65.22	68.18	71.43	75.00
Baoding	62.50	65.22	71.43	71.43	78.95	83.33	83.33	83.33
Xingtai	48.39	48.39	65.22	55.56	71.43	68.18	71.43	68.18
Handan	48.39	48.39	60.00	55.56	71.43	57.69	71.43	71.43
Dingzhou	65.22	65.22	68.18	71.43	75.00	75.00	78.95	78.95
Xinji	57.69	45.46	62.50	62.50	71.43	71.43	78.95	71.43
Anyang	45.46	45.46	46.88	45.46	65.22	51.72	65.23	57.69
Mean	54.81	54.96	60.49	61.03	68.02	68.55	72.21	72.57
Network in-Centralization	44.62		40.78		44.66		47.60	
Network out-Centralization	53.01		72.30		69.48		60.61	

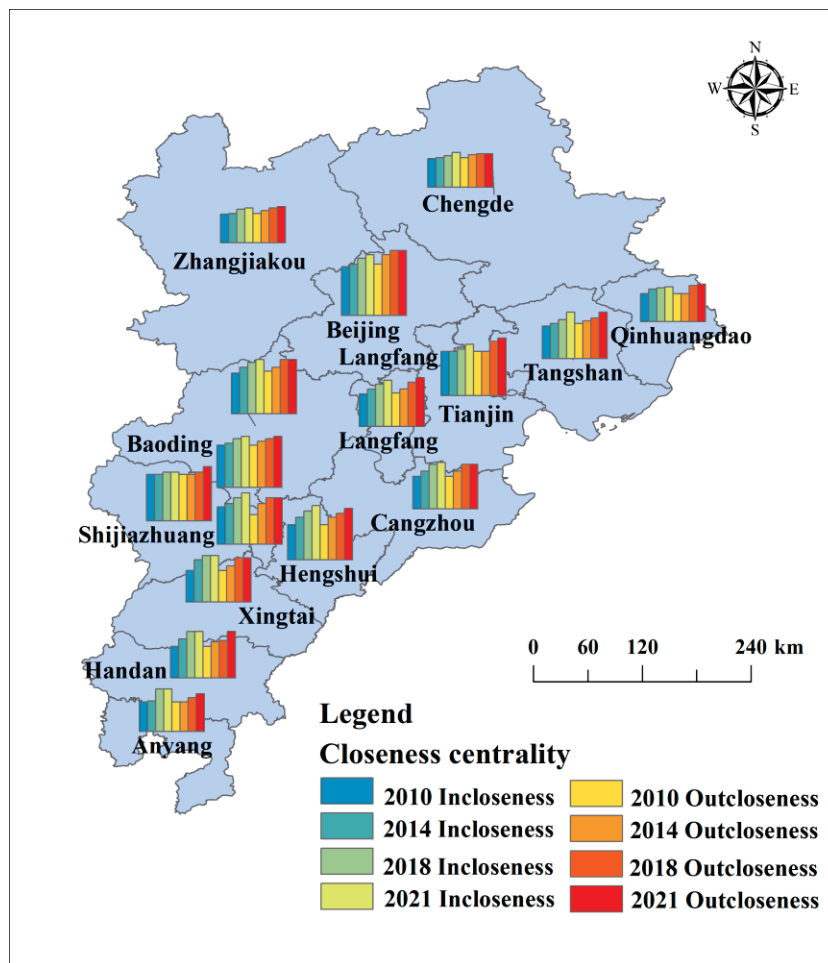


Figure 7. Closeness centrality map.

To summarize, by 2021, Beijing, Tianjin, Shijiazhuang, and Baoding together form a core circle with close ties and are radiating the others' urban development while also promoting the connection between other cities.

(3) Betweenness centrality

Table 7 displays the results of betweenness centrality. A high value signifies increased control over interconnectivity and a more pivotal position within the BTHRTN. From Table 7 and Figure 8, first, there is a significant disparity in betweenness centrality values among cities in the BTH agglomeration. Second, the overall betweenness centrality values show a decreasing trend throughout the study period. These observations suggest a gradual reduction in the role of intermediary cities in the network, allowing cities to engage in direct interconnectivity more effectively. Beijing, Tianjin, Shijiazhuang, Baoding, and Dingzhou function as prominent hubs, enhancing the interconnectivity of the BTHRTN and serving as crucial bridges to other cities. In contrast, Zhangjiakou, Chengde, Qinhuangdao, and Anyang consistently maintain a betweenness centrality value of zero, indicating their marginalization and isolation.

Table 7. The values of the betweenness centrality.

City	2010	2014	2018	2021
Beijing	87.62	82.61	62.14	43.50
Tianjin	40.16	21.12	14.00	17.89
Shijiazhuang	44.98	17.47	5.86	4.64

Table 7. Cont.

City	2010	2014	2018	2021
Zhangjiakou	0.00	0.00	0.00	0.00
Chengde	0.00	0.00	0.00	0.00
Qinhuangdao	0.00	0.00	0.00	0.00
Tangshan	5.37	4.05	2.09	4.02
Cangzhou	0.00	2.55	3.07	2.28
Hengshui	1.60	8.12	3.26	5.03
Langfang	0.33	1.37	5.70	7.35
Baoding	11.78	12.51	10.95	6.09
Xingtai	1.33	4.39	2.29	0.74
Handan	1.33	3.21	0.91	1.43
Dingzhou	16.48	8.94	7.85	4.64
Xinji	1.00	1.65	3.89	3.38
Anyang	0.00	0.00	0.00	0.00

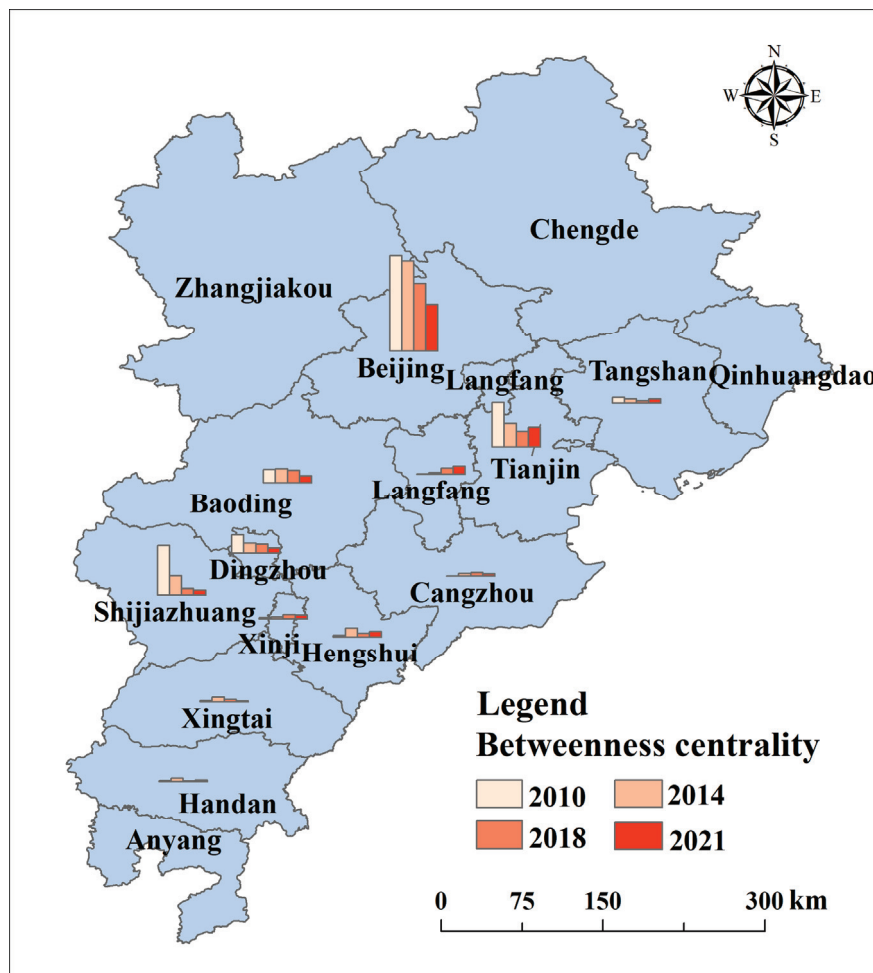


Figure 8. Betweenness centrality map.

4.3.3. Cohesive subgroup analysis

This study employs the Convergence of Iterative Correlations (CONCOR) method in Ucinet 6.5 software to examine the correlations among cities within the BTHRTN. The analysis is conducted with a maximum cut depth of three, achieving an R-squared value of 0.7 or higher. Figures 8 and 9 illustrate the division of the BTH urban agglomeration into four secondary cohesive subgroups and eight tertiary cohesive subgroups.

Some secondary cohesive subgroups have experienced significant changes in membership from 2010 to 2021. The original subgroups shifted from a single-core subgroup centered around Beijing to a dual-core subgroup involving both Beijing and Tianjin. This evolution results in progressively closer connections among the cities surrounding Beijing, including Zhangjiakou, Chengde, and Langfang. Changes in the first subgroup also influence the second subgroup, enhancing interconnectivity in the eastern part of the BTH urban agglomeration. Conversely, the third and fourth subgroups remained stable throughout the same period. In summary, Figure 9 clearly shows that the spatio-temporal evolution of the BTHRTN exhibits characteristics of integration and stability.

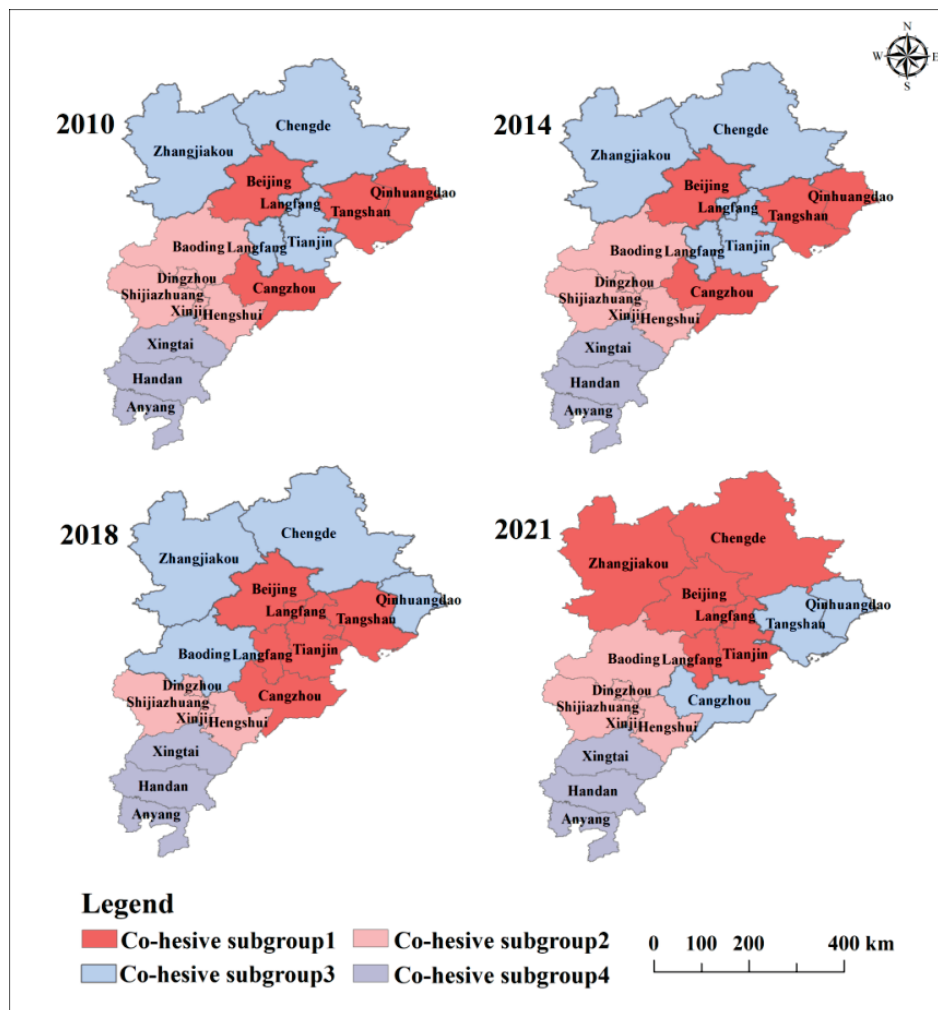


Figure 9. The secondary cohesive subgroups members.

Within the tertiary cohesive subgroups, the number of stable relationship pairs increased from 2010 to 2014. However, only one cohesive subgroup formed among Shijiazhuang, Hengshui, and Xinji. In 2018, a subgroup emerged comprising Beijing, Tianjin, Langfang, and Cangzhou. In 2021, a subgroup consisting of Beijing, Tianjin, and Langfang was formed, building upon the configuration established in 2018. In summary, Figure 10 reveals relatively stable interaction patterns among cities, characterized by a high number of relationship pairs but a limited number of stable cohesive subgroups. There is a need to enhance collaborative development.

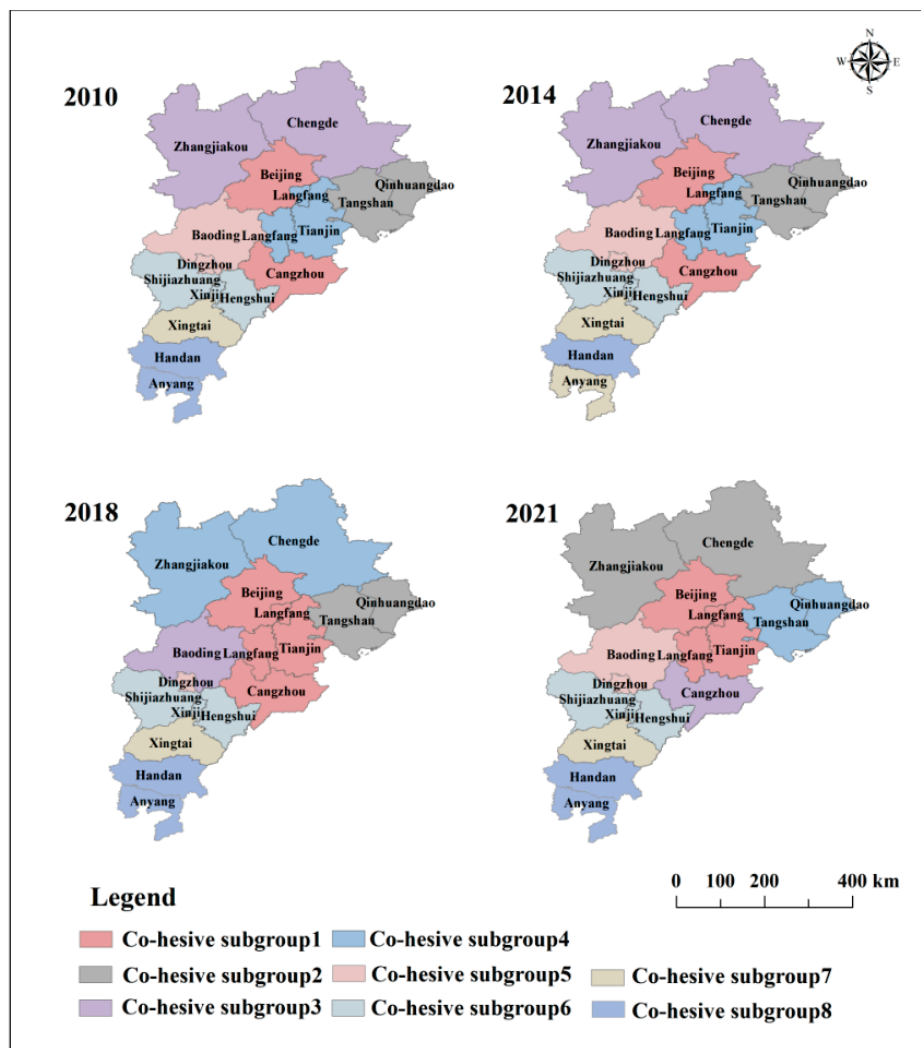


Figure 10. The tertiary cohesive subgroups members.

5. Discussion

5.1. Discussion

This study takes the BTH urban agglomeration as a case study and constructs a framework to evaluate rail transit interconnectivity and explore the network's spatial structure of the BTH urban agglomerations. This framework is designed to integrate three methods: multi-attribute decision-making, improved gravity models, and social network analysis. In the enhancement of the gravity model, the AHP-CRITIC method is employed in this study to determine indicator weights, and the TOPSIS method is utilized to calculate model parameter values. Through the process of this framework, a more comprehensive investigation into the rail transit interconnectivity of urban agglomerations can be conducted, with a focus on the characteristics of node cities, the degree of rail transit interconnectivity, and the spatial structure of the BTHRTN. This facilitates a more thorough analysis of the spatio-temporal evolution characteristics of rail transit interconnectivity in urban agglomerations, providing a more robust basis for spatial planning. The above analysis reveals the complex evolutionary characteristics of rail transit in the BTH agglomeration. These insights are crucial for advancing research in regional rail transit construction and the spatial planning of urban agglomerations. Furthermore, the discussion of our priority findings is shown as follows:

- (1) The uneven pattern and spatial disparities in the interconnectivity degree of rail transits. One significant importance of urban agglomeration development is to pro-

mote regional integration, address the issue of imbalanced regional development, and leverage the development of core cities to better drive the development of peripheral cities. However, in this study, we uncovered significant inequalities in rail transit interconnectivity across the BTHRTN. Core cities such as Beijing, Tianjin, and Shijiazhuang play central roles, while non-core cities demonstrate lower rail transit interconnectivity. Imbalances and asymmetries persisted throughout the study period within the BTHRTN. The spatial configuration, characterized by “three hubs and numerous weak links,” indicates that rail transit burdens are concentrated in a few core cities. This emphasizes the urgent need to optimize resource allocation to address these disparities. This finding is consistent with existing research, as most studies suggest that the current urban agglomeration is in a three-core stage, although some argue that it may still be in a two-core stage [15]. Nevertheless, regardless of the stage, the status of Shijiazhuang within the urban agglomeration needs further enhancement. Initiatives aimed at enhancing the interconnectivity of non-core cities should be informed by this critical insight. Strategically allocating resources and investments can effectively foster the development of a more balanced and integrated rail transit network within the BTHRTN.

- (2) The evolution of the relationship between rail transit interconnectivity and urban development. Data analysis uncovers a correlation between cities with high interconnectivity degrees and superior urban integrated quality. Cities with lower urban integrated qualities, such as Zhangjiakou, Chengde, Qinhuangdao, and Hengshui, show relatively weaker interconnectivity with non-core cities. This connection emphasizes the importance of simultaneously considering both transportation and urban development in urban planning and rail transit construction. These findings mirror those of Fang et al. [2], who also observed a positive correlation between network spatial connectivity and the hierarchy of cities in the urban agglomeration. In the future, delving deeper into the mechanisms of this mutual relationship and exploring ways to better integrate them will be essential.
- (3) The role of rail transit interconnectivity in shaping the spatial structure of urban agglomerations. Despite the uneven development and significant disparities in rail transit interconnectivity, interestingly, exploration of the BTHRTN structure evolution guided by the space of flows theory suggests that rail transit construction enhances the interconnectivity, integration, and stability of the spatial structure in the urban agglomeration. Additionally, this study highlights a specific challenge: limited improvement in polycentricity, indicating a potential area for further exploration and targeted interventions. This finding aligns with other studies linking rail transit with urban spatial structure [63]. This could be attributed to various factors, including the incomplete nature of the railway network, insufficient investments, and competition from other modes of transportation. Nevertheless, rail transit interconnectivity is considered a potential mechanism driving the polycentric development of urban agglomerations. Therefore, future research should focus on enhancing rail transit interconnectivity to foster a more balanced and sustainable polycentric development within urban agglomerations.

5.2. Suggestion

Through a detailed analysis of the BTHRTN's interconnectivity and spatial structure, customized recommendations are proposed to address issues with rail transit interconnectivity and facilitate the development of spatial integration in urban agglomerations.

- (1) Focusing on spatial disparities in the interconnectivity degree of rail transits at the urban agglomeration scale. This disparity arises from varying urban capacities to attract and radiate the exchange of element flows with other cities. The key to alleviating this situation lies in addressing the disequilibrium in the urban integrated quality. It is necessary to implement national-level policies that foster a balanced allocation of traffic resources. Moreover, it is necessary to promote coordination

between northern and southern BTH regions, leverage the advantages of the north, especially Beijing's capital and policies, and recognize its leadership role. Additionally, it is recommended to concentrate on increasing the network density of rail transits and expanding the length of rail transit lines as well as the overall network scale.

- (2) Enhancing polycentric development in the rail transit network to elevate the status of non-core cities. The existing BTHRTN comprises three core cities: Beijing, Tianjin, and Shijiazhuang. Although these three cities exert a growing influence on nearby cities through their radiation effects, the overall interconnectivity degree remains relatively weak. Therefore, the urban planning sector must promote the trend toward a polycentric development pattern and enhance the interconnectivity of non-core cities. To achieve this goal, it is necessary to elevate the status and transportation hubs of Tianjin and Shijiazhuang. The construction of a "1 h functional circle" in Hebei Province can enhance the interconnectivity degree of non-core cities. Moreover, the BTH urban agglomeration should draw valuable insights and best practices from both domestic and international urban agglomerations, particularly in areas related to legal protection, urban planning and construction, and route coordination [64].
- (3) Developing tailored policies for rail transit interconnectivity based on different city statuses. Cities occupy various geographic locations in rail transit networks and perform distinct functions. Therefore, it is imperative to implement more accurate and differentiated policies that suit local circumstances. Cities acting as communication hubs and less susceptible to the influence of nearby cities must fully leverage their intermediary roles. This entails strengthening the bidirectional spillover effects across regions and enhancing urban interconnectivity frequencies. Furthermore, policymakers should prioritize enhancing intelligent services and resilience in key nodal cities to improve the overall robustness of rail transit networks within urban agglomerations, thus promoting sustainability.

6. Conclusions

With rapid urbanization and expansion, researchers and policymakers are increasingly interested in the spatial relationship between rail transport development and regional spatial planning. In this study, an initial objective of the project is to determine the impact of the rail transit interconnectivity on the regional spatial structure in urban agglomerations to optimize the spatial planning for sustainable urban agglomeration development. This study innovatively employs a framework combining AHP-CRITIC, TOPSIS method, gravity model, ArcGIS, and SNA method to evaluate rail transit interconnectivity and explore the network's spatial structure at the urban agglomeration scale, considering multi-element flows. The contribution of this study can inform policy development for rail transit interconnectivity and spatial optimization in urban agglomerations. Additionally, the study draws the following conclusions:

- (1) The interconnectivity degree of rail transit in the BTH urban agglomeration exhibits an uneven pattern known as "three cores and numerous weak links," characterized by spatial polarization. Over the study period, the figures for the interconnectivity degree of rail transits reveal persistent regional disparities between core and non-core cities. Beijing, Tianjin, and Shijiazhuang firmly occupy the core positions in the BTHRTN, while non-core cities like Zhangjiakou, Chengde, and Qinhuangdao have limited connections with cities beyond the cores. Analysis of BTHRTN characteristics indicates a decreasing trend in centralization, emphasizing imbalances and asymmetries in rail transit interconnectivity within the BTH urban agglomeration.
- (2) From 2010 to 2021, the interconnectivity degree of rail transit in the BTH urban agglomeration experiences significant growth and shows a coordinated development trend. The total interconnectivity degree of the BTH urban agglomeration has risen by 82% from 2010 to 2021. The network density of the BTHRTN has consistently grown over the study period. Figures for incloseness and outcloseness are on the rise, while their disparity is decreasing. These findings suggest an overall increase in the inter-

connectivity degree of the BTHRTN, accompanied by a narrowing disparity between cities. The central region, led by Beijing, and the southern region, with Shijiazhuang as the focal point, are actively fostering synergy in the BTH urban agglomeration through two high-degree interconnectivity corridors: “Beijing-Tianjin-Longfang” and “Beijing-Baoding-Shijiazhuang”. These corridors will strengthen overall interconnectivity and promote coordinated development between the two regions. The emerging pattern of BTH-coordinated development is starting to manifest tangible results.

- (3) The BTH urban agglomeration exhibits a polycentric development trend driven by core cities, yet the influence of rail transit interconnectivity on this polycentric pattern is comparatively feeble. The foundational framework of “BTH on the track” has solidified and clarified, designating Beijing, Tianjin, and Shijiazhuang as the three core cities. While the three core cities radiate and guide the development of the BTHRTN, they remain somewhat isolated. Additionally, Shijiazhuang, the capital of Hebei province, holds the third-highest interconnectivity degree. However, it is noteworthy that its rankings in betweenness centrality and closeness centrality are gradually decreasing, indicating a weakening hub position. Simultaneously, the positions of Baoding and Langfang within the BTHRTN are rising. As a result, the full emergence of the third pole in the world-class urban agglomeration centered on Shijiazhuang is yet to be realized. Moving forward, emphasis should be placed on enhancing the impact of rail transit interconnectivity on the polycentric development pattern.
- (4) Rail transit interconnectivity generates multi-element flows that impact the spatial structure networking in urban agglomerations. The SNA method unveils the crucial role of rail transit in enhancing interconnectivity and integration among cities through the analysis of the spatial evolution of the BTHRTN. Both the network density and the degree of centrality show an increasing trend. Furthermore, applying the CONCOR method to evaluate city correlations within the BTHRTN indicates an integrating spatial pattern, while the interaction relationships among cities remain stable. Going forward, emphasis must be placed on fostering coordinated development among cities within the urban agglomerations.

While this study has uncovered significant findings, it is not without limitations. Firstly, the indicator system in this study incompletely captures the dynamics of an intelligent rail transit system due to factors such as data accessibility. Future research can enhance this by utilizing multi-source big data for the integrated analysis of intelligent transportation systems. Secondly, although the study explores the network structure’s evolution characteristics over four key years (2010, 2014, 2018, and 2021), it fails to explore the impact of changes in the interconnectivity degree on the dynamic optimization of spatial structures in the BTH urban agglomeration at different time stages. Future research can explore employing machine learning methods and multi-source big data for continuous simulation of rail transit interconnectivity. Comparing and analyzing these simulations with real-world situations could offer practical insights for the sustainable development of rail transit interconnectivity in urban agglomerations.

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Article

“Pasture Not Pavements”: Governmental Planning Failure and the Slow Death of Melbourne’s Green Belt

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Abstract: Extensive literature on peri-urban issues has paid only occasional attention to the details of spatial planning systems and their impacts on peri-urban natural resources. This paper investigates the relationships between a deregulated land use planning system and declining natural resource and agricultural values in the peri-urban area of Melbourne, in the state of Victoria, Australia. This paper uses a case study area consisting of Melbourne’s green belt and an outer peri-urban area northeast of Melbourne, concentrating on the effectiveness of an urban growth boundary and controls over land uses. A document analysis was undertaken on the provisions of the land use planning system, supporting documents, urban and peri-urban development, land ownership, land uses, and natural resources in the case study area. Threats from urban and rural–residential development, land fragmentation, and land development were identified, and the impacts of the planning system on current and future land uses were analysed. Particular reference was given to the debate on the concept of multi-functional land uses. This paper investigates the likely impacts of peri-urban development and the spatial planning framework on a range of sectors, particularly agricultural production, biodiversity, and landscapes, and highlights the failure of the spatial planning system to protect remnant peri-urban natural resources from increasing threats.

Keywords: peri-urban development; land use; spatial planning; urban growth boundary; multi-functional land use

1. Introduction

Although still only covering less than one percent of the world’s total land area, urban land cover is fast outpacing urban population growth. A recent assessment found that the global urban footprint had doubled in the previous 19 years by comparison with the urban population doubling in 43 years [1]. These data serve to underscore an unprecedented historical trend. Perhaps not surprisingly, in their classic 2002 text, *Cities: Reimagining the Urban*, Amin and Thrift conclude that “we see the city as an agitation of thought and practice” (p. 157) [2].

With the provisos that more recent scholarship focuses greater attention on the transition area of the rural–urban fringe and the reality of *Homo (sub)urbanus* rather than *Homo urbanus*, their description perfectly characterises the subject matter of the present contribution [3–6]. Fundamentally, Amin and Thrift emphasised that cities are always political battlegrounds over clashing values, power, and governance [7]. In particular, there have long been profound differences of opinion in Australian society over limitless growth as a central national and sub-national guiding principle and the role of the state in regulating the actions of individuals, political parties, industry groups, and institutions that hold growth as their grand vision [8–10]. From its inception, the entrenched structure of Australia’s federal government system has actively encouraged the “growth syndrome” by pitting one state against another for lucrative competitive Commonwealth funding in such areas as infrastructure, transport, and housing. The same competitive model also operates at the

state and local government levels. Ever-higher population growth rates and demands for housing lead to more pressure for continued growth. The constantly fuelled leadership competition between cities at the global level measured against a range of metrics reinforces this trend.

But growth also comes with considerable costs and is not universally embraced by local communities [11]. Population and related infrastructure and consumption pressures on natural resources are increasing exponentially, and the resulting development is leading to ongoing conflict over land and water uses [12]. Spearheaded by a number of influential think tanks, the 1970s and 1980s in Australia witnessed a sustained and, ultimately, successful attack on the welfare interventionist state and the promotion of the need to adopt a limited-government, neoliberal ideology. The predominance of this now well-entrenched political orthodoxy has led to the dismantling of the traditional regulatory role of spatial planning in Australia as a principal means for supporting sustainable land and water management. This is despite mounting pressure on natural resources and the incontrovertible evidence of serious, ongoing environmental deterioration, exacerbated by climate change.

The progressive deregulation of Australian land use planning systems follows an agenda set by the *Leading Practice Model for Development Assessment*, prepared by the Development Assessment Forum (DAF) in 2005. This forum is composed primarily of development and professional groups. Powerful property interests, such as the Property Council of Australia (PCA), Urban Taskforce Australia (UTA), the Urban Development Institute of Australia (UDIA), and the Housing Industry Association (HIA), have exerted successful political pressure on governments to progressively implement the DAF model and deregulate planning systems without public consultation [13]. These groups have concentrated on the need for the continuous ‘unlocking’ of land on the fringes of cities and in urban heritage areas for housing and a range of other commercial developments [14]. However, projected demand figures for housing and claims of an undersupply of housing have frequently been exaggerated. This advocacy strategy is widely acknowledged as *framing*, as “political actors focus attention to certain elements in detriment of others, define what is problematic about a situation, and what should be the appropriate courses of action” [15]. The re-established Commonwealth National Housing Supply and Affordability Council’s 2024 first assessment report reinforced the property industry’s position, arguing for the reduction of “impediments to supply, such as planning reforms” [16,17], and the Commonwealth government’s *National Housing Accord* and many Australian states have imposed housing targets on urban municipalities [18]. Both the imposition of large housing targets on communities and urban expansion into rural areas on the fringes of cities are increasingly being used internationally by governments.

Building upon the substantial body of published research by the Peri-Urban Research Group at Melbourne’s RMIT University, as well as Foodprint Melbourne, this paper presents a political and policy update involving the relationships between deregulated spatial planning systems and declining natural resource and agricultural values [19–22] in the peri-urban area of Melbourne, in the state of Victoria, Australia. Relatively little attention has been paid, in extensive literature on peri-urban issues, to the impacts of detailed land use planning systems on peri-urban natural resources. This paper describes the failure of land use planning systems to protect remnant natural resources in a case study area of Melbourne’s green belt and an outer peri-urban area northeast of Melbourne. It examines the use of urban growth boundaries and planning measures, such as zones, to protect the rural characteristics of green belts and broader peri-urban areas from urban-related uses. It relates the findings of these two key elements to international literature on peri-urban areas. Particular reference is given to the debate on the concept of multi-functional land uses.

This paper investigates the likely impacts of peri-urban growth and the spatial planning framework on a range of sectors, particularly agricultural production, biodiversity, and landscapes, and highlights the failure of spatial planning systems to protect peri-urban communities from increasing threats. This failure is strongly related to the lack of an effective cross-sectoral planning policy that integrates decision making across sectors, such

as agriculture, biodiversity conservation, and economic and social development. Nadin et al. [23], for example, have pointed to such integrated policy development in Europe, while Stead and Meyers [24] have pointed to an explanation of policy integration as a co-ordination of sectoral policies or policy co-operation and co-ordination. The concept of policy integration can be further explained as the need for reciprocal sectoral consideration of all the sectoral impacts of proposals and the need to relate proposals to overarching strategic objectives. This paper argues that spatial planning systems can be a major integrative policy force, focusing on the relationships between spatial planning, agriculture, and biodiversity as key elements in resource depletion or protection. Peri-urban natural resources are threatened not only by urban expansion but also by other land use factors and factors such as climate change, invasive species, habitat loss, overexploitation, and pollution. Land use practices, such as closer, small-lot rural subdivision and development; native vegetation removal; and landscape changes, also affect natural resources in rural areas beyond the threat of urbanisation. Other depletion factors, such as the impacts of pesticides or economic factors, are beyond the scope of this paper. Following McFarland, also, a core argument here is that peri-urban areas in Australia can be characterised as a “planning tangle”. In this, “Law, science, and economics actually contest the same ground... in addressing peri-urban land use, each does so using different paradigms and based on different philosophies” [25].

2. Population, Urban Growth, and Environmental Constraints: The Big Picture

With a total area of around 8 million square kilometres, Australia is the world’s sixth largest nation by size. A mere two percent of the country’s land area is classified as urban, and 86 percent of the population currently lives in urban areas. This makes Australia one of the world’s most highly urbanised countries. The United Nations defines countries as hyper-urbanised when 90 percent of their population lives in urban areas. In advance of the UK, Canada, and the United States, Australia is projected to reach this benchmark in 2044 [26].

Fuelled mostly by immigration, Australia’s rate of population increase is also one of the highest in the affluent world. Moreover, in marked contrast to Europe or the United States, for example, a small number of large cities dominate the settlement distribution. This primacy pattern was established well over a century ago. In 1900, Melbourne’s population was eleven times that of the state’s next largest city and higher than Sydney’s by nine times. These ratios have held over time, and the concentration of the population has strengthened and spread along the eastern seaboard in the three major conurbations of Sydney, Melbourne, and Southeast Queensland. Greater Melbourne is now close to being home to 80 percent of Victoria’s total population, and the comparable figure for Sydney is 70 percent.

By world standards, Australia’s cities are characterised by extremely low residential densities. Historically, detached dwellings on large blocks have been the popular norm. Especially in the immediate aftermath of World War II, this style of living was deliberately encouraged by government policies seeking to attract migrants from high-density and overcrowded European cities in particular [27–29]. Fundamental changes in the structure and form of Australia’s urban fabric have been evolving at least since the 1960s. But despite a recent boom in the construction of high-rise, strata-title apartment complexes, the ultimate dream of home ownership of a detached house with a garden persists to this day.

Thus, with a population of some 5.3 million, Greater Melbourne sprawls over approximately 10,000 sq. km. Sydney has a similar population spread over 12,000 sq. km. The average resulting population densities are 520 persons per square kilometre for Melbourne and 440 persons per square kilometre for Sydney. By comparison, Greater London takes in around 1572 sq. km and has an average population density of 5640 persons per square kilometre, and with a similar-sized population to Melbourne, Barcelona has an average population density of 16,000 persons per square kilometre. Utilising a strict statistical definition of ‘suburb’, Gordon and Maginn calculated that for Australia’s 16 largest cities,

75–80 percent of the population could be classified as ‘suburban’. They concluded, “In short, such is the extent of suburbia in Australia; it merits specific research and policy attention” [30].

Australia’s population is currently around 27 million and, at present trends, is projected to reach 30.9 million by 2034 and 40 million by 2060 [31]. Unchecked growth at this scale inevitably will place unparalleled pressure on existing agricultural landscapes and already stressed natural ecosystems, especially given the enduring low density of the large cities. As Seccombe explains, the 2060 projection is “an increase equivalent to the combined current populations of Sydney, Melbourne, and Brisbane” [32]. The recent annual population growth rate has been 1.9 percent.

3. Literature Review

Peri-urban regions are areas outside urban areas into which cities expand and which cities influence. Such regions may include designated green belts located the closest to an urban area. Green belts traditionally have been defined as predominantly rural landscapes outside city limits, containing rural land uses commonly protected by legislative or land use planning controls. More recently, however, the concept of multi-functional uses, including urban-related land uses, has been proposed for green belts. Broader peri-urban regions extend, generally, up to 100 km beyond a city’s edge to predominantly rural or semi-rural landscapes locating diverse activities, including smaller regional townships. They hold high strategic, social, economic, and environmental significance and generally contain important natural resources, providing recreational opportunities, health benefits, food and ecosystem services, water resources, and, often, significant reserves of remnant biological diversity. Urban growth boundaries are a clear demarcation intended to differentiate between urban and rural lands by defining an edge to urban areas. Their purpose is to protect rural landscapes outside the urban limit and to redirect growth pressures to adjoining metropolitan centres or elsewhere, such as to distant regional centres, as a part of a network-city strategy. Such boundaries may be inflexible, intended to permanently prevent the expansion of urban areas into rural areas, or aimed at growth management, and, so, subject to change in accommodating urban expansion in an orderly manner [33–36].

An urban growth boundary’s effectiveness in preventing or controlling outward urban growth is determined by two factors: the status of the boundary and the clarity of the demarcation between urban and rural uses. Ultimately, planning practice depends on whether boundaries are designed to manage growth into green belts and rural lands regarded as ‘urban land-in-waiting’ or inviolate from urban uses [37,38]. An impermanent status will apply to boundaries that constantly expand as urban growth approaches. Nevertheless, some jurisdictions have successfully implemented the managed growth model, for example, Portland, Oregon, where several municipalities have co-operated on a regional basis over a long time period to maintain the orderly application of a growth boundary. A Land Conservation and Development Commission requires every Oregon city and county to develop a plan that meets common goals. This plan must provide for an orderly transition from rural to urban uses, prevent excessive designation of new urban land, achieve greater efficiency of urban land through higher density, and protect farmland and environmental resources.

Urban growth boundaries also are often unclear, allowing for a gradation of land uses, such as larger residential lots, rural–residential “hobby farms”, and a “jumble of rural, urban, and suburban” uses (p. 13) [39] in “a polyglot of landscapes” (p. 137) [40]. Permissive zoning and other land use provisions often enable urban uses to ‘leapfrog’ boundaries in a de facto expansion of the boundary designed to exclude such uses [41]. Allen and Davila (2002) pointed to a multi-functional land use pattern in a peri-urban mosaic of rural and urban uses [42]; and Sturzaker and Mell, Manns et al., and Cadieux and Taylor have challenged the traditional green belt protectionist ideology and have proposed changing land use planning rules to allow for a wide range of residential, rural–residential, and commercial developments and uses [43–45]. In contrast, Buxton has proposed limiting

functionality to a wide range of strictly rural uses according to Frank and Hibbard's definition as "a condition in which rural landscapes and their communities concurrently serve production, consumption, and protection functions" [46,47]. A range of studies show that the introduction of urban growth boundaries without controls on subdivision and urban land uses outside the boundary will lead to ongoing fragmentation and urban land uses that potentially change the rural nature of rural landscapes [48,49].

Rural landscapes dominated by small rural–residential lots and a broad range of urban and rural functional uses are defined commonly as "consumption landscapes", where landowners are said to 'consume' amenities and increasingly banish traditional agricultural production [50–53]. Much agricultural activity is consistent with the concept of multi-functional rural landscapes, where remnant biodiversity, native vegetation, and intact water resources co-exist, particularly with innovative localised food production contrasting with traditional industrial farming [54]. Underlying these policy approaches are three different perspectives on the nature of green belts and broader peri-urban areas. An urban perspective regards such rural areas as land within the sphere of influence of adjacent urban centres [55]. A rural perspective, in contrast, focuses on the resilience of rural activities and criticises the view that rural activities outside cities are fragile [56]. A third depiction is of a dynamic interfacial zone in transition, neither urban nor rural, where change is endemic [57–59].

These differing perspectives underlie increasing threats to long-established urban growth boundaries and green belts. The spread of urban settlements is continuing to severely impact natural resources. The extent of urbanised land is predicted to double in size in Europe within 20–40 years [60] and triple in size globally by 2050 [61]. Yet even traditional green belts in countries such as the UK, Canada, and Australia are being increasingly threatened by urban growth. These threats are being driven generally by increased housing needs arising from population growth and development pressure and point to the need to couple the protection of urban growth boundaries and green belts with the provision of urban land supply. Many commentators argue that England's 15 green belts covering 14% of the country and the London green belt comprising over 1 million hectares are the logical locations for more housing [62,63]. Between 2011 and 2017, 4840 ha of UK green belt land was lost to development, and in 2018, 460,000 new dwellings were planned for UK green belt land despite sufficient land available for 720,000 dwellings outside green belts in municipalities with green belt land [64]. A contrasting policy position also is provided by the Vancouver, Canada, and Adelaide, Australia, green belts, which shift the focus from concentration on urban containment to defining the rural values to be maintained. This approach forces governments to look elsewhere for urban growth options.

Three-quarters of Earth's land surface has been altered significantly, and one million species, or one-eighth of all the plants and animals, are threatened with extinction [65]. Cities are often located in biodiversity-rich areas, and the multi-functional urban nature of peri-urban areas means that significant biological resources remain in peri-urban areas. However, remnant habitat is threatened by urban expansion. Bekessy et al. (p. 140) [66] have shown that in Australia, "over 50% of threatened species occur within the urban fringe, and accelerating urbanisation is now a key threat". National and international research projects and related policy documents addressing urban density and sprawl over the last decade emphasise the need to increase residential densities and make cities more compact to reduce urban impacts on remnant rural natural resources [67]. Increasingly, these studies use large, sophisticated datasets to compare hundreds of cities across the world in order to track changes in density and urban form over time [68]. A comparison between over 400 cities with one million+ inhabitants in both the Global North and Global South found that "cities in the Global North exhibit significantly lower UPD (urban population density) values, which have been decreasing over time" [69]. The 2024 *Benchmarking Melbourne* report noted that "Melbourne has recently sprawled faster than others. Its total built-up footprint has grown more than 10% faster than that of its peers and is now the fourth

largest of its 20 peer cities” [70]. Yet despite green belts making important contributions to protecting biodiversity globally, no international treaties govern their operation.

As Allen et al. highlight in relation to sprawl reduction in Australia, progress “has been slow and uneven” [71]. This issue has also been the focus of critical attention by the OECD in its *Rethinking Urban Sprawl* report, as well as in the Australian government’s newly released *National Urban Policy Consultation Draft* [72,73]. The debate over a favoured economic path for Australia has coalesced around national and sub-national responses to the *Sustainable Development Goals Report* (2024) [74], particularly the attainments of Goal #2, “Zero Hunger”, and Goal #11, “Sustainable Cities and Communities” [75] and the issue of ‘urban sprawl’. This report concluded that

“Cities sprawled, or grew outwards, up to 3.7 times faster than they densified, or grew upwards, from 2000 to 2020 based on recent data from 17 cities in 185 countries. Globally, from 2000 to 2010, the average annual rate of sprawl reached 5.6 percent, while the annual densification rate lagged at 1.47 percent” [76].

Urban issues are also inextricably connected with a range of other Sustainable Development Goals, particularly Goals 6 and 7 (Water and Sanitation; Energy) and Goals 13 and 15 (Climate Action; Biodiversity). A recent appraisal of global progress towards meeting food- and land-system SDG targets paints a less-than-encouraging picture [77]. Since the 1990s, global targets to arrest biodiversity decline consistently have not been met, and this is by a considerable margin. Park and Gunaydin have drawn attention to the ‘19 ecosystems in Australia that are in a state of collapse, with the potential to affect the food system and drinking water for major cities’ [78]. As further evidence, a recent study comparing the National Biodiversity Strategies and Action Plans (NBSAPs) of France, Sweden, and Australia has highlighted systemic policy design failure and the need for transformative governance change in all three countries [79]. By contrast, using a statutory metric, the UK’s 2024 *Environment Act* mandates that all new planning applications must show an associated net biodiversity gain of at least 10 percent.

Despite the diversity of traditional rural activities in multi-functional peri-urban landscapes, changing patterns in intensified industrial agriculture threaten remnant biodiversity, habitats, and landscapes. Controversy continues over the importance of peri-urban agriculture for global food production, as illustrated by debate in the US. The US National Agricultural Lands Study [80] estimated the annual farmland loss at 3 million acres and that 77 million additional acres would be needed by 2000. Others criticised both figures as overestimates [81,82]. Using the US as an example, Fischel claimed that the loss of farmland, nationally, in the US was small, that the impacts on production were minor, and that the loss of farmland could be offset elsewhere by new methods of production [83]. However, between 1949 and 1997, the US lost 20% of its agricultural land. Nelson estimated that one-fifth of the prime agricultural land in the US was located within 50 miles of the 100 largest urban areas; that between 1982 and 1992, nearly 10 million acres of cropland were lost in the US; and that the total sales of farm produce fell by over \$42 billion. In peri-urban areas, sales of farm produce fell by \$19 billion [84]. Loss is caused by urbanisation and is continuing, taking 31 million acres out of production in the US between 1992 and 2012, double those of previous estimates [85], but with 84% of the loss expected to occur in Asia and Africa. There is widespread agreement that peri-urban agriculture matters because of the irreplaceable benefits of its location near urban settlements, the prime quality of the land and produce, and the relative lack of reliance on major irrigation schemes [86].

4. Methodology

A case study examines land use in Melbourne’s green belt and an outer peri-urban area. Melbourne’s peri-urban region consists of two non-urban belts of land around the city and their associated townships extending to about 160 km from the Melbourne central business district. The first, or inner, belt is the Melbourne green belt extending from the metropolitan urban growth boundary to the outer rural boundary of 17 municipalities, encompassing over 8829 km². This area contains a complex mix of private and public lands,

with national and state parks and conservation reserves making up around one-third of the total area. For decades, successive governments have enlarged a network of regional, state, and national parks.

The second, or outer, belt covers over 15 000 km² and extends over a range of landscapes from mountain forests, woodlands, and lowland forests to cleared farming land and coastal areas. Seven municipalities in this outer peri-urban belt form a part of the case study area, as shown in Figure 1. These are Ballarat, Central Goldfields, Greater Bendigo, Hepburn, Macedon Ranges, Moorabool, and Mount Alexander municipalities, with a combined population of almost 400,000 people unevenly distributed throughout an area of approximately 12,130 km². The two largest regional settlements are Ballarat, with a population of 108,000, and Bendigo, with a population of 110,000. The study area also includes a number of medium-sized towns and small towns. It contains many historic features and is predominantly rural in appearance, with 23% of the land area zoned for public use and the remaining rural land zoned for rural production, rural conservation, or rural living uses. The study area is biophysically diverse, combining areas where the predominant land use is agricultural with others where forests dominate, often containing valuable native species and high levels of biodiversity. The two parts of the case study area are notable for their landscape quality, biological diversity, rural production, and tourism.



Figure 1. Outer peri-urban case study area. Source: Buxton et al. [87].

A document analysis was undertaken of the urban and peri-urban developments, land uses, and natural resources in the case study area, drawing particularly from the RMIT University studies of the Melbourne peri-urban areas and the Melbourne University studies of the Melbourne Foodbowl. Documents recording the major provisions of the land use planning system and related supporting documents were analysed, along with spatial analyses of land ownership. The land use planning system studied was established between 1997 and 2003, and its key elements affecting Melbourne's peri-urban rural land remain substantially unchanged. The relevant elements of this planning system are described and later documents addressing the performance of the system analysed. Local councils are expected to continually revise land use planning controls, but the data

recorded in the RMIT and Melbourne Foodbowl studies remain substantially unaltered today, a factor that highlights the inadequacy of the planning process. In the municipalities studied, land tenure is the key factor in a complex network of interacting variables and reciprocal relationships.

A qualitative analysis of the local planning schemes of the seven municipalities in the study area [88], together with the use of a geographic information system (GIS), was used to provide a geospatial and quantitative analysis of the distribution of planning controls [89] and recently granted planning permits [90] and to assess the capacity of the spatial planning framework to manage impacts.

Threats from urban and rural-residential developments were identified in the discussion of the results from the spatial analyses and by analysing the land use planning provisions. The impacts of the planning system on current and future land uses were then analysed. Land uses and the potential for further land fragmentation were related to existing and proposed future land uses.

The details on the land uses, natural resources, and spatial form for the case study area were then related to the broader literature, and conclusions were drawn about the consistency between the case study area and global trends and the relationships between the land use planning regimes, land uses, and spatial form. Forecast trends in land development, demand, and population growth were used to estimate the most likely environmental impacts on rural landscapes.

5. Results and Discussion

Land use planning in peri-urban areas has continually sought to reconcile competing factors, principally, the impetus to grow and protection of natural resources. Land use planning systems traditionally have been the principal mechanisms in Western countries for managing such conflicting pressures. However, the application of neoliberal ideology to land use planning has reduced the capacity of planning systems to control adverse development impacts on natural resources, particularly in peri-urban areas. In the two decades leading up to 1992, successive governments in the state of Victoria used planning systems to address adverse impacts on natural resources left by past land use practices in Melbourne's peri-urban area, particularly a legacy of inappropriate subdivision. Progressive deregulation from 1997 abruptly reversed this trend and reduced the capacity for planning systems to remedy generally acknowledged past mistakes.

Melbourne's peri-urban area consists of inner and outer areas. The inner area corresponds to a conventional green belt incorporating green wedges between urban growth corridors (Figure 2) depicts the urban growth boundary (the blue line) drawn around the Melbourne metropolitan area, the green belt (in light grey), and the outer peri-urban area (hatched).

Inner peri-urban area: The analysis of the documents first addresses two means for protecting or managing the Melbourne green belt: the planning system's control of the land use and development and the delineation of an urban growth boundary. This approach follows the two basic principles adopted in Section 16 of the planning authority's 1981 *Metropolitan Implementation Report*: (i) "to ensure the permanent retention of wedges of countryside between the urban corridors and protect scenic landscapes, farming areas, native vegetation, and wildlife habitats" and (ii) "maintain a clear demarcation between urban and non-urban uses and eliminate urban expectations from rural areas". The evolution of land use planning controls provides a model of the failure to maintain consistent rules to protect identified natural resources in the green belt, considered as vital for the future functioning of the Melbourne metropolis. This failure has led to the urbanisation of much of the city's original food-producing areas, loss of habitat and biodiversity, and degradation of landscapes. No fewer than 21 planning strategies have been produced since 1929, all subject to countless amendments. Most have prioritised development over other landscape values. Tsutsumi and Wyatt have summarised Melbourne's repeated attempts at strategic metropolitan planning as being 'fairly ineffectual' [91].



Figure 2. Melbourne's inner and outer green belts.

Melbourne's first planning strategy and planning scheme were developed in 1929 but never implemented. Renewed post WWII confidence led to the establishment of a metropolitan planning authority, the Melbourne Metropolitan Board of Works (MMBW). This body developed a second comprehensive planning strategy and a planning scheme in 1954 for a future population of 2.5 million within an area of some 700 sq. km. 'Sprawl' and 'containment' were highlighted as issues but were never addressed [92].

Melbourne's third planning strategy in 1971 covered an area of 2400 square kilometres and officially established a green belt incorporating green wedges. The government's objectives for this area have remained constant because to protect and conserve biodiversity, natural resources, including water resources and landscapes, provide open space networks; encourage agriculture; safeguard sites for vital infrastructure, sand, and stone; and encourage diverse tourism and recreation. This strategy was reinforced in the 1981 plan, with nine green wedges being expanded into a broad green belt. The MMBW developed and administered one overall planning scheme, the Melbourne Metropolitan Planning Scheme (MMPs), applying standard zones to both metropolitan Melbourne and its hinterland. Regulatory zones in the green wedges were designated as 'non-urban', strictly excluding urban-related uses. The MMBW drew from two studies in its development of this zoning structure: the *Review of Planning Policies for Non-Urban Zones* and the *Metropolitan Farming Study*. Each recommended robust planning provisions to protect rural values. Five non-urban zones were applied to green wedges: *Conservation*, *Landscape Interest*, *Special Extractive*,

Intensive Agriculture, and General Farming. Over time, these were further delineated into more particular zones, such as General Farming A and B, but no Rural Living Zone.

In 1985, the planning powers of the MMBW were devolved to the local government, but the regulated zones remained. A new state government from 1997 removed these zones, replacing them with liberalised standardised zones, leading to major consequences for Melbourne's green belt. A comparison between the MMPS and the zones introduced between 1997 and 1999 demonstrates the shift away from regulation to development facilitation. The MMPS prohibited almost all forms of urban-related uses, maintaining for almost 40 years a clear pattern of non-urban zones based on a planning philosophy that aimed to separate urban from non-urban uses. Industry, retail, offices, and other forms of accommodation, such as caravan parks and hotels, other than one dwelling to a lot, were prohibited. Almost all other urban-related commercial uses, including restaurants, were also prohibited. Rural retail was prohibited, except for plant nurseries. Rural industry was allowed, subject to permits, as were educational establishments, reformatory institutions, hospitals, outdoor recreation parks, tourist establishments, places of assembly, and places of worship.

In comparison, Victoria's planning system progressively introduced, from the late 1990s, a series of multi-layered provisions of a deliberately designed discretionary nature, that is, providing few mandatory measures and relying on enabling measures to assess planning permit applications. The most important provisions are zones and overlays. Zones outline intended land uses, application requirements, and conditions and classify land uses into three sections: permit not required, permit required, and prohibited. Overlays are an additional level of control applying to single issues. Guidelines to consider permit applications are generally not quantified and require interpretation according to a complicated network of policies and other measures.

The system originally included three rural zones: Rural Zone, Environmental Rural Zone, and Rural Living Zone. The main zone used, the Rural Zone, contained only three prohibited uses, allowing for offices, retail, industry, and a wide range of commercial uses. These zones abolished the urban–rural distinction and converted the green belt to a 'holding zone' for any kind of future urban development. This shift from a regulated planning system to one designed to facilitate development initiated numerous planning applications that were previously prohibited. Between 1996 and 2001, over 4000 ha was approved for residential development, along with function centres/accommodations/commercial complexes, residential estates, and small-lot rural developments. The removal of state control led to a disorderly series of permits and rezoning projects initiated by development companies and local councils. The result was rapid fundamental change [93].

In 2002, another new state government reintroduced zones intended to revert to the MMBW principles in the MMPS for separating urban from rural uses, as a part of the implementation program for a new metropolitan strategy, *Melbourne 2030*. This strategy applied four zones to a broad green belt and replaced the Rural Zone with the Green Wedge Zone as the main non-urban zone. However, these zones allowed for many commercial uses, subject to permits, contradicting the previous prohibitions on urban-related uses in the former MMPS. The government sought to control these by requiring an association with agriculture, introducing maximum development sizes and mandating minimum sizes of land for developments. However, such exemptions have led to extensive further development pressure and conflict. This government also introduced a more comprehensive mandatory suite of four rural zones in the broader peri-urban areas outside the Melbourne green belt.

The current planning controls have now operated since 2002. In 2024, the government introduced a new plan for the Melbourne green belt, the *Planning for Melbourne's Green Wedges and Agricultural Land Action Plan* [94]. This plan stated that the range of land uses competing for rural land makes green wedges the most contested areas in the state, threatening rural land uses. Parbery and his colleagues developed a preliminary typology

of green wedge landholders [95], illustrating the complex nature of competing interests, as shown in Table 1.

Table 1. A typology of rural landholders.

Amenity Lifestyler	Green Commercial Farmer
Horse Lifestyler	Struggling Farmer
Green Lifestyler	Hybrid Operator
Part-Time Farmer	Non-Farm Businesses
Commercial Farmer	Residential Land Speculator

Source: Parbery et al. [95].

The *Action Plan* was designed to meet an election promise to “permanently protect Melbourne’s green wedges from overdevelopment by strengthening statutory planning controls... and strengthening permanent planning controls and legislation to protect and support agricultural land surrounding Melbourne”. However, it fails to deliver stronger planning controls to protect the rural land uses of green wedges. Instead, after six years of investigation, it includes measures such as policies that must compete with other contradictory policy statements and practice notes without statutory effect to guide decisions, defers action to future undefined measures, and avoids mandatory measures and prohibitions of uses that are incompatible with the rural nature of the green belt. As a result, it retains the list of non-urban uses allowed, subject to permits, in the green wedge, now including caravan parks, exhibition centres, function centres, group accommodations, materials recycling, places of assembly, places of worship, primary schools, research and development centres, research centres, residential buildings, residential hotels, restaurants, restricted places of assembly, secondary schools, and solid fuel depots. The tourism industry has been a major proponent of development in the green belt, together with a wide range of development interests pursuing housing construction and further subdivision. This process illustrates the difficulty democratic governments experience in defending public interest objectives against powerful interests and an ideology of deregulation.

The second principle was to maintain a clear demarcation between urban and non-urban uses, that is, establish an urban growth boundary (UGB). A boundary between urban and rural areas was delineated based on planning scheme maps administered by the MMBW and later by councils. However, the minister for planning could easily vary these, often without public notification or rights of objection. As a result, as a part of the 2002 *Melbourne 2030* strategy, the government removed the minister’s power to vary the boundary by passing legislation, the *Planning and Environment (Metropolitan Green Wedge Protection) Act*, requiring approval by both houses of parliament for any change. This plan continued a ‘star-like’ configuration dating back to the 1971 plan of four growth corridors for future housing and commercial developments along major transport arteries and nominated a ring of 12 green wedges of protected rural land between growth corridors, along with a broader green belt. However, damning criticisms of the implementation of Melbourne’s ‘tokenistic’ UGB, by concerned urban scholars, appeared in 2005 and again in 2021 [96,97]. At their core, these critiques highlight a serious failure of planning policy, as urban-related developments began to ‘leapfrog’ the boundary, negating its purpose, followed by expansions of the boundary. The growth corridors signalled to housing companies where to purchase adjoining rural land and lobby for its rezoning. Within six months, the boundary had been moved to expand growth corridors by 1610 ha, followed by another 11,132-hectare expansion allowed in 2005. Another revised strategy—*Melbourne @ 5 Million*—was released in 2010, leading to a further expansion by 43,000 ha to accommodate an additional 284,000 new dwellings, followed by another 2000 ha in 2013, see Figure 3.

One of the targeted areas for residential growth to the west of Melbourne features the only remaining remnants of the country’s rarest ecosystem, with less than one percent of its range now surviving. Each of these incursions could have been prevented by an increase in

the urban corridor's density [98]. Such incremental incursions inevitably create uncertainty and establish precedents that, together, are fatal to the green wedge concept.

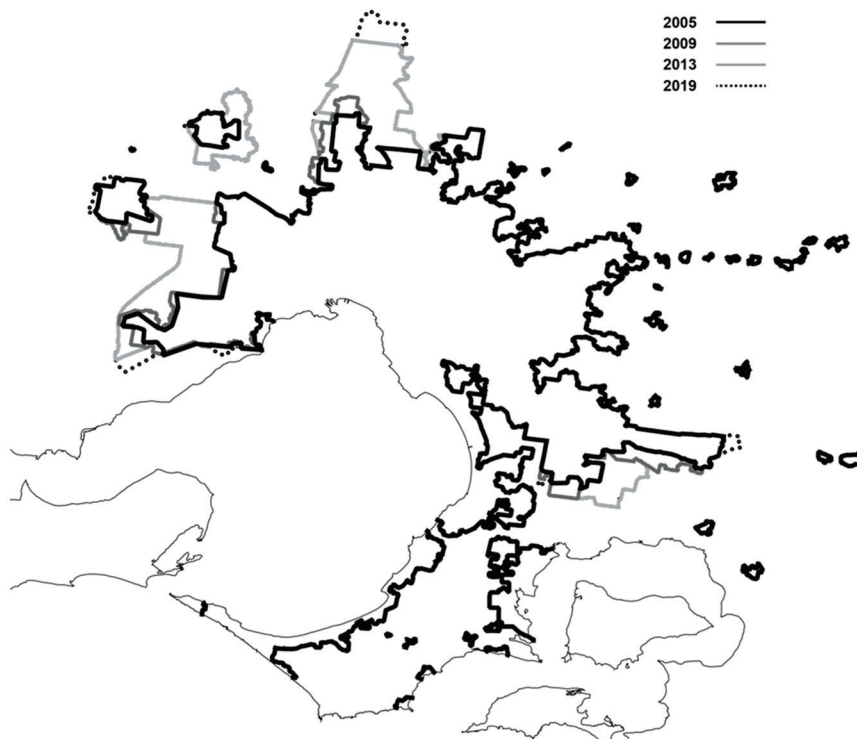


Figure 3. Progressive expansions of the Melbourne green belt. Source: Buxton and Butt [21].

Outer peri-urban region: The outer peri-urban group of seven municipalities in the case study area showed a combination of extensive land fragmentation, together with inappropriate matching of land use controls to land characteristics. A large oversupply of lots exists in the rural areas. Under business-as-usual projections, demand is unlikely to ever lead to this supply being used for housing. A total of 79,075 lots existed in the six zones studied (three rural and three township zones on the urban edge of townships), while 31,316 contained dwellings. The vast majority of the existing lots, 71,990, are situated in the three rural zones. Large numbers of these lots are situated away from population centres, where demand for new dwellings is low because of slow population growth. The total development capacity of 87,195 lots in the six zones is shown in Table 2. This comprises 47,759 existing vacant lots and a potential of 39,436 through subdivision under current planning schemes, including the three township zones currently in rural use, while the projected rural dwelling demand is only 15,010. Subdivision capacity excludes the substantial potential for additional dwellings under excision clauses (which lead to the creation of additional lots over those allowed under subdivision rules for zones). In addition, the range of non-urban uses, such as commercial uses, which are allowed in the green wedge zone, are also allowed in the rural zones, adding significantly to potential development pressures.

Table 2. Development capacity of rural lots.

Lot Size	From 0 to 4	From 4 to 10	From 10 to 20	From 20 to 40	From 40 to 80	Over 80	Total
Total Number of Lots	29,372	14,919	8072	18,370	9065	7397	87,195
Proportion of All Lots	34%	17%	9%	21%	10%	8%	100%

Source: Buxton et al. [87].

The Farming Zone contained, by far, the greatest number of existing rural lots, 47,732, on 710,686 ha and, therefore, possessed the greatest potential development capacity. Most lots are small, with almost 75 percent being 10 ha or smaller on 93,994 ha. The construction of dwellings on these small rural lots would have significant impacts on this region. The large number of ‘hobby farm’ lots would substantially reduce the agricultural capacity, remove remnant biodiversity, and alter landscapes over broad areas. Fragmentation is represented in Figure 4 as follows:

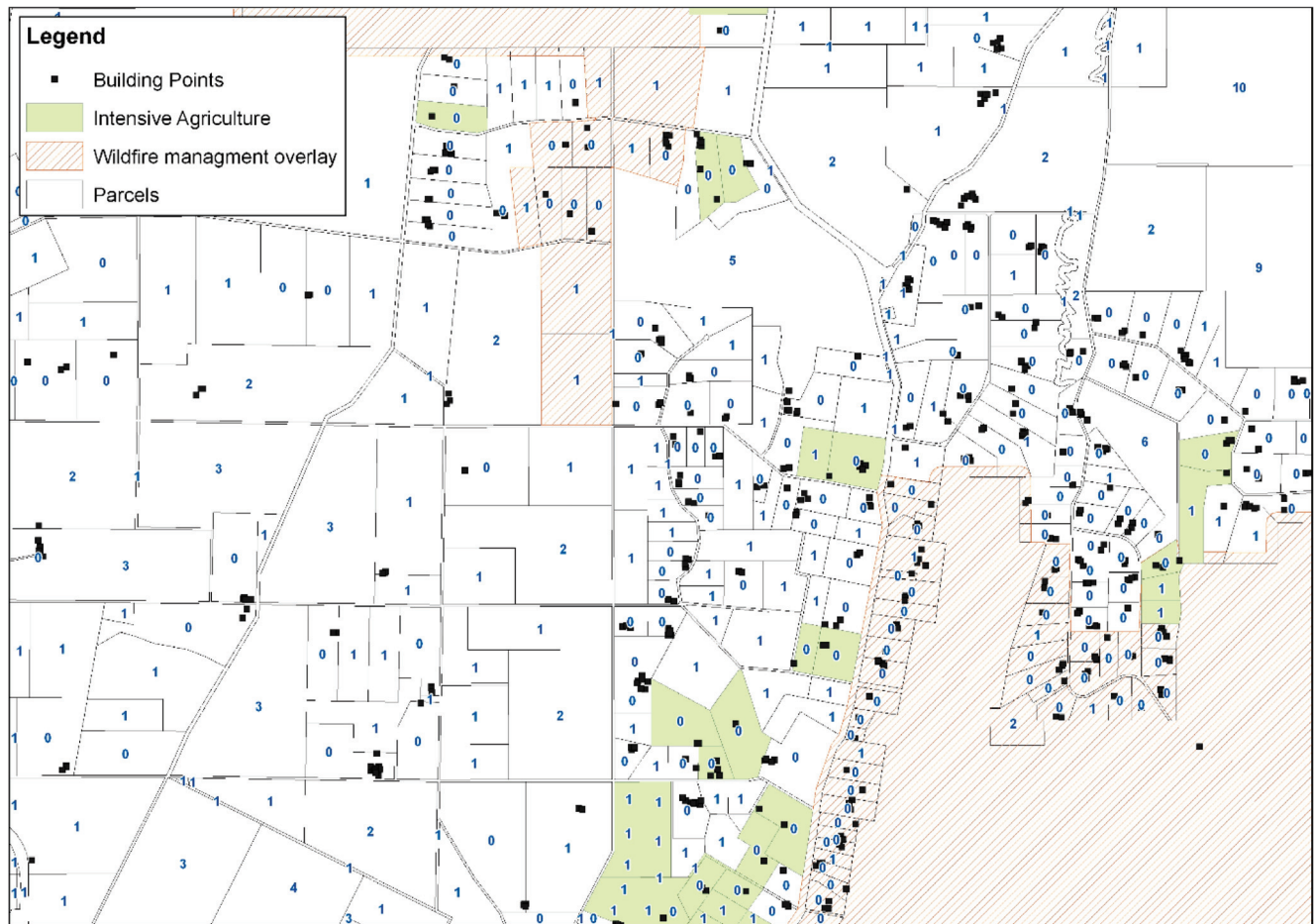


Figure 4. Lot fragmentation in Melbourne’s outer peri-urban study area. Source: Buxton et al. [87].

However, over 3500 lots over 40 ha exist on a significant land area of 286,280 ha, or about 45 percent of the rural land area. These large lots represent much of the study area’s future, allowing for diverse forms of agricultural production to continue and maintaining options for future agriculture while containing much of the remnant biological diversity.

The three main rural zones used in this case study area are the Farming Zone (FZ), Rural Conservation Zone (RCZ), and Rural Living Zone (RLZ). The RCZ is the most restrictive, with 17 prohibited uses compared to 14 in the RLZ and 9 in the FZ and a higher level of protection of environmental qualities, such as remnant vegetation and landscapes. The RCZ and FZ minimum lot sizes applying to subdivisions are generally similar. The most regulatory controls are applied the least to the bulk of the rural landscapes, with the result that further development is possible over most of the rural areas. The FZ is used the most extensively, generally applying to two-thirds of the rural land, leaving important environmental values less-well protected and reflecting the preference of rural landowners for less-regulated planning controls. Negligible use is made of the RCZ in five municipalities, as shown in Figure 5.

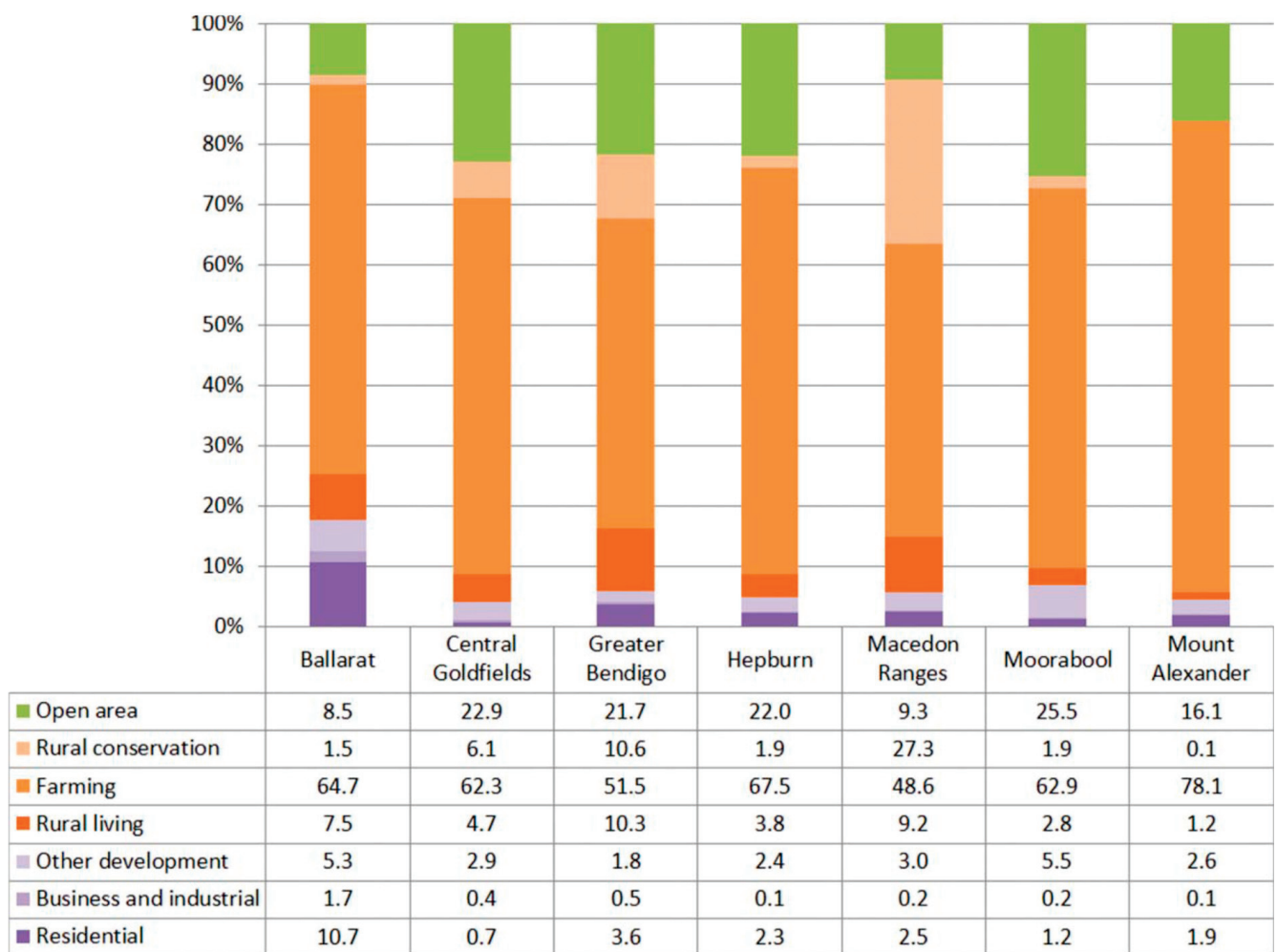


Figure 5. Proportion of planning zones in each case study municipality. Source: Llausas et al. [99].

The misapplication of planning controls is even more marked in the use of planning overlays. The Significant Landscape Overlay provides a much higher level of environmental protection than the Environmental Overlay but is used rarely or never in all the municipalities but one: Macedon Ranges Shire. Much of this region contains extensive areas of remnant native vegetation on private land, but the Vegetation Protection Overlay, designed for its protection, is also used rarely or not at all. State planning regulations to protect native vegetation have been weakened significantly since originally introduced as statewide measures in 1989. The lack of council protection reinforces the continuing loss of native vegetation. The misapplication of such planning measures is leading to continuing loss of agricultural land, degradation of landscapes, loss of biodiversity protection, and emerging problems in land and water management. Another feature of the use of land use planning provisions is the lack of continuity in the use of the measures between municipalities. Different planning provisions are applied over similar landscapes between municipalities, often abruptly ending a level of protection for natural resources at a municipal boundary. The cumulative effects on natural resources of individual development approvals are rarely considered. The legacy of fragmented land titles, inadequate subdivision, and land use controls led to 4000 new dwelling approvals between July 2007 and July 2013 [100], a trend that is continuing, see Figure 6.

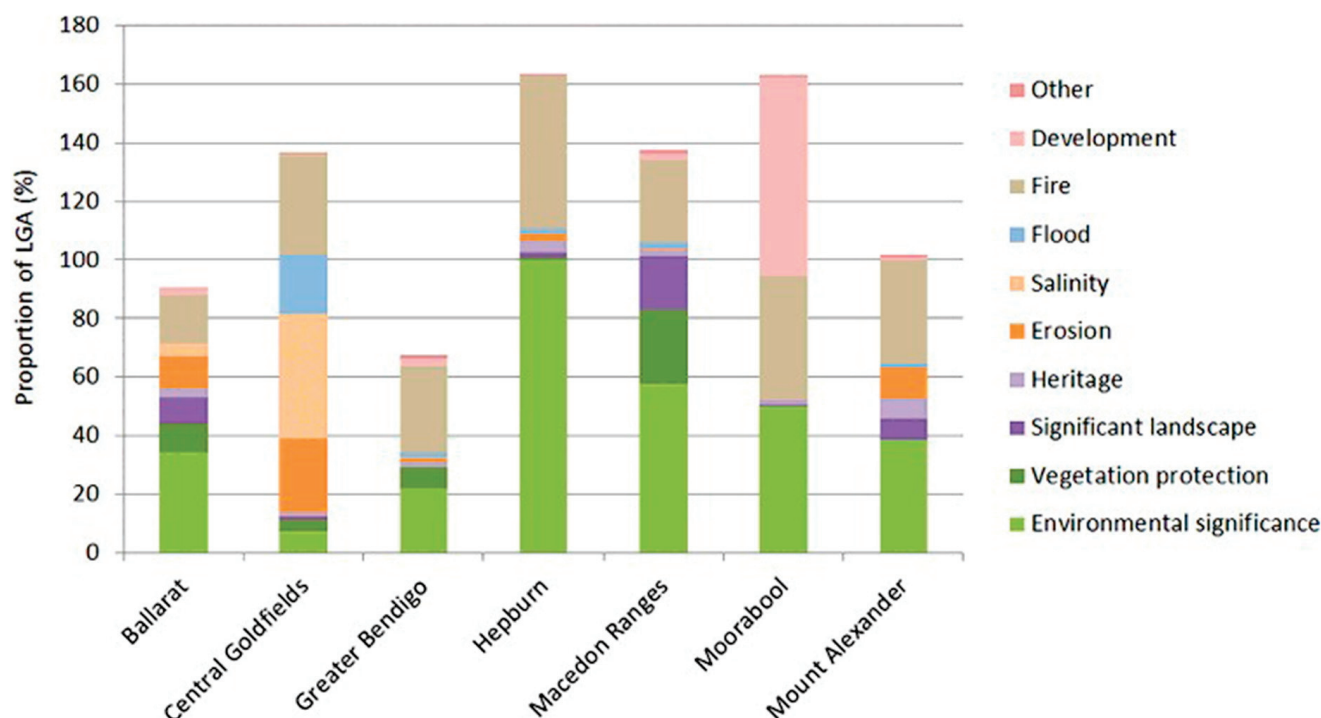


Figure 6. Use of overlays in the study area as a proportion of the municipal area. Source: Llausas et al. [101].

Agricultural practices in the inner and outer peri-urban zones: Recent years have seen growing academic and political interest in the positive role that peri-urban food production can play in increasing urban food security and resilience [102]. Australian Commonwealth and state governments also have recently begun to demonstrate increased interest in the relationships between urban development and the retention of peri-urban agriculture. The Victoria state government, in 2023, began an inquiry into securing the Victorian food supply in the context of urban sprawl and the impact of population growth on the farming industry and arable land. In November 2023, the House of Representatives Standing Committee on Agriculture, presented its final report on food security. Recommendation 13 notes that “...the Australian government, in conjunction with state, territory, and local governments, should develop a strategic plan to protect agricultural land from urban sprawl and utilisation for non-agricultural purposes” [103]. Also of note are three other related investigations in Victoria: *Protecting Melbourne’s Strategic Agricultural Land*, *Inquiry into Ecosystem Decline in Victoria*, and *Protecting Victoria’s Environment—Biodiversity 2037* [104,105].

The submissions to these inquiries provide a rich source of documentary material on the relationships between land use and agricultural practice. The Housing Industry Association (HIA) proposed that the state government “desist with the use of urban growth boundaries (UGBs) because they have proven to be an ineffective tool in facilitating new urban supply or protecting existing land uses” [106]. In contrast, most submissions, involving a wide cross-section of interest groups, such as small farmers, food justice groups, local governments, academics, and other individuals, supported retaining a fixed UGB and protecting green wedges from further non-urban incursions. The local government pointed to the costs and difficulties for protecting the green belt when confronted by a lack of government support and developer pressure. The submissions also referred to the effect on farming feasibility of the dominance of the two major supermarket chains of peri-farming pricing and produce. This matter also is being considered by the Australian Competition and Consumer Commission [107].

Agricultural practice in the peri-urban region displays different characteristics than those applying to Australia’s broad-scale agriculture. Australian agriculture is predomi-

nantly characterised by the efficient large-scale export-oriented production of commodities. Although production has risen, agriculture's share of the gross national product has declined substantially from 20% 50 years ago to 4% today, and farm numbers have halved. Agriculture accounts for less than 3% of the Australian workforce and 15% of export income [108].

However, peri-urban agricultural practice differs in many ways from this national picture. Melbourne's peri-urban region is typical of many others internationally, characterised by land fragmentation, large numbers of lifestyle 'hobby farms', rising populations, and steadily increasing development pressure from the adjacent metropolis. The heterogeneous nature of such peri-urban areas has led some commentators to describe the Melbourne green belt and broader peri-urban area as 'amenity', 'post-production', or 'multi-functional transition' landscapes. Yet Australian peri-urban agriculture matters. Intensive farming, horticulture, viticulture, vegetable growing, and diverse grazing activities co-exist with new, specialised, niche farming activities. Melbourne's green belt (or inner peri-urban area) is the second highest producer of agricultural products in the state of Victoria, with an output per hectare of four times that of the state average [109]. The average income is \$1085 per acre per year for agriculture generally and \$10,585 for vegetables [110,111]. The green belt contributes \$2.45 billion per annum to Melbourne's economy and creates 21,000 full-time-equivalent jobs, providing 41% of Melbourne's food, including 47% of Victoria's vegetables; 12% of its dairy; 67% of its eggs; most of its chicken, meat, and lettuce; and almost all its herbs, asparagus, and berry fruits [112]. Specialised forms of agriculture are highly concentrated and localised. For example, 40% of Australia's strawberries are produced in the Melbourne green belt. The number of producers has remained stable in the outer peri-urban area, dominated by small livestock businesses, with significant contributions from larger enterprises, such as horticulture, meat production, nurseries, and flower production.

Yet continuing urban pressures threaten the future of this foodbowl. The beliefs that the process of urban expansion and that the relocation and substitution of rural land uses in green belts can continue indefinitely have long dominated Australian urban planning to the marginalisation of food as an issue [113]. Between 2000 and 2006, Melbourne, Adelaide, Perth, and Sydney lost between 4% and 11% of the land area available for fruit production. The equivalent for vegetable production fell by 28% in Brisbane and 14% in Perth. Then, between 2011 and 2016, the land classified as being under primary production in the Foodbowl of Greater Western Sydney declined from 292,643.9 ha to 99,519.2 ha, a fall of 66 percent [114].

Historically, the area of the agricultural land has been substantially reduced over time, declining by 18% between 1986 and 2001 [115], a trend that is continuing [116]. Even controls on urban development are likely to further reduce agricultural output. Scenarios modelled by Deloitte Access Economics [117] showed a reduction in the value of the agricultural output from Melbourne's Foodbowl of \$32 million per annum in a 'constrained urban sprawl' scenario compared to \$111 million for a 'moderate urban sprawl' scenario. Foodprint Melbourne showed that population growth and urban sprawl could reduce the region's food production capacity from the current 41% to 18% by 2050 [118].

Melbourne's peri-urban food production is important for the reasons such areas remain important globally. First, the location of many cities on fertile soil in liveable climates provides a resource that should be protected for its high-value, high-intensity food production capacity. Second, the location close to metropolitan areas provides efficient and effective transport systems with ready access to markets. Third, water resources are available at a reasonable cost through adequate rainfall or recycling programs using urban storm- and wastewaters. Fourth, chronic and uncertain social and physical circumstances are likely to place increasing pressure on global food resources and supply chains as transport costs rise and the availability of food from distant sources becomes increasingly tenuous, reinforcing the need for caution in continued reliance on distant sources of food.

6. Conclusions

The introduction of a more-deregulated land use planning system in Victoria in the late 1990s led to closer relationships between the Victorian government and development interests. It separated spatial planning from other sectoral activities, fragmented decision making, and replaced decades-long government attempts to integrate policy for Melbourne's green belt and broader peri-urban area. There was no place for cross-sectoral policy in a governance regime devoted to deregulation and reducing the role of the government.

The potential of the land use planning system to protect peri-urban natural resources depends on its role as a means for integrating decision making over a range of other sectors. The deregulation of the Victorian planning system led to a weakening of planning controls and to progressive developments incompatible with the protectionist principle that led originally to the establishment of a green belt. A brief period of partial reregulation in 2003 could not resist for long the prevailing neoliberal ideology.

Land use planning also is a powerful independent factor affecting peri-urban areas by defining allowable land uses and affecting other factors, such as land prices, amenities, and production. The land use planning system is the principal cause of the land use transition in peri-urban municipalities, as it allows for the creation of small lots and the introduction of a multi-functional commercial landscape. Yet the details of land use planning systems and their impacts on natural resources are understudied internationally. The three most important peri-urban land use factors in the Melbourne peri-urban areas are the large number of existing rural lots, which, if developed, would change the character and functioning of the region, the potential for future subdivisions of larger properties into smaller lots, and the permitted uses for land and accompanying developments.

Effective land use planning is a necessary but not a sufficient condition to manage rural landscapes and land use. Regulatory controls can prevent unwanted activities but cannot ensure desired uses of land. Nevertheless, regulatory land use measures, such as zoning, can increase the likelihood of desired land uses by preventing incompatible uses and developments, controlling land prices, and maintaining future land use options. Lot sizes and prices are strongly correlated, with the per hectare value of smaller lots being much higher than that of larger lots. Exclusive farm zones can protect agricultural land from development. Large-lot requirements for subdivision help to maintain lots of an adequate size for feasible farms and protect the environment by preventing development. Zones, or their equivalent, can require owners to amalgamate multiple small lots when constructing new dwellings or can prevent building on small lots. In these ways, zoning can maintain future options that help communities to adapt to change.

Land tenure becomes the key factor in a complex network of interacting variables and reciprocal relationships. Without the use of stronger spatial planning techniques to prevent further land fragmentation, it is unlikely that other measures will be able to maintain peri-urban landscapes because income from rural uses, such as farming, or the value of incentives cannot usually compete with short-term financial gains from development. Spatial planning factors can reinforce the expression of the price in the suitability of the land for agricultural production, increase the comparative rate of return from agriculture, and facilitate land purchases for the creation of larger agricultural lots.

The historical relationships between the land tenure, land use planning controls, and natural resources in the Melbourne peri-urban region have aroused international interest and contain implications for broader practice.

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Article

Ecosystem Service Trade-Offs in Peri-Urban Landscapes: Drivers, Governance Obstacles and Improvements

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Abstract: Trade-offs in ecosystem services (ESs) manifest when the enhancement of one service leads to the diminishment of another. These trade-offs pose a notable challenge, impacting the sustainability of particular socioecological system peri-urban landscapes (PULs). This issue arises from the dynamic processes associated with peri-urbanization, which threaten natural ecosystems and their services in peri-urban areas. Additionally, the escalating demand for ecosystem services in PULs contributes to these trade-offs. Policymaking and planning concerning ES trade-offs in PULs should prioritize promoting a balance between conflicting services and fostering synergies among them. However, it is noteworthy that ES trade-offs in PULs are not given high priority in policy and planning agendas. Knowledge regarding policy development and planning for ES trade-offs in PULs often remains concealed within specific country and regional case studies. Consequently, this research seeks to characterize the ES trade-offs in selected PUL case studies, with the objective of identifying potential commonalities among them. Furthermore, this study aims to identify (i) the factors driving ES trade-offs, (ii) challenges related to how policymaking and planning address ES trade-offs in PULs, and (iii) recommendations for enhancing governance practices to better manage peri-urban ES trade-offs. We designed a semi-quantitative survey and collected information about 24 case studies located across the world. The answers from this survey were analyzed using principal component analysis. The results showed that the most common trade-offs occurred between “cultural and provisioning” and “regulating and provisioning” ESs. It was found that urban development is the primary driver behind the emergence of the examined trade-offs. To address this issue at the governance level, this study recommends establishing mechanisms to facilitate collaboration among stakeholders. This should be accompanied by robust dissemination efforts and the promotion of awareness among actors regarding the fundamental concepts of ESs and PULs.

Keywords: awareness; conflict; planning; principal component analysis; similarity patterns

1. Introduction

1.1. Ecosystem Service Trade-Offs in Peri-Urban Landscapes

Ecosystems are often modified to enhance the provision of specific services [1]. Peri-urban landscapes (PULs) are examples of specific areas where land-use changes occur in a very dynamic way, producing modifications in the provision of services of the related ecosystems. PULs are wide portions of man-modified landscapes embedded in

a (semi)rural context in a continuous spatiotemporal manner and often within large metropolitan regions [2]. PULs are characterized by a low-density urban fabric and different types and mixes of land uses and urban services, including residential, commercial, industrial, farmlands, and semi-natural areas and ecosystems [3]. Such a mixture of land uses is the result of dynamic socioecological changes, occurring faster than in other urban contexts and usually involving higher rates of soil consumption, with many environmental generated externalities [4,5]. If not correctly planned or managed, such rapid changes can often lead to trade-offs in the provision of ecosystem services (ESs). ES trade-offs represent a situation where one ES decreases as a result of the increase of another ES [6]. Very often, ES trade-offs occur in situations where two types of ESs support different objectives [1]. The specificity of ES trade-offs depends on the context in which they are identified [7]. Trade-offs also occur when there is a difference between the supply and demand for certain services, leading to an unbalanced or unfair distribution of services to people [8]. So far, ES trade-offs have been studied from different perspectives over the past decades, e.g., focusing on categories of spatial, temporal, reversible, and among-service trade-offs [9]. The typifying ES trade-offs presented in this study build on the previous research addressing explicit ES trade-offs [6] discussing them explicitly in peri-urban contexts [3]. Our study explores all pairs of trade-offs.

1.2. Drivers and Governance of Ecosystem Service Trade-Offs in Peri-Urban Landscapes

A driver is a factor related to human management activities that affects ESs [1]. Specifically, many ES trade-offs are driven by land use and land cover changes [9] or urbanization processes [10]. These processes have significant relevance in peri-urban contexts due to the dynamic changes in land use and land cover. Drivers can change dynamically over time, especially in transitioning landscapes like PULs. Thus, drivers of ES trade-offs need to be analyzed in a specific time context and cannot be generalized over time. Ignoring the history of a landscape and its related ecosystems might lead to an increase in trade-offs instead of synergies among ESs [10]. Failing to recognize and address drivers of ES trade-offs could lead to inequalities in ES provision and, to some extent, irreversible damage for some ecosystems [11]. Identifying potential trade-offs occurring in a certain landscape enables the design of effective management decisions aimed at minimizing social conflicts and possible environmental issues [12]. Nevertheless, ES trade-offs are still a problematic issue for policymakers and planners, mainly due to difficulties in assessing relationships among ESs [13], even though promoting synergies among ES trade-offs needs to be one of the priorities of current land-use policies [14]. Moreover, recent research shows that instruments for environmental management and policymaking could themselves be one of the drivers of ES trade-offs [9], classified as a socioecological group of drivers [1]. In particular, political practices, socioeconomic incentives, and technological progress are a set of drivers potentially generating ES trade-offs [15]. The interaction between different administrative and hierarchical levels of governance actors could also be seen as one of the important drivers of ES trade-offs [16], as specific services increased for higher administrative levels can be followed by losses at a more local level.

When looking at PULs, important ES trade-offs are related either to agricultural activities [17] or recreational activities, both of which intensively emerge in such landscapes [18]. Although some cities develop different policy mechanisms to address sustainable food production in PULs and reduce ES trade-offs, the efficiency of these policies is either difficult to assess or rather low [19]. The integration of top-down and bottom-up governance approaches has also been advocated [3], e.g., to achieve this goal, it is important to address influential users and context setters, as those actors are often responsible for ES trade-offs [7], and to implement more efficient spatial planning measures in PULs. Overall, spatial planning measures are needed to support the improvement of the rural–urban relationship, which represents the most typical peri-urban feature [19].

1.3. Research Gap and Research Aims

In this paper, we aim to examine real-world examples of ES trade-offs in PULs identified in 24 case study regions, with particular reference to normative instruments, policies, and plans that attempt to address some ESs in different geographical contexts. To this aim, we performed a detailed survey with regional experts on ESs to gain knowledge related to policymaking and spatial planning for the specific context of PULs. More specifically, this paper has the following specific objectives: (i) to characterize the case study regions containing PULs and analyze the ES trade-offs, identifying possible similarity patterns among them according to the administrative level, continent, and economic development level; (ii) to describe the drivers of peri-urban ES trade-offs in each case study region; (iii) to characterize the obstacles related to how ES trade-offs in PULs are addressed by policy instruments and spatial planning documents in each case study region; and (iv) based on the case studies analyzed, to describe possible improvements of how ES trade-offs could be better addressed by policymaking and planning in PULs.

2. Materials and Methods

To facilitate our research objective, we implemented and analyzed an online explorative survey. We chose the explorative method to provide the knowledge for closing the unexplored knowledge gap. This qualitative research method has several advantages mainly related to its flexibility [20], e.g., reduces interview biases, simplifies data collection, and increases the convenience of respondents [21]. Other ES-related studies have successfully implemented this method to display the advantages and risks of using the ES concept in participatory planning or to discuss the academic teaching of ESs [22]. The survey was forwarded to members of the following networks: International Association of Landscape Ecology (IALE), Global Land Programme (GLP), and IUFRO Landscape Ecology Working Party. We also used our personal scientific networks to contact scientists and peers working in governance, planning, and ESs in peri-urban contexts. The survey was forwarded with a notice of data protection and the explanation of objectives and contained a total of 25 questions (17 close-ended and 8 open-ended). Questions were organized into six sections: (i) the profile of the respondent, (ii) information of the case study region where PULs are located, (iii) ES trade-offs, (iv) ES trade-off drivers, (v) policy instruments, and (vi) planning documents. The first section allowed us to gather general information about respondent profiles. The second section contained questions about the case study region where PULs are located, with basic statistical data and details of the natural ecosystem types and ESs present in the region. Section three allowed us to gather information about the ES trade-offs in the analyzed PULs. The following pairs of ES trade-offs were analyzed: (i) cultural and provisioning, (ii) cultural and regulating, (iii) regulating and provisioning, (iv) different types of cultural ESs, (v) different types of provisioning ESs, and (vi) different types of regulating ESs. Section four contained close-ended questions about the drivers of ES trade-offs, where answers were predefined based on other studies [4]. Section five collected data about policy instruments, while section six included the planning documents that addressed the ES trade-offs in the analyzed case study regions. Open-ended questions were about (i) the obstacles related to specific policy instruments/planning documents to better address ES trade-offs (questions #18 and #24) and (ii) potential improvements to specific policy instruments/planning documents to better address ES trade-offs (questions #19 and #25). The answers to these open-ended questions were analyzed. Finally, the answers of close-ended questions were binary coded: “1” for positive answers (e.g., a selection of an available answer option by a respondent) and “0” for negative answers (e.g., a lack of selection of an available answer option by a respondent). The detailed questions together with their codes are presented in Table A1.

This approach allowed us to collect 24 diverse case studies of PULs, where a single case study was described by a separate answer to our survey. The case studies are located in different countries and regions (Table A2): ten are located in Europe (42%), six in South

America (29%), three in Asia (13%), three in Africa (13%), and two in North America (Figure 1).

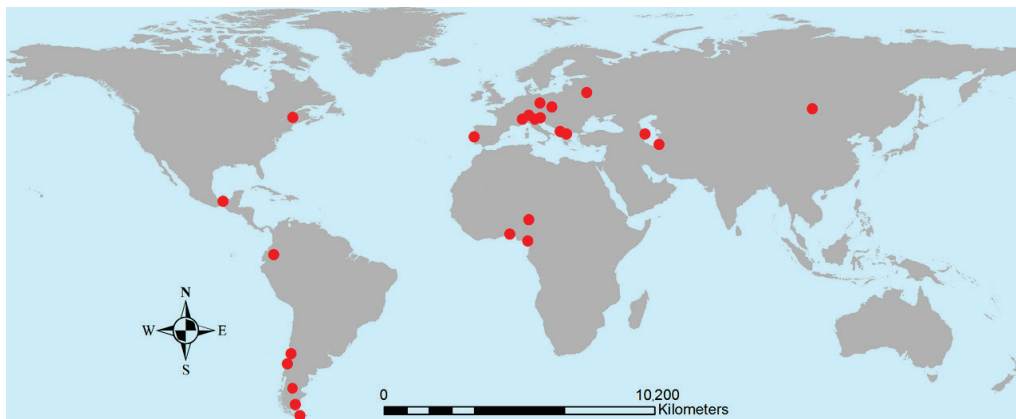


Figure 1. Localization of the case study regions (red dots).

Case studies were classified into 3 categories of administrative level: regional, metropolitan-area, and single-municipality PULs. The characterization of these case studies depended on the following factors: (1) ecosystem types (Figure A1), (ii) types of ESs (Figure A2), and (iii) types of ES trade-offs (Figure A3). The two types of ES trade-offs “cultural and provisioning” and “regulating and provisioning” were mentioned in almost all of the case studies. The data showed a relatively even distribution across the three categories of administrative level with “regional PULs” slightly more represented than the other two. The category of “different types of regulating ES trade-offs” emerged only in 54% of the case studies. It is worth noting that in more than 80% of the analyzed case studies, all types of ES trade-offs are considered challenging.

Descriptive statistics were used to characterize the case study regions and PULs. The answers provided to the open-ended questions about the obstacles related to how ES trade-offs in PULs are addressed by policy instruments and spatial planning documents (e.g., questions #18 and #24) were analyzed. The recurring aspects identified in those answers were listed and used for presenting the results (Table A3). A similar analytical procedure was applied to questions #19 and #25 regarding improvements to better address peri-urban ES trade-offs in governance and planning. To evaluate the similarities among the 24 study cases identified by respondents, we performed two separated principal component analyses (PCAs): (i) one to characterize the case studies and (ii) another for ES trade-offs. PCA reduces data multidimensionality and minimizes information losses, allowing to detect relevant characteristics to represent variability [23–25]. We used a Monte Carlo permutation test ($n = 999$) to assess the significance of each axis and set correlation coefficients among columns for the final cross-product matrices. For each PCA, we analyzed the whole group of responses (41 variables for characterization and 36 variables for ES trade-offs), but we only used those with a low redundancy and higher correlation with Axes 1 and 2 in the graphical representation (eigenvalues >0.200 for the two first axes). For each PCA, similarity patterns were explored in relation to (i) administrative-level types (single municipality, metropolitan area, region), (ii) continents (America, East Europe, West Europe, Africa, and Asia), and (iii) economic development levels (low, medium, high) according to their Human Development Index (HDI) [26]. For this last classification, three categories were defined: low for $HDI < 0.76$ (Azerbaijan, Cameroon, Ecuador, Mongolia, Nigeria), medium for $HDI 0.76–0.87$ (Argentina, Belarus, Chile, Iran, Mexico, Portugal), and high for $HDI > 0.87$ (Germany, Greece, Italy, Poland, Slovenia, US). Complementary, we used multi-response permutation procedure (MRPP) tests with Bray–Curtis distance to evaluate significant differences among groups according to geographical area types (single municipality, metropolitan area, regional), continents (America, East Europe, West Europe, Africa, Asia), and economic development levels (low, medium, high) based on the PCA analyses.

We calculated the MRPP statistic (T) with the chance-corrected within-group agreement (A) and the associated probability (p) [27]. Subsequent pairwise groupings were tested to determine the significance of the differences ($p < 0.05$) [28]. We performed the multivariate analyses in PC-ORD 5.0 software [29].

3. Results

3.1. Characterization of Case Studies

In the PCA using the case study characterization (Figure 2), the first two axes were significant (Axis 1: eigenvalue = 21.958, $p = 0.001$; Axis 2: eigenvalue = 17.399, $p = 0.001$), explaining 38.4% and 30.5% of the variance (68.9% explained accumulated variance). The more relevant characteristics were, in decreasing order, the presence of inland wetlands (B11) and inland waters (B13) among ecosystem types, as well as the domination of large (A2) or small (A3) cities, or sparse population regions (A7) (codes are explained in Table A1; eigenvectors for each variable are presented in Table A4). In the PCA about ES trade-offs (Figure 2), the first two axes (Axis 1: eigenvalue = 14.218, $p = 0.027$; Axis 2: eigenvalue = 11.138, $p = 0.010$) explained 27.6% and 21.6% of the variance (49.2% explained accumulated variance).

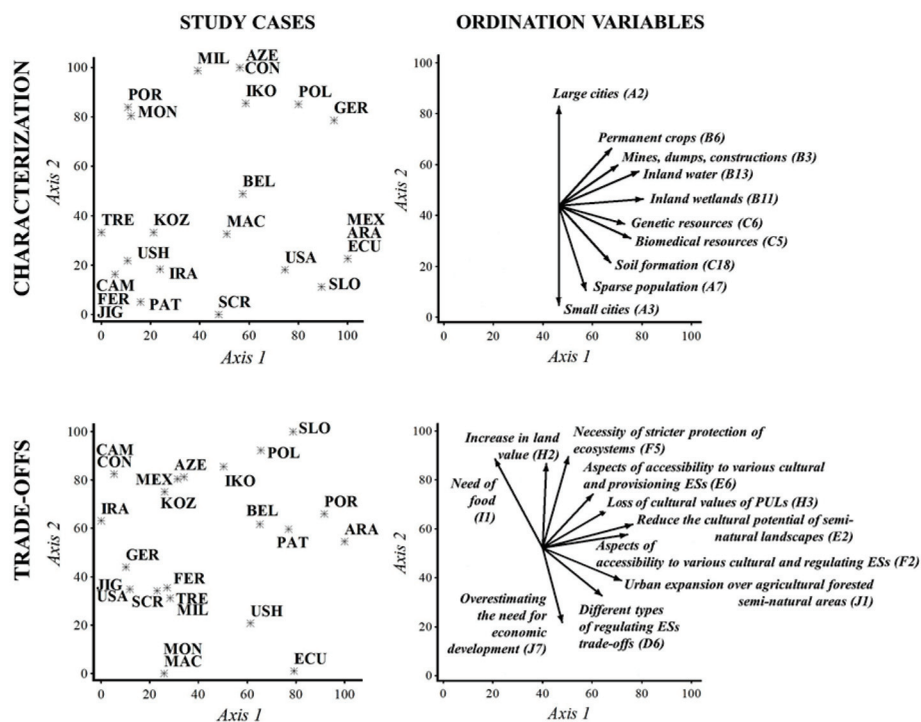


Figure 2. Case studies (left) and ordination variables (right) after principal component analysis for the characterization of case studies and trade-offs. Case studies that are closer indicate greater similarities between them; longer vectors indicate a higher influence in the case study's ordination. For the characterization analysis (**upper**), graphs are vertically flipped and 28° rotated; for the trade-off (**lower**) analysis, graphs are vertically flipped and 35° rotated. See codes for the ordination variables in Table A1. Codes explaining the location of the case studies: ARA = La Araucanía region (Chile); AZE = Greater Baku urban area (Azerbaijan); BEL = Mahiliou (Belarus); CAM = Niger Delta-Bakassi (Cameroon); CON = Concepción metropolitan area (Chile); ECU = Ecuador state (Ecuador); FER = Ferrara (Italy); GER = Berlin metropolitan area (Germany); IKO = Ikorodu (Nigeria); IRA = Gorgan (Iran); JIG = Jigawa State (Nigeria); KOZ = Kozani (Greece); MAC = West Macedonia region (Greece); MEX = Cardenas (Mexico); MIL = Southeast part of Milan metropolitan area (Italy); MON = Ulaanbaatar (Mongolia); PAT = Patagonian valleys region (Argentina); POL = Wrocław functional area (Poland); POR = Lisbon metropolitan area (Portugal); SCR = Santa Cruz province (Argentina); SLO = Osrednjeslovenska region/Central Slovenian (Slovenia); TRE = Trento (Italy); USA = Hinesburg, Vermont (United States); USH = Ushuaia urban area (Argentina).

The more relevant characteristics were, in decreasing order, the reduction in potential cultural ESs as cultural and provisioning ES trade-offs (E2), the loss of cultural ESs as a trade-off among cultural ESs (H3), the need for stricter protection of ecosystems as cultural and regulating ES trade-offs (F5), the need to provide food for a growing urban core as provisioning ES trade-offs (I1), and the emergence of regulating ESs at each case study (D6) (Table A4). In the PCA for case study characterization, the classification by geographical area type displayed the more significant grouping (Figure 3) and was validated by the MRPP results (Table A5). The three categories of case studies split by area type (single municipality, metropolitan area, and region) strongly differed among themselves ($p = 0.062$), while differences among the groups of case studies by continent or development level were not detected ($p = 0.199$) (Table A5 and Figure 3). In the PCA for ES trade-offs, the classification of case studies according to continent displayed the more significant grouping (Figure 3) and also was validated by the MRPP results (Table A5). The case studies grouped in East EU strongly differed from those in America, West EU, Africa, and Asia ($p = 0.064$), while significant differences were not detected ($p = 0.162$) among other comparisons (e.g., America and West EU, Africa or Asia) (Table A5). Likewise, a slight difference was observed between metropolitan area and regional classifications ($p = 0.092$), while weak similarities were observed for other comparisons such as geographical area categories ($p = 0.212$) and development levels ($p = 0.334$) (Table A5 and Figure 3).

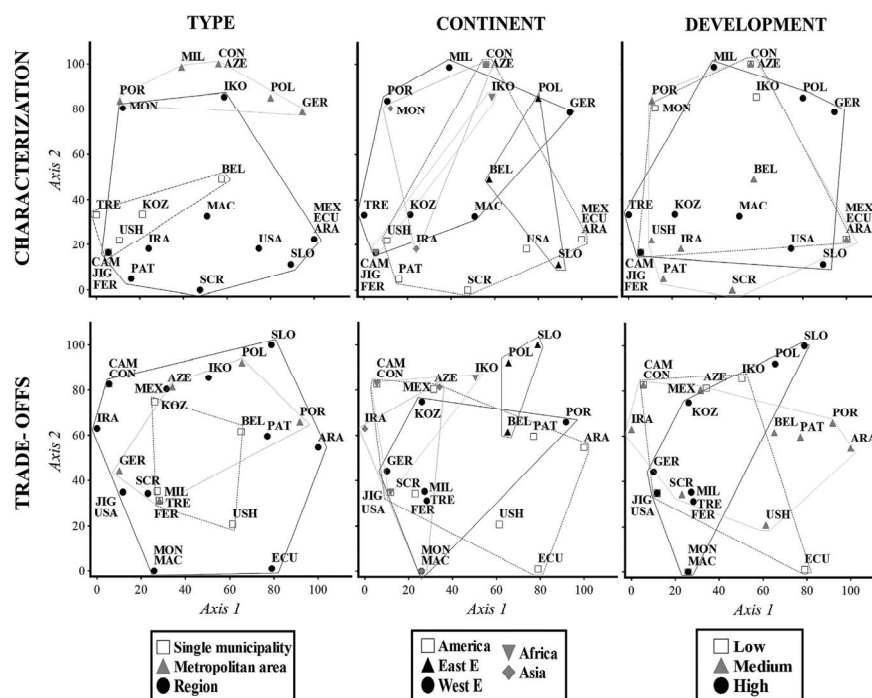


Figure 3. Classification of the case study PULs for the characterizations (**upper panel**) and trade-offs (**lower panel**). The principal component analyses (PCAs) presented in Figure 2 show geographical area type (single municipality, metropolitan area, regional), continent (America, East EU, West EU, Africa, Asia), and development level (low, medium, high).

3.2. Drivers of Ecosystem Service Trade-Offs in the Case Studies Containing Peri-Urban Landscapes

Drivers of ES trade-offs were identified by the analysis of the responses in the survey. Concerning the cultural and provisioning ES trade-offs, 71% of the respondents indicated the main driver as the conflict between current land use and those requested for ESs by local governance actors. Moreover, other drivers emerged from the survey, such as the reduction in the provision of the recreational, aesthetic, and spiritual potential of semi-natural landscapes (46%), as well as the reduction in the amenity value of the PULs (42%). The remaining groups of drivers were the reduction in the productivity of farmlands

(25%), conflicts arising from the intense recreational use of farmlands and agricultural infrastructure, unwanted trespassing, littering (21%), accessibility to other ESs (25%), and private grounds traditionally used for growing vegetables which were replaced with lawns and playgrounds (13%). When it comes to cultural and regulating ES trade-offs, the reduction in the regulating capacity of ecosystems was indicated as the most relevant driver (63%). The other drivers were aspects of accessibility to different ESs (25%), sealing surfaces (46%), decrease in water-retention potential (38%), and the need for stricter protection of ecosystems (54%). Regarding regulating and provisioning ES trade-offs, the main challenges related to forest management were the most often mentioned (63%). Other conflicts types were conflicts related to food production (50%) and the transformation of productive farmlands into public areas (green areas) (38%). For different types of cultural ES trade-offs, the most mentioned driver was related to the conflicts between new and old PUL inhabitants with different expectations of those groups (58%), while increased land value (46%) and the loss of the sense of place, aesthetics, and spiritual values of PULs (38%) were less frequently mentioned. Regarding the different types of provisioning ES trade-offs, the need to provide food for the urban core and the use of arable land for food or energy purposes were both in 42% of responses, while other drivers were the need to reduce the cost of food production (33%), the decrease in forest production (25%), and planting biofuel-related plants (17%). Regarding the different types of regulating ES trade-offs, it was observed that urban expansion over agricultural forested semi-natural areas covered 42% of case study regions. The other drivers were considered less relevant, including intensified agricultural production (13%), former heavy industrial activity (8%), lack of general awareness about ES concepts (4%), food insecurity (4%), lack of effective (strict) planning (21%), and lastly, the overestimation of the need for economic development (17%).

3.3. Obstacles in Addressing Ecosystem Service Trade-Offs by Policy and Planning

Content analysis showed the recurring aspects in the answers to the open-ended questions about the obstacles to addressing different types of ES trade-offs by policy instruments and planning documents (Table A3). The obstacles are reported in Figure 4 together with their relative frequencies. The obstacle “The proposed policy instrument/planning document (PI/PD) is not explicitly addressing ES trade-offs” emerges as the most relevant. This answer points to a lack of adequate policy instruments or planning documents that can efficiently address the existence of peri-urban ES trade-offs in each case study region. This is particularly evident in the “Metropolitan areas” as reported in Figure 4.

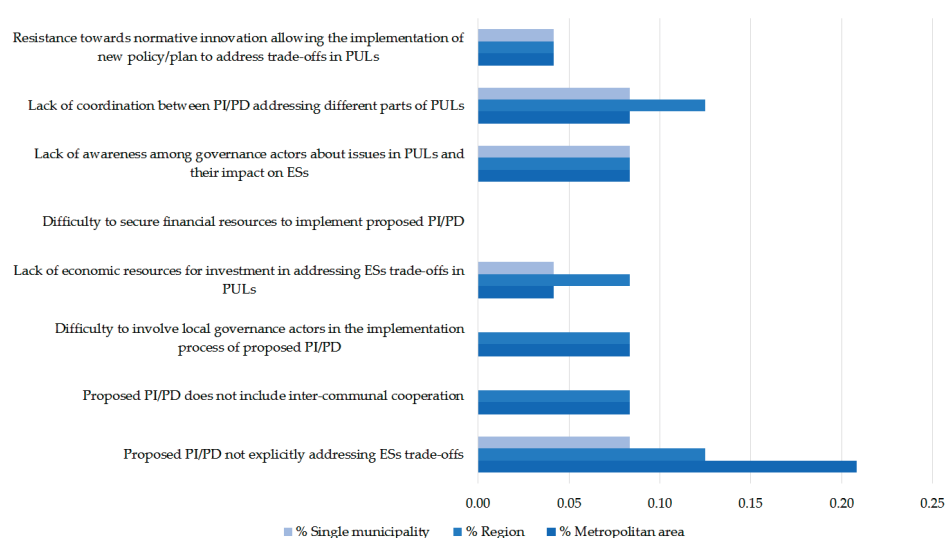


Figure 4. Type of identified possible obstacles (8 categories distributed by geographical area) related to ecosystem service (ES) trade-offs in peri urban landscapes (PULs). PD = planning document, PI = policy instrument.

In addition, a cross-analysis between the indicated obstacles and the seven categories of ES trade-offs was conducted to analyze the frequency distribution of the obstacles and categories of trade-offs (Figure A4). It can be interesting to observe how the three types of obstacles can interact with each category of ES trade-offs. In particular, the obstacle “resistance towards normative innovation” presented the highest frequencies for all categories of ES trade-offs, especially for “cultural vs. provisioning” and “regulating vs. provisioning”. Further, the obstacle “it is difficult to constantly secure financial resources to implement the proposed policy instrument/planning document” has the lowest frequencies for all categories of ES trade-offs, except for the “different types of regulating ES trade-offs”. In general, the latter is the category of ES trade-offs with the highest frequencies for all types of obstacles.

3.4. Improvements to Better Address Peri-Urban Ecosystem Service Trade-Offs in Policymaking and Planning

Content analysis showing the recurring aspects identified in the answers to the open-ended questions identifying improvements to better address peri-urban ES trade-offs in policymaking and planning, which are presented in Table A3. Further, we distilled several suggestions to address ES trade-offs. They are described in Figure 5 together with their relative frequencies. In terms of the type of possible improvements, it is observed that “implementation of the proposed policy instrument/planning document should be based on improved cooperation/communication of different governance actors” is the most relevant in more than 45% of the case studies.

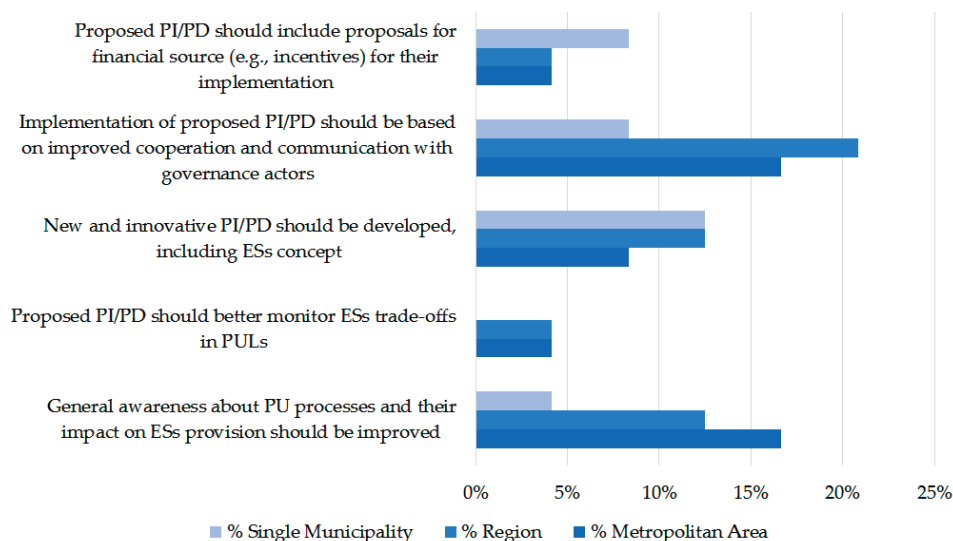


Figure 5. Types of identified improvements (categories from 1 to 5 by administrative level) proposed for better addressing ecosystem service (ES) trade-offs in peri-urban landscapes (PULs). PD = planning document, PI = policy instrument.

Moreover, the distribution of the data according to administrative level seems quite similar, where the categories “regional” and “metropolitan area” are the most preponderant ones. This study analyzed the existing connections (cross-analysis) among the types of possible improvements and categories of ES trade-offs (Figures A4 and A5). According to these results, the types of possible improvements, e.g., “general awareness about PU processes and specifically their impact on ES provision should be improved”, and “new and innovative policy instrument/planning documents should be developed, which include/incorporate the ES concept based on a better understanding of this concept” have reported higher frequencies for all the categories of ES trade-offs. Furthermore, the “implementation of the proposed policy instrument/planning document should be based on the improved cooperation/communication of different governance actors” underlines the need for more interaction among all different governance actors.

4. Discussion

The supply and demand for urban ESs differ greatly across the globe [30]. In PULs, ESs are influenced by various increasing demands for food, recreation, and housing, which are driven by the characteristics of the cities and human settlements, where development policies address these demands by increasing housing and commercial site areas at the expense of agricultural and natural lands [31]. In our research, the case studies presented dissimilarities in their natural characteristics and showed different trade-offs, resulting in a greater dispersion in the multivariate analyses. The dispersion of the case studies based on natural characterization was mainly influenced by city size, e.g., large (A2) or small (A3) cities, or sparsely populated regions (A7). This dispersion was independent of the continent or development level of the country but was influenced by the geographical area size (e.g., single municipality compared to regional level). The increase in the rate of urbanization across the world, particularly in Europe, is causing ES losses, especially at the PUL level [32]. These changes affect their capacity to supply ESs [33], consequently decreasing human well-being for current and future generations [34]. While compact cities aim to reduce land consumption, densification puts pressure on the remaining green areas, influencing ES provision and ultimately the quality of life for the growing urban population [30,35]. Greater differences among geographical area types than among continents and development levels suggest that geographical area types are similar across continents (e.g., cultures) and development levels. In this sense, the characteristics of the single municipalities in these case studies were more similar to regional than metropolitan areas (e.g., SCR and JIG). Recent efforts to improve sustainability at the landscape level have increased the interest in connecting socioeconomic and biophysical systems, where cultural ESs are identified as one of the main influential factors at different spatiotemporal scales and levels of organization [36,37], e.g., the provision of ESs at the landscape level in Southern Patagonia was greatly influenced by cultural ESs, which are related to city size [36] and influence conservation and supporting ESs [38]. Additionally, another influential factor that differentiated the case studies based on their natural characteristics was the presence of water (e.g., inland wetlands and inland water). Water presence was identified as a powerful proxy for ES provision [31]. Water bodies influence cultural ESs [36] and have a positive effect on aesthetic values [39] and recreation due to the phenomenon of hydrophilia [40,41]. However, the magnitude of their influence is related to their abundance in the landscape, e.g., they influence cultural ESs more where they are scarce (e.g., arid landscapes in Southern Patagonia) and aesthetic values more where they are frequent (e.g., Tierra del Fuego mountain landscapes) [36].

The differences among the case studies based on trade-offs were less evident in the multivariate analyses. The most important factors distinguishing the case studies were the need for stricter protection of ecosystems as cultural and regulating ES trade-offs (F5), the need to provide food for a growing urban core as provisioning ES trade-offs (I1), and the emergence of regulating ESs in each case study (D6) (see Table A3). The second axis highlights the reduction in potential cultural ESs as cultural and provisioning ES trade-offs (E2), and the loss of cultural ESs as a trade-off among cultural ESs (H3). Cueva et al. [32] recommend that trade-off patterns among ESs in PULs must be considered in the management and design of city planning, where more multifunctional and climate-resilient areas must guarantee ESs and human well-being. These factors had a greater influence in East EU compared to the rest of the world (America, West EU, Africa, Asia), despite their geographical area type (single municipality, metropolitan area, regional) or development level (low, medium, high). This could suggest specific patterns of peri-urban development within East EU. This aspect would require more studies comparing PULs in East EU and other regions or concerning the peri-urbanization of Europe [42]. The differences among European PULs could be related to development patterns in both parts of the continent and planning traditions [43]. ES interactions need to be carefully managed by integrating different policy fields at regional and local levels to sustain ES provision in peri-urban areas [31].

4.1. Drivers of Ecosystem Service Trade-Offs in Peri-Urban Landscapes

Drivers in the context of ESs are understood as the direct factors influencing specific changes in ESs [44]. Respondents to the survey identified specific drivers but did not mention large-scale drivers related to the implementation of large-scale policies or plans, e.g., policies for nature conservation or national planning requirements. Many of the drivers identified in our study were characteristic of peri-urbanization processes. Similar to other studies on peri-urban issues [3,5], our results highlight that peri-urbanization processes like sealing surfaces, growth of an urban core, intensification of agricultural production, and transformation of productive farmlands into public areas are important drivers of ES trade-offs. Moreover, other processes not addressed by our study but still resulting from peri-urban development, such as increased land value or decreased water-retention potential, generate specific ES trade-offs in PULs. Aspects related to land use or land cover changes are also seen by other authors as significant drivers [9,45]. From the analysis of survey responses, different conflicts emerged, e.g., misunderstandings about land-use management, the promotion of specific ESs by governance actors, or tensions between new and old residents. This finding confirms how PULs are vulnerable to land use, socioeconomic, ethnic, and human–wildlife conflicts [46].

4.2. Governance of Ecosystem Service Trade-Offs in Peri-Urban Landscapes

As shown in the results section, ES trade-offs in PULs are related to various drivers. Among those drivers, different types of conflicts form a significant group. Mitigating peri-urban conflicts is an important task on the way from ES trade-offs to ES synergies in such contexts [46]. The results showed several obstacles concerning how ES trade-offs are addressed by policy instruments and spatial planning documents. Specifically, the lack of adequate policies or planning documents dealing with ES trade-offs was the most common obstacle. Currently, the scientific debate is looking at aspects of PUL governance and planning in a general way [47], with limited knowledge related to practical tools or policy experiences to mitigate ES trade-offs. Such knowledge is hidden in specific niches of governance, by local planners and policymakers implementing policy and planning on-site [3]. In terms of suggestions to improve the inclusion of ES trade-offs in policymaking and planning, the results suggest that there is a need to develop sufficient and effective methods for the cooperation of governance actors to pave the way from trade-offs to synergies. Thus, a way to improve ES trade-off governance should be based on identifying the variety of actors responsible for such trade-offs. The identification and cooperation of all groups of governance actors, such as planners, householders, citizens, farmers, students, and scientists, is very important for the successful implementation of sustainable development goals in peri-urban contexts [48]. Such cooperation can be implemented with the support of the Delphi method, which has shown its usefulness in consensus-building processes in PULs [49].

An initial step in establishing and implementing cooperation methods could be based on raising awareness about trade-offs. As other studies show, the ES concept proves its usefulness in participatory planning processes and can be used as a common language to communicate about the various benefits that people obtain from landscapes. To this end, basic training on the ES concept represents a fundamental step in raising awareness [22]. This is in line with our results, showing that more awareness is needed not only concerning the ES concept but also peri-urbanization as a multifaceted and open process. PULs, like other landscapes, need to be conceptualized in a holistic way. As displayed in the literature for several decades, holistic approaches have shown their usefulness in governance and planning [50]. To this end, addressing the social perspective of landscapes and specifically understanding that place-specific peri-urban flows and the way in which they are understood and managed by governance actors is a basis for human well-being could be a good starting point to mitigate ES trade-offs.

One of the basic challenges in developing and implementing governance instruments in PULs relies on the difficulty of delimiting such landscapes in a geographic and/or

administrative way [51]. This challenge aligns with the discussion about the most effective administrative level where peri-urban systems can be governed [52]. As they are part of wider metropolitan systems where cross-administrative boundary issues exist, there is a need for more complex and advanced planning schemes and instruments. Links among different planning levels should be revised and strengthened, from the master-plan level to zoning. It has been advocated that a combination of different governance tools (e.g., traditional and innovative, top-down and bottom-up) can be used at different and integrated scales, from the more strategic (e.g., the regional/metropolitan) to the more operational (urban/district). However, such a combination requires full coordination among different planning levels, which can be achieved only with a strong normative framework. Finally, it should be underlined that none of the respondents mentioned the possible use of more specific mechanisms or management approaches to address ES trade-offs, such as multicriteria decision analysis via participatory approaches, which can be a valuable practical instrument to facilitate the learning of ES trade-offs and the explicit identification and evaluation of stakeholders' preferences [53].

4.3. Limitations and Outlook

Our results are based on a relatively small number of analyzed case studies. Moreover, our set of case studies is dominated by European ones, with several located quite close to each other (e.g., case studies from northern Italy). Thus, it is important to keep in mind that the generalizations provided in this study must acknowledge this aspect. On the other hand, our online survey method allowed us to gather experiences directly related to specific governance activities implemented in the case study regions, which concern the governance of ES trade-offs in PULs. To further develop this study, methods allowing direct discussion with local governance actors who took part in policy or planning processes should be included. When selecting the case studies, we aimed to collect as many diverse examples of PULs as possible where ES trade-offs are described as problematic from the planning perspective. We chose this explorative approach because we believe more scholarship is needed to compare various processes related to ES trade-offs in peri-urban contexts across developed and less-developed regions. To the best of our knowledge, this study is a pioneer in this regard which can open a broader scientific discussion concerning the different urbanization and peri-urbanization processes taking place in the Global North and South regions. In our opinion, interesting scientific insights and useful planning and governance results can emerge from such research, which will be important for understanding and addressing different sustainability challenges, including ES trade-offs.

5. Conclusions

This research conducted an analysis of 24 regional case studies situated in peri-urban landscapes. It involved characterizing these landscapes, identifying similarity patterns, and offering insights into existing ES trade-offs. A notable clustering of case studies was observed based on geographical area type. Similar ES trade-offs were noted among North America, Western Europe, Africa, and Asia, with the most prevalent trade-offs being categorized as “cultural and provisioning” and “regulating and provisioning”. The primary drivers of these trade-offs were directly linked to peri-urbanization, encompassing factors such as surface sealing, urban core expansion, and increased agricultural production intensity. Specific drivers were associated with various conflicts emerging in PULs. A significant challenge was the lack of identification and mitigation of these conflicts. This research identified a critical issue, e.g., the absence of explicit policy or planning documents addressing ES trade-offs in PULs, highlighting the need for innovative forms of governance. Furthermore, it emphasized the necessity of developing methods for fostering cooperation among governance actors to address these trade-offs in PULs. This collaborative effort should be rooted in a comprehensive dissemination and understanding of concepts such as ESs and PULs.

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Appendix A

Table A1. List of questions presented in the online survey.

Profile of the respondent 1. Country of residence 2. Type of institution • University • Research institute • NGO • Consultancy • Public administration • Company • Other
Information about case study region 3. Characteristic of the case study region - A1 Urban region - A2 Region dominated by large cities (more than 500 K inhabitants) and metropolitan areas - A3 Region dominated by small (less than 100 K) and medium sized cities (100–500 K) - A4 Rural region - A5 Region dominated by natural ecosystems - A6 Densely populated region - A7 Sparsely populated region 4. Natural ecosystem types present in the case study region Please provide multiple answers. The names are equivalent with CORINE land cover classes, level 2; see: https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html , accessed on 1 December 2022. - B1 Urban fabric - B2 Industrial, commercial and transportation units - B3 Mine, dump and construction sites - B4 Artificial, non-agricultural vegetated areas - B5 Arable land - B6 Permanent crops - B7 Pastures - B8 Heterogeneous agricultural areas - B9 Forests, scrub and/or herbaceous vegetation associations - B10 Open spaces with little or no vegetation - B11 Inland wetlands - B12 Maritime wetlands - B13 Inland waters - B14 Marine waters

Table A1. Cont.

5. What types of ecosystem services (ESs) exist in your case study region? <i>Based on MEA—Millennium Ecosystem Assessment</i> C1 Provisioning: food C2 Provisioning: fresh water C3 Provisioning: fuelwood C4 Provisioning: fiber C5 Provisioning: biochemicals C6 Provisioning: genetic resources C7 Regulating: climate regulation C8 Regulating: disease regulation C9 Regulating: water regulation C10 Regulating: water purification C11 Cultural: spiritual and religious C12 Cultural: recreation and ecotourism C13 Cultural: aesthetics C14 Cultural: inspirational C15 Cultural: educational C16 Cultural: sense of place C17 Cultural: cultural heritage C18 Supporting: soil formation C19 Supporting: nutrient cycling C20 Supporting: primary production
Ecosystem service (ES) trade-offs 6. Are ES trade-offs in PULs a challenge in your region which needs to be better addressed with policymaking and planning? • Yes • No 7. What kind of ES trade-offs emerge in your region? Please classify the trade-offs into: D1 Cultural and provisioning ES trade-offs D2 Cultural and regulating ES trade-offs D3 Regulating and provisioning ES trade-offs D4 Different types of cultural ES trade-offs D5 Different types of provisioning ES trade-offs D6 Different types of regulating ES trade-offs 8. Please explain why cultural and provisioning ES trade-offs in PULs are challenging in your region. E1 Conflicting land uses and local governance actors advocating specific ESs E2 Reduce the provision of the recreational, aesthetic and spiritual potential of semi-natural landscapes E3 Reduce the amenity value of the PULs E4 Reduce the productivity of farmlands E5 Conflicts arising from intense recreational use of the farmland and agricultural infrastructure, unwanted trespassing, littering E6 Aspects of accessibility to various ESs E7 Private grounds traditionally used for growing vegetables have been replaced with lawns and playgrounds 9. Please explain why cultural and regulating ES trade-offs in PULs are challenging in your region. F1 Hamper the regulating capacity of ecosystems F2 Aspects of accessibility to various ESs F3 Sealing surfaces F4 Decrease in water-retention potential F5 Necessity for stricter protection of ecosystems 10. Please explain why regulating and provisioning ES trade-offs in PULs are challenging in your region. G1 Challenges related to forest management G2 Conflicts related to food production G3 Transformations of productive farmlands into public areas (green areas) 11. Please explain why different types of cultural ES trade-offs in PULs are challenging in your region. H1 Conflicts between new and old PUL inhabitants related to the different expectations of those groups H2 Increase in land value H3 Loss of the sense of place, aesthetics, and spiritual values of PULs 12. Please explain why different types of provisioning ES trade-offs in PULs are challenging in your region. I1 The need to provide food for a growing urban core I2 The need to reduce the cost of food production I3 Decrease in forest production I4 The use of arable land for food or energy purposes I5 Planting biofuel-related plants

Table A1. Cont.

13. Please explain why different types of regulating ES trade-offs in PULs are challenging in your region. J1 Urban expansion over agricultural forested semi-natural areas J2 Intensify agricultural production J3 Former heavy industrial activity J4 Lack of general awareness about the ES concept J5 Food insecurity J6 Lack of effective (strict) planning J7 Overestimating the need for economic development
Policy instrument (PI) 14. Please name the existing PI in your region which addresses ES trade-offs in PULs. 15. Please shortly describe the existing PI in your region which addresses ES trade-offs in PULs. 16. Please name the governance actors involved in the implementation of the PI. <i>Stakeholders defined as having a particular interest as they represent a community or group interest (stake); citizens/laymen as the group being affected, but not organized to represent a shared interest; experts/scientists defined as objective knowledge holders</i> • Stakeholders • Citizens • Experts/scientists 17. Please assess the efficiency of a specific PI in addressing the ES trade-offs in PULs. <i>Assessment on the Likert scale: 1—not efficient at all to 5—very efficient</i> 18. What are the main obstacles related to this PI in better addressing ES trade-offs in PULs? <i>Please name the driver as described in questions 1.2–1.7 and please provide a short obstacle description for the chosen driver</i> 19. What are the necessary improvements to your PI to better address ES trade-offs in PULs? <i>Please name the driver as described in questions 1.2–1.7 and please provide a short improvement description for the chosen driver</i>
Planning document (PD) 20. Please name the existing PD in your region which addresses ES trade-offs in PULs 21. Please shortly describe the existing PD in your region which addresses ES trade-offs in PULs 22. Please name the governance actors involved in the implementation of the PD <i>Stakeholders defined as having a particular interest as they represent a community or group interest (stake); citizens/laymen as the group being affected, but not organized to represent a shared interest; experts/scientists defined as objective knowledge holders</i> • Stakeholders • Citizens • Experts/scientists 23. Please assess the efficiency of a specific PD in addressing the ES trade-offs in PULs <i>Assessment on the Likert scale: 1—not efficient at all to 5—very efficient</i> 24. What are the main obstacles related to this PD in better addressing ES trade-offs in PULs? <i>Please name the driver as described in questions 1.2–1.7 and please provide a short obstacle description for the chosen driver</i> 25. What are the necessary improvements to your PD to better address ES trade-offs in PULs? <i>Please name the driver as described in questions 1.2–1.7 and please provide a short improvement description for the chosen driver</i>

Table A2. List of peri-urban regions which are part of the study.

	Name of the Case Study Region	Country	Geographic Area
1	Ushuaia	Argentina	Single municipality
2	Patagonia valleys	Argentina	Regional
3	Kozani	Greece	Single municipality
4	Ferrara	Italy	Single municipality
5	Santa Cruz	Argentina	Regional
6	West Macedonia	Greece	Regional
7	Hinesburg, Vermont	United States	Regional
8	La Araucanía	Chile	Regional
9	Berlin Metro Area	Germany	Metropolitan area
10	Jigawa State	Nigeria	Regional
11	Area Metropolitana de Concepcion	Chile	Metropolitan area
12	Osrednjeslovenska region/Central Slovenian	Slovenia	Regional
13	Ulaanbaatar	Mongolia	Single municipality
14	Cardenas	Mexico	Regional
15	Greater Baku urban area.	Azerbaijan	Metropolitan area
16	Southern-east of Milan Metropolitan area	Italy	Metropolitan area
17	Mahiliou	Belarus	Single municipality
18	Wrocław Functional Area (WFA)	Poland	Metropolitan area
19	Ecuador	Ecuador	Regional
20	Trento	Italy	Single municipality
21	Gorgán Según	Iran	Regional
22	Niger Delta—Bakassi	Cameroon	Regional
23	Ikorodu	Nigeria	Regional
24	Metropolitan Area of Lisbon	Portugal	Metropolitan area

Table A3. Results of the content analysis of open-ended questions #18, #19, #24, and #25.

Section	Question with Its Number	Recurring Aspects Identified in the Answers to the Open-Ended Questions
Policy instrument (PI)	18. What are the main obstacles related to this PI in better addressing ES trade-offs in PULs?	1. The proposed PI is not explicitly addressing ES trade-offs 2. The proposed PI does include inter-communal cooperation 3. It is difficult to involve local governance actors in the implementation process of the proposed PI 4. There is an existing lack of economic resources for investment in addressing ES trade-offs in PULs 5. It is difficult to constantly secure financial resources to implement the proposed PI 6. There is a lack of awareness among governance actors about issues in PULs and specifically their impact on ES provision 7. There is a lack of coordination between different PIs that are addressing different parts of PULs 8. There is a resistance (for political or bureaucratic reasons) in normative innovation that would allow the implementation of a new policy/plan to address trade-offs in PULs
	19. What are the necessary improvements to your PI to better address ES trade-offs in PULs?	1. General awareness about peri-urbanization processes and specifically their impact on ES provision should be improved 2. The proposed PI should better monitor ES trade-offs in PULs 3. New and innovative PIs should be developed, which include/incorporate the ES concept (based on a better understanding of this concept) 4. Implementation of the proposed PI should be based on the improved cooperation/communication of different governance actors 5. The proposed PI should include options/proposals for financial sources (incentives, other economic/fiscal mechanisms) for their actual implementation
Planning document (PD)	24. What are the main obstacles related to this PD in better addressing ES trade-offs in PULs?	1. The proposed PD is not explicitly addressing ES trade-offs 2. The proposed PI does include inter-communal cooperation 3. It is difficult to involve local governance actors in the implementation process of the proposed PD 4. There is an existing lack of economic resources for investment in addressing ES trade-offs in PULs 5. It is difficult to constantly secure financial resources to implement the proposed PD 6. There is lack of awareness among governance actors about issues in PULs and specifically their impact on ES provision 7. There is a lack of coordination between different PDs that are addressing different parts of PULs 8. There is a resistance (for political or bureaucratic reasons) in normative innovation that would allow the implementation of a new policy/plan to address trade-offs in PULs
	25. What are the necessary improvements to your PD to better address ES trade-offs in PULs?	1. General awareness about peri-urbanization processes and specifically their impact on ES provision should be improved 2. The proposed PD should better monitor ES trade-offs in PULs 3. New and innovative PDs should be developed, which include/incorporate the ES concept (based on a better understanding of this concept) 4. Implementation of the proposed PD should be based on the improved cooperation/communication of different governance actors 5. The proposed PD should include options/proposals for financial sources (incentives, other economic/fiscal mechanisms) for their actual implementation

Table A4. Relevant ordination variables and eigenvector for Axes 1 and 2, according to characterization and ecosystem service (ES) trade-off PCA, performed for the 24 study cases. See codes for ordination variables in Table A1.

Characterization PCA			ES Trade-Off PCA		
Ordination Variable	Eigenvector 1	Eigenvector 2	Ordination Variable	Eigenvector 1	Eigenvector 2
A2	0.2403	−0.4514	D6	0.1174	0.3842
A3	−0.2403	0.4514	EE2	0.4642	0.1750
A7	−0.0743	0.4551	EE6	0.3799	−0.0747
B3	0.3885	−0.0313	F2	0.4116	0.2020
B6	0.3959	−0.1242	F5	0.3820	−0.3087
B11	0.4282	0.1888	H2	0.2655	−0.3465
B13	0.4736	0.0522	H3	0.3971	0.0373
C5	0.2713	0.3333	I1	0.0544	−0.5247
C6	0.2770	0.2548	J1	0.2477	0.3780
C18	0.1156	0.3934	J7	−0.1363	0.3748

Table A5. Multi-response permutation procedure (MRPP) results to compare differences in groups according to area type (single municipality—SM, metropolitan area—MA, regional—R), continent (America—AM, East Europe—EE, West Europe—WE, Africa—AFR, Asia—AS), and development level (low, medium, high), for the characterization and ecosystem service trade-offs informed by the 24 case studies, using a matrix with the more relevant ordination variables detected by PCA (Table A3).

Evaluation	Factor	Group Comparison	T	A	p
Characterization	Area type	Overall	−5.7936	0.2375	0.0002
		SM vs. MA	−5.3135	0.3816	0.0016
		SM vs. R	−1.7527	0.0593	0.0622
		MA vs. R	−5.8024	0.2189	0.0006
	Continent	Overall	−0.3613	0.0225	0.3265
		AM vs. EE	−0.2873	0.0197	0.3145
		AM vs. WE	−0.6628	0.0296	0.2090
		AM vs. AFR	−0.3652	0.0296	0.2838
		AM vs. AS	−0.4771	0.0368	0.2625
		EE vs. WE	−0.5960	0.0403	0.2423
		EE vs. AFR	−0.7851	0.1478	0.1988
		EE vs. AS	0.2068	−0.0241	0.5324
		WE vs. AFR	0.4552	−0.0414	0.6023
		WE vs. AS	0.8596	−0.0617	0.8069
		AFR vs. AS	−0.2455	0.0408	0.2984
	Development level	Overall	1.0592	−0.0427	0.8864
		low vs. medium	0.2140	−0.0100	0.9566
		low vs. high	0.8851	−0.0446	0.8588
		medium vs. high	1.1407	−0.0401	0.9566
ES trade-offs	Geographic area type	Overall	−0.9641	0.0282	0.1620
		SM vs. MA	0.5121	−0.0248	0.6704
		SM vs. R	−0.7101	0.0195	0.2115
		MA vs. R	−1.4056	0.0373	0.0922
	Continent	Overall	−1.1085	0.0493	0.1353
		AM vs. EE	−2.2379	0.0957	0.0220
		AM vs. WE	−0.8133	0.0247	0.1963
		AM vs. AFR	−0.0393	0.0023	0.4161
		AM vs. AS	0.7748	−0.0378	0.7685
		EE vs. WE	−2.1406	0.1221	0.0327
		EE vs. AFR	−2.4655	0.2530	0.0255
		EE vs. AS	−1.6393	0.1227	0.0643
		WE vs. AFR	−0.9495	0.0554	0.1624
		WE vs. AS	0.8070	−0.0539	0.7814
		AFR vs. AS	1.3425	−0.1332	0.9194
	Development level	Overall	0.2219	−0.0064	0.5457
		low vs. medium	−0.2400	0.0080	0.3345
		low vs. high	0.9391	−0.0347	0.8322
		medium vs. high	−0.3246	0.0080	0.3380

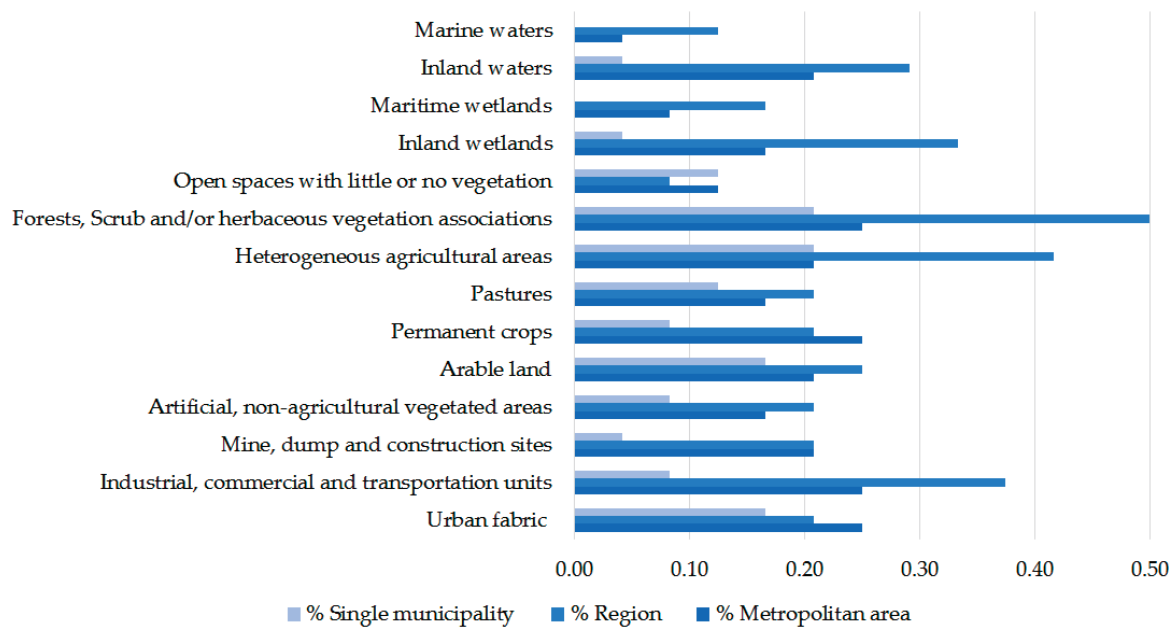


Figure A1. Distribution of the relative frequency of data on the types of ecosystems present in the case study regions.

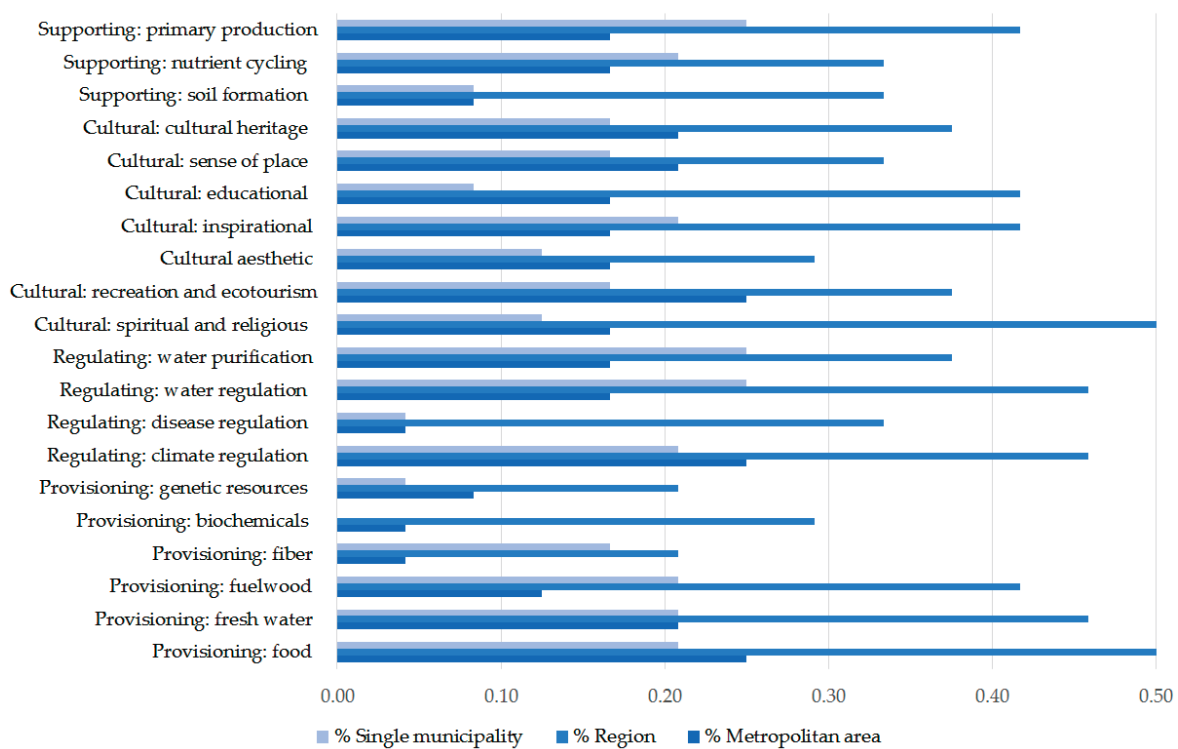


Figure A2. Relative frequency of the data distribution concerning the types of ecosystem services in the case study regions.

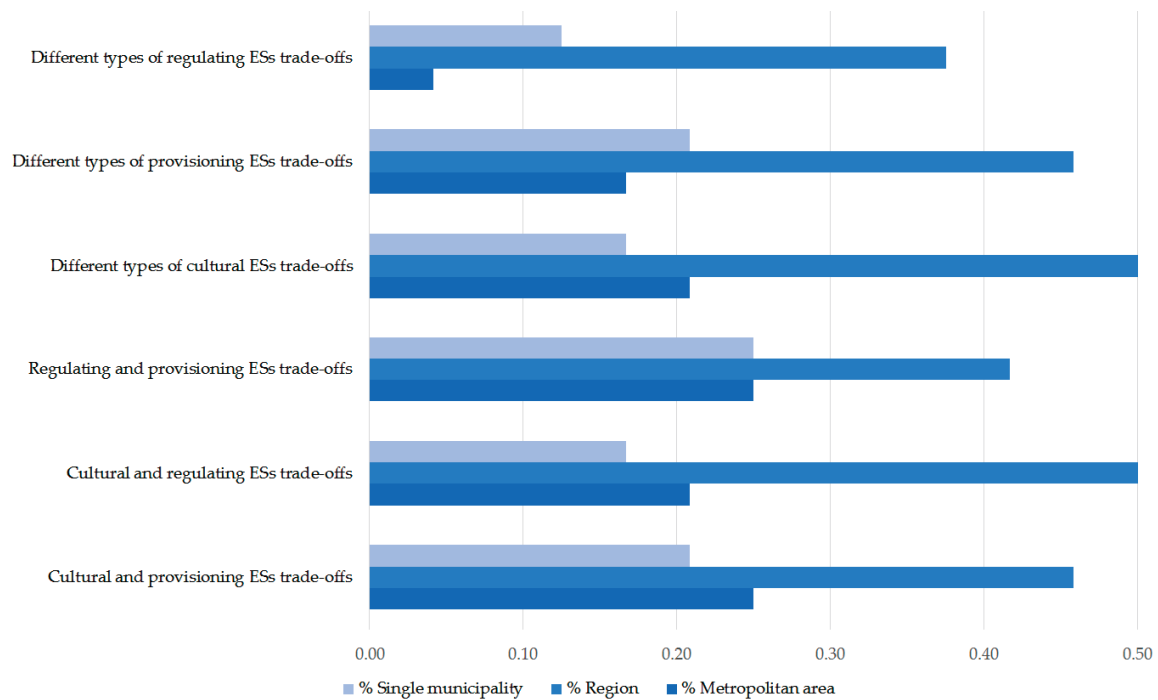


Figure A3. Relative frequency of the data distribution concerning the pairs of peri-urban ecosystem service trade-offs in the case study regions, across the geographic area categories.

	Resistance towards normative innovation that would allow the implementation of new policy/plan to address trade-offs in PULs	Lack of coordination between PI/PD addressing different parts of PULs	Lack of awareness among governance actors about issues in PULs and their impact on ESs provision	Difficulty to secure financial resources to implement proposed PI/PD	Lack of economic resources for investment in addressing ESs trade-offs in PULs	Difficulty to involve local governance actors in the implementation process of proposed PI/PD	Proposed PI/PD does not include inter-communal cooperation	Proposed PI/PD is not explicitly addressing ESs trade-offs
Cultural and provisioning ESs trade-offs	3	6	5	0	3	3	3	10
Cultural and regulating ESs trade-offs	3	6	5	0	3	4	3	8
Regulating and provisioning ESs trade-offs	2	6	6	0	3	3	3	10
Different types of cultural ESs trade-offs	3	6	5	0	3	4	3	8
Different types of provisioning ESs trade-offs	3	4	6	0	4	3	1	7
Different types of regulating ESs trade-offs	2	5	3	0	3	3	2	5

Figure A4. Cross-analysis between the identified obstacles concerning how ecosystem service (ES) trade-offs in peri-urban landscapes (PULs) are addressed by policy instruments and spatial planning documents and the seven categories of ES trade-offs. PD = planning document, PI = policy instrument. Colors varied from minimum (green) to maximum (red).

	Proposed PI/PD should include options for financial sources (e.g., incentives) for their implementation	Implementation of the proposed PI/PD should be based on improved cooperation and communication of different governance	New and innovative PI/PD should be developed including ESs concept	Proposed PI/PD should better monitor ESs trade-offs in PULs	General awareness about PU processes and their impact on ESs provision should be improved
Cultural and provisioning ESs trade-offs	3	9	8	2	8
Cultural and regulating ESs trade-offs	3	8	7	1	7
Regulating and provisioning ESs trade-offs	3	10	8	2	8
Different types of cultural ESs trade-offs	3	8	8	2	8
Different types of provisioning ESs trade-offs	4	7	7	1	7
Different types of regulating ESs trade-offs	3	4	6	1	3

Figure A5. Cross-analysis between the identified improvements to better address peri-urban ecosystem service (ES) trade-offs in policymaking and planning and the seven categories of ES trade-offs. PD = planning document, PI = policy instrument. Colors varied from minimum (green) to maximum (red).

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Article

Planning for People with People: Green Infrastructure and Nature-Based Solutions in Participatory Land-Use Planning, Co-Design, and Co-Governance of Green and Open Spaces

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Abstract: Green infrastructure (GI) and nature-based solutions (NBSs) in land-use planning and landscape architecture represent a holistic, interdisciplinary response to environmental and societal challenges. Although integrated into Slovak legislation since 2019, their formal implementation has progressed rather slowly, creating a gap that has been increasingly addressed by civic initiatives (CIs) of diverse types and legal forms. This study examines approaches and methods of CIs in Slovakia implementing GI and NBSs, while focusing on their legal forms, activities, spatial delimitations, and their impact on green space development and governance. Analysis of seventeen case studies shows that many CIs operate at multiple levels—local, national, and international—often delivering professional, conceptually grounded solutions. The most frequent NBS activities involve creating or enhancing parks, green public spaces, and community gardens, as well as restoring natural and semi-natural areas through nature-based management. Knowledge creation and awareness-raising are central strategies, including environmental education centres, citizen science, public campaigns, and informal learning platforms. The transformation of derelict areas into multifunctional public spaces emerges as a notable practice, combining ecological regeneration with cultural and social uses. The findings highlight the growing role of civic actors in advancing inclusive, participatory, and knowledge-based environmental management and call for stronger institutional support to integrate their contributions into formal administrative frameworks.

Keywords: bottom-up initiatives; civic engagement; environmental stewardship; green infrastructure; nature-based solutions; stakeholder participation

1. Introduction

The European Union (EU) environmental policy is built upon a long-term vision of sustainability, encompassing principles of circular economy, green finance, digital transformation, and participatory governance [1]. The need for a more sustainable way of existence is urged by global trends, challenges, and crises worldwide. Addressing this challenge is “a shared responsibility of all states, market, and civil society” [2]. Future progress will not only depend on the strength of regulatory frameworks, but also on a meaningful engagement of stakeholders—businesses, scientists, entrepreneurs, and citizens alike. Environmental policy must continue to evolve as a dynamic governance instrument, capable of navigating uncertainty while ensuring that ecological integrity and human well-being remain central to sustainable development [1,3]. There is a growing understanding of the need to enable bottom-up initiatives and develop more participatory strategies to

mainstream solution-oriented approaches in spatial planning, including co-design, co-production, and co-management [4]. This reflects a broader trend in sustainability and other societal domains towards the co-production of solutions by researchers and societal stakeholders [5].

1.1. Solution-Oriented Planning Approaches in Sustainable Development

The planning and design of sustainable, resilient, and healthy landscapes, cities, and communities is firmly rooted in the 2030 Agenda for Sustainable Development and the Sustainable Development Goals (SDGs) adopted by the United Nations General Assembly in 2015. GI and NBSs are increasingly recognised as key concepts within EU policy discourse, promoted as solution-oriented planning approaches that integrate the objectives of nature conservation, urban development, and climate change adaptation [6]. The contemporary concepts of NBSs, GI, ecosystem services (ESs), and other environmentally based approaches are closely related and integrated [7,8]. NBSs are inspired and/or supported by nature, they are cost-effective, and capable of simultaneously delivering multiple environmental, social, and economical services and benefits. These approaches introduce diverse natural features and processes into urban, rural, and coastal contexts through locally adapted, resource-efficient, and systemic interventions [9]. They also operationalise environmental and socio-economic goals through inclusive dialogue among policymakers, scientists, practitioners, and the public [10]. GI is regarded as an innovative concept across disciplines and governance spheres. It is defined as an interconnected network of green spaces that conserves ecosystem functions and delivers associated human benefits [11]. GI holds significant potential for steering urban and rural areas towards sustainable and resilient development pathways [12]. Ecosystem services (ES) provide a complementary, integrative framework linking nature and human well-being across natural, social, and economic sciences. The functional roles of GI and NBSs closely align with ES, which—broadly defined—represent the contributions of natural and semi-natural ecosystems to human well-being [11,13]. Although on the rise, NBSs are not yet mainstream in urban development [14]. Thus, planning, designing, implementing, and managing GI and NBSs remains a complex task, requiring multi-level coordination across local, regional, national, and international contexts and spanning different landscape scales and governance structures [15].

1.2. Civic Engagement and Participation in Green Space Development

Civic engagement (CE) broadly refers to collective actions undertaken in pursuit of socially oriented goals, encompassing activities such as volunteering, community involvement, and social or political participation [16,17]. It can also be understood as a set of individual and collective efforts aimed at generating positive societal change while simultaneously developing the knowledge, skills, values, and motivations needed to sustain such efforts [18,19]. Active citizenship or bottom-up initiatives are increasingly recognised as forms of social innovation, where citizens act as voluntary producers or co-producers of social equity and urban sustainability [20,21]. Acts of environmental stewardship may include tree planting, green space maintenance, and community-based projects in parks, gardens, and other public spaces [19]. These initiatives play an important role in nature creation and environmental governance, particularly in urban and peri-urban areas [21], offering alternative models that can complement or challenge traditional top-down policy-making approaches [22]. Unlike public participation, which is typically government-led, active citizenship arises from community self-organisation and the lived experiences of individuals [23–25]. Citizens engaged in these processes often seek to support the development of sustainable neighbourhoods, address specific aspects of the local landscape, and promote democratic practices in environmental governance [26].

In the context of green space planning and governance, involving professionals, civic associations, and lay actors enables diverse perspectives to be integrated into planning processes, thereby stimulating interdisciplinary dialogue and collaboration in decision-making frameworks [10,23,27]. However, the presence and role of NGOs vary significantly across Europe. In regions with an established tradition of civic activism, there tends to be greater engagement in participatory processes. Conversely, in areas where NGOs are less active, the capacity for public involvement is weaker. In some countries, NGO involvement in green space planning is becoming increasingly institutionalised, while in others it remains limited or absent [27,28].

1.3. Environmental Stewardship and Green Space Planning in Post Socialist Slovakia

In these complicated times of ongoing climate, economic and social crises, many stakeholders from the Slovak academic, business, and civic sectors, as well as the public administration, see only a little progress towards a “Sustainable Slovakia”. According to the main findings of the study by Huba and Kaščáková [29], the state faces numerous challenges at both national and regional levels. These include dysfunctional public administration, the absence of coherent strategies and integrated planning, environmental degradation and pollution, landscape destruction, a shortage of competent leadership, and limited citizen participation in public affairs. There is a notable absence of effective mechanisms for integrating sectoral and disciplinary approaches, as well as for coordinating actions across different planning levels. Dysfunction within the current system limits the capacity of top-down planning to adequately support the implementation of objectives at regional and local levels [1].

Current issues in Slovakia are rooted in post-socialist transitions, marked by rapid privatisation and the retreat of state planning. These shifts, along with emerging opportunities such as civic society development and changing societal values, have influenced all policy areas, including green space development and management. As such, green spaces can be seen as mirrors of broader societal transformation in post-socialist contexts [30]. Although the era of state socialism is commonly associated with political repression, it also laid the foundations for modern environmental advocacy in Slovakia [27]. The democratic shift of November 1989 promised extensive public participation in decision-making [31], and early “green recreation” activities—aimed at preserving cultural landscapes—evolved into broader environmental and civil rights discourses [32]. Conservation efforts soon attracted state surveillance and opposition [33], but this only bolstered public support, especially among urban intellectuals [34].

Principal international frameworks—such as the Aarhus Convention (1998) and the EC Directive (2003)—further enshrined participatory rights in Slovak law [27], enabling citizens to organise in both informal collectives and formal nongovernmental organisations that form mobilisation networks [35]. The 2010 municipal elections marked a turning point when environmentalists successfully campaigned for democratic and sustainable urban development, signalling a declared break from previous practices and the need for a “new political culture” to enable grassroots participation [31]. This activism drew on socialist era volunteer traditions (e.g., tree planting and community “brigades”), illustrating how greenspace stewardship has long served as a vehicle for social norms, place making, and local identity [36]. Unlike earlier activism focused on wilderness preservation [37], contemporary movements prioritise “everyday nature” in urban settings [38]. Stewardship is defined here as voluntary action to conserve, manage, monitor, advocate for, or educate the public about the local environment [19].

Green infrastructure entered the Slovak planning law in 2019 via the Nature and Landscape Protection Act No. 543/2002 [39], which was generally considered a promising

opportunity to be used in planning sustainable urban development and resilient urban landscapes. Despite initial optimism, implementation has stalled due to limited political support and vested interests [40]. Many EU-led initiatives (e.g., urban climate adaptation guidelines, Natura 2000) are viewed as external burdens rather than opportunities to enhance urban quality of life [30]. A significant reform came with Act No. 200/2022 on Spatial Planning, effective since April 2024, which requires municipalities to prepare spatial plans incorporating nature protection, climate adaptation, and GI [41]. Although the new policies that have been implemented seem to be moving in the right direction, it will take time to confirm that they are being applied in practice. The slow pace of legal enactment towards the sustainable development future of Slovakia has created a niche now filled by civic associations and bottom-up initiatives [23].

1.4. Analytical Framework and Thematic Scope

A review [42] focusing on stakeholder engagement in the context of NBSs identified a marked increase in related publications since 2017, underscoring the growing relevance of this topic across various national contexts. However, Slovakia was notably absent from this review, which highlights the added value of the study.

Urban greening is increasingly seen as a “public good” initiative delivering a range of multiple health and well-being benefits [43,44]. This confirms nearly 1000 NBSs involved in the global database “Urban Nature Atlas” (UNA), developed within the NATURVATION project in 2017 [45]. Green spaces now offer citizens direct roles in climate action—one of the UN’s Sustainable Development Goals [46]. While in countries with longer democratic traditions, local governments typically facilitate wide-ranging actor participation in climate adaptation [22], in Slovakia, these activities are predominantly initiated and governed by NGOs. This is due to weak top-down green space planning processes that lack interdisciplinary collaboration and face insufficient regulatory frameworks and inadequate public involvement in decision-making [40].

The study aims to explore the scope and diversity of NBSs implemented by CIs and examine how these grassroots actors engage with, adapt, and contribute to sustainable urban and rural transformations through green and blue infrastructure activities.

The analytical framework draws on the methodology developed by the NATURVATION project. The UNA was designed to gather evidence on NBSs and serve as a foundation to analyse the socioeconomic and innovation dynamics related to NBS implementation globally. It supports both the public and policymakers in understanding how communities worldwide are leveraging nature to confront the impacts and causes of climate change across diverse urban settings, ecosystems, and governance systems [45]. The database features numerous projects initiated by NGOs or civil society, which represent the second-largest group of initiators after local governments. Although Slovakia is represented in the Atlas, only municipally led projects were included.

The analysis is structured around five interrelated thematic dimensions:

- Legal form of civic initiatives CIs (Table A2), distinguishing between formalised entities—such as registered civic associations and non-profit organisations—and informal collectives without legal status.
- Spatial context of engagement, identifying whether initiatives operate primarily in urban or rural settings.
- Spatial scale of impact (Table A3), categorised as local, national, or international, reflecting the geographical reach of activities from community-based projects to cross-border engagements.
- Typology of NBSs implemented (Table A4), including blue infrastructure (e.g., river-bank restoration), productive gardens (e.g., allotments, community gardens), storm

water management systems (e.g., rain gardens, swales), green–grey integration, parks, and unmanaged areas.

- Activity focus (Table A5), encompassing creation and maintenance of green spaces, ecological restoration, policy advocacy, knowledge dissemination, and food production.

This multidimensional framework facilitates a comprehensive understanding of how civic actors contribute to sustainable urban and rural transformation through NBS practices across varying spatial and institutional contexts.

2. Materials and Methods

2.1. Case Identification and Data Collection

Slovakia is administratively divided into eight self-governing regions (SGRs) (Figure 1), which served as the territorial basis for case selection to ensure geographic diversity and regional representation. The initial phase of the study focused on identifying CIs in Slovakia that prioritise environmental protection, ecological restoration, and public participation in environmental decision-making. To conduct this search systematically, we used the online Business Register of the Statistical Office of the Slovak Republic to identify registered civic associations operating in these domains.

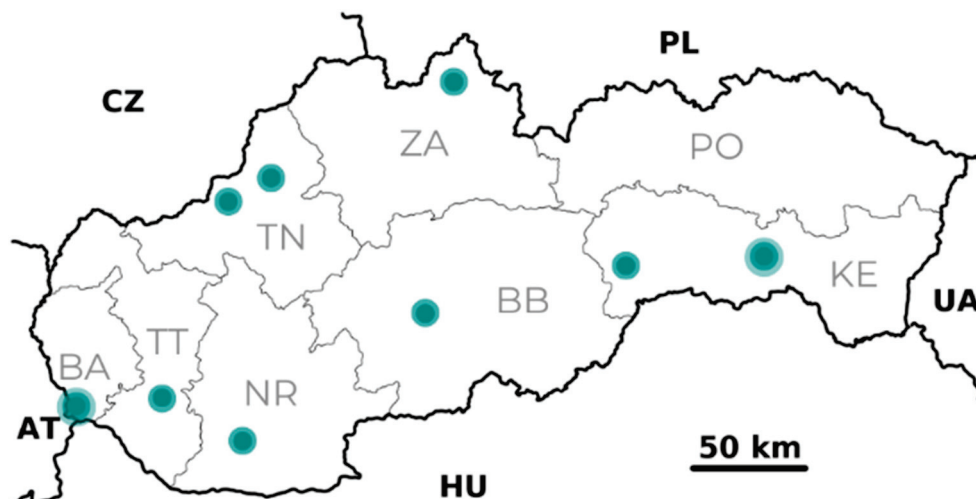


Figure 1. Location and distribution of studied CIs within Slovakia (indicated with green dots in the map). Bordering countries of Slovakia are the Czech Republic—CZ; Poland—PL; Ukraine—UA; Hungary—HU; and Austria—AT. Eight self-governing regions of Slovakia: Bratislava region—BA; Trnava region—TT; Trenčín region—TN; Žilina region—ZA; Banská Bystrica region—BB; Poprad region—PO; Košice region—KE.

To build the case study (CS) database, the general selection criteria were applied to ensure relevance to the research objectives. Eligible cases were required to address urban or rural societal challenges, involve interventions that altered or enhanced the function of a specific area, and apply nature-based principles—either directly or conceptually—to respond to environmental, spatial, or social issues. These interventions included both physical transformations (e.g., green infrastructure, habitat restoration) and discursive actions (e.g., educational programs, participatory management approaches). Each case also had to demonstrate engagement with civil society or other relevant stakeholders.

A total of 17 CSs were identified across both urban and rural contexts within Slovakia. These include: 7 CSs from the Bratislava Self-Governing Region (SGR), 2 CSs from Trenčín SGR, 1 CS from Trnava SGR, 2 CSs from Nitra SGR, 1 CS from Žilina SGR, 2 CSs from Banská Bystrica SGR, and 2 CSs from Košice SGR. Each case study entry includes general

information such as the legal status of the initiative, its goals and objectives, and relevant contact details (Table A1).

CS.01_Národný trust—The National Trust of Slovakia, Legal form: Non-profit organisation. Location: Bratislava (BA-SGR). Focus: Protection, restoration, and public access to Slovakia's cultural and natural heritage, particularly historic parks and gardens, as well as valuable trees, avenues, and heritage landscapes.

CS.02_Vnútroblok. Legal form: Civic association. Location: Bratislava (BA-SGR). Focus: Initiative was founded to transform unused or derelict urban spaces—vacant lots, courtyards, or disused schoolyards—into active, community-led mobile gardens.

CS.03_KoZa v Háji. Legal form: Civic association. Location: Bratislava (BA-SGR). Focus: Initiative represents a compelling example of how small, urban community gardens can be catalysts for ecological education, community resilience, and spatial revitalisation. Through participatory gardening, environmental workshops, and intergenerational collaboration, it offers both a knowledge-rich environment and a collective platform for urban resident empowerment.

CS.04_Hrad—Slavín. Legal form: Civic association. Location: Bratislava (BA-SGR). Focus: The initiative is committed to improving urban living conditions through safeguarding greenery, preventing unwarranted development, and advocating for urban environmental quality. The organisation actively monitors tree felling and campaigns against improper removal of mature trees. The association took part in rescuing the historically significant Mičurin botanical site, a national cultural monument in decline, advocating for its preservation and restoration.

CS.05_BROZ—Regional Association for Nature Conservation and Sustainable Development. Legal form: Civic association. Location: Bratislava (BA-SGR). Focus: Professionally staffed NGO dedicated to practical conservation and restoration of Natura 2000 habitats across Slovakia, with particular focus on the Danube floodplain, Little and White Carpathians, Záhorie, and the Bratislava region. Their mission is to halt habitat degradation and biodiversity loss through science-based, site-specific interventions and stakeholder collaboration.

CS.06_DAPHNE—Institute of Applied Ecology. Legal form: Civic association. Location: Bratislava (BA-SGR). Focus: The organisation specialises in applied ecological research, habitat conservation, and education, particularly targeting small non-forest ecosystems such as meadows, marshes, peatlands, saline systems, and sand dunes in Slovakia. With a core team of approximately ten professionals supported by external collaborators, DAPHNE integrates science, policy, and civic engagement in its work.

CS.07_NašeZálesíčko. Legal form: Civic association. Location: Zálesie (BA-SGR). Focus: Exemplifies how a small village association can activate local landscapes through blue-green infrastructure, artful community planning, and lifelong learning. By merging environmental design with culture and civic engagement, they have redefined a suburban area as a model of sustainable, bottom-up stewardship and ecological resiliency.

CS.08_ŽiTo v SÝPKE. Legal form: Civic association. Location: Moravské Lieskové (TN-SGR). Focus: Initiative emerged from community efforts to revitalise a former agricultural estate—including a disused granary—into a vibrant educational, cultural, and ecological hub. The association is committed to creating a space that connects people through sensory experiences, environmental knowledge, and community values.

CS.09_eDeN v meste. Legal form: Civic association. Location: Nová Dubnica (TN-SGR). Focus: The organisation is engaged in creating a community garden, planting trees, restoring wetlands, and constructing educational trails focused on local biodiversity.

CS.10_Zelený plán. Legal form: Civic association. Location: Galanta (TT-SGR). Focus: Sustainable, high-quality public spaces and environmental stewardship through participatory interventions, educational outreach, and applied landscape-architectural

design. The organisation promotes environmental literacy by illustrating how public greenery can improve climate resilience, biodiversity, and social cohesion in everyday urban life.

CS.11_VíZia—Rural Green Infrastructure. Legal form: Civic association. Location: Tvrdošovce (NR-SGR). Focus: A mission to promote and implement green infrastructure solutions in rural municipalities. It engages in environmental education, tree planting, and biodiversity-enhancing initiatives, collaborating closely with the local community and municipality.

CS.12_Strom darom. Legal form: Informal project. Location: Nové Zámky (NR-SGR). Focus: Aims to encourage civic engagement through a simple yet meaningful act: residents purchase and plant a tree as a gift to the city, someone else, or for a special occasion. The initiative actively monitors tree felling and campaigns against the improper removal of mature trees.

CS.13_Alter Nativa. Legal form: Civic association. Location: Brdárka (KE-SGR). Focus: Established in a small village with approximately 40 households and over 4000 cherry trees, the organisation fosters sustainable land stewardship, genetic biodiversity conservation, and permaculture education as part of its ethical and communal mission. The association emerged from a desire to cultivate meaningful, ecologically responsible lifestyles rooted in permaculture, traditional crafts, and rural community cohesion.

CS.14_Pod'nadvor. Legal form: Civic association. Location: Košice, (KE-SGR). Focus: Focused on community gardening and place-based interventions. Through cleaning, planting, artistic interventions, and communal gatherings, the group fostered a neighbour-driven transformation of public space.

CS.15_Spolka. Legal form: Civic association. Location: Košice (KE-SGR). Focus: Their mission is to foster sustainable, inclusive cities driven by public discourse and engagement in urban transformation. It is a collective of architects, sociologists, and designers committed to reshaping urban space through participatory processes, critical research, education, and civic co-creation.

CS.16_Združenie Slatinka. Legal form: Civic association. Location: Zvolen (BB-SGR). Focus: The association emerged in response to renewed plans for a controversial water reservoir on the Slatina River. The association successfully contributed to securing the river valley's official recognition as a Natura 2000 protected area. Manages a local natural site as well—Lanice Park in Zvolen—and the surrounding floodplain meadows, supporting stewardship and ecological maintenance. Engages children and youth through school-based ecological programming and hands-on trail maintenance.

CS.17_Živý priestor. Legal form: Civic association. Location: Námestovo (ZA-SGR). Focus: The organisation aims to revitalise public spaces around the Oravská priehrada (Orava Reservoir) and adjacent waterways. Their goal is to foster place-based creativity, reconnect communities with local nature, and promote sustainable regional development through participatory interventions and cultural events.

2.2. Analysis of Civic Initiative's Activities Within Nature-Based Solutions

Discourse analysis [45] was used to examine how civic associations in Slovakia frame and legitimise their practices related to NBSs and landscape transformation. Drawing on websites, public presentations, and interview transcripts, the study identified narratives, metaphors, and framings that articulate values such as ecological care, resilience, and community stewardship. Using a critical discourse analysis lens [47–49], it explored how initiatives position themselves within governance structures, how certain discourses gain legitimacy and how they influence public engagement and policy. This method provided insight into how civic actors shape local landscape imaginaries and embed ecological thinking into place-based interventions [49].

To identify and categorise the NBSs implemented by CIs, the study employed a typological framework grounded in the ecological function and spatial characteristics of the interventions. There is a table within each NBS category that includes the number (n) of CSs per studied area.

Six distinct categories of NBSs (Table A4) were used as analytical indicators: blue infrastructure, productive gardens, green areas for stormwater management, grey infrastructure integrating green, parks and other green spaces, and intentionally unmanaged areas. NBSs may be implemented at a small scale; for example, pocket parks, community gardens, or tree-lined streets. They may also be realised at a larger scale, such as through city-level projects involving the creation of green corridors, riverbank restoration, or the adoption of city-wide biodiversity strategies that incorporate multiple green space elements [45,50].

The study examined the topic using a qualitative content analysis to examine the focus and activities of CIs implementing NBSs. Data collection involved identifying and categorising initiatives based on a predefined framework of focus areas and main activities, as outlined in Appendix E, (Table A5). The analysis utilised ten indicators of NBS engagement: creation of new green areas, maintenance and management of green spaces, ecological restoration of ecosystems, protection of natural ecosystems, transformation of previously derelict areas, knowledge creation and awareness raising, strategy and policy development, improved governance of green or blue areas, monitoring and maintenance of habitats, and food production through permaculture. Each initiative was assessed for its alignment with one or more of these categories by examining its documented activities, goals, and implemented actions. This approach enabled a systematic comparison of the ways in which civic actors contribute to ecological, social, and governance-related dimensions of NBS across diverse urban and rural contexts.

3. Results

3.1. Legal Form, Spatial Delimitation and Impact of Initiatives

An analysis of the legal forms adopted by CIs reveals that most ($n = 15$ (88%)) of the CSs operate as civic associations. The predominance of this legal form may be attributed to its greater flexibility in organisational structure and comparatively lower administrative burden relative to other non-profit legal forms (Table 1).

Table 1. Analysis of legal forms, spatial delimitation and impact of civic initiatives.

Studied Area	Sub-Area	Civic Initiatives
Legal form	Non-profit organisation ($n = 1$)	CS.01
	Civic association ($n = 15$)	CS.02, CS.03, CS.04, CS.05, CS.06, CS.07, CS.08, CS.09, CS.10, CS.11, CS.13, CS.14, CS.15, CS.16, CS.17
	Informal, project ($n = 1$)	CS.12
Spatial delimitation	Urban ($n = 9$)	CS.02, CS.03, CS.04, CS.09, CS.10, CS.12, CS.15, CS.16, CS.17
	Rural ($n = 4$)	CS.07, CS.08, CS.11, CS.13
	Urban + Rural ($n = 4$)	CS.01, CS.05, CS.06, CS.14
Impact	Local ($n = 17$)	CS.01, CS.02, CS.03, CS.04, CS.05, CS.06, CS.07, CS.08, CS.09, CS.10, CS.11, CS.12, CS.13, CS.14, CS.15, CS.16, CS.17
	National ($n = 6$)	CS.01, CS.04, CS.05, CS.06, CS.14, CS.16
	International ($n = 4$)	CS.01, CS.05, CS.06, CS.16

In terms of spatial context (Table 1), our findings indicate that in $n = 4$ (24%) cases, CIs engage in both urban and rural environments. Civic engagement and innovation are no longer confined only to urban environments, which account for $n = 9$ (52%) cases of interventions. Notably, $n = 4$ (24%) of the initiatives engage in rural areas too, highlighting the growing role of active communities beyond city boundaries. In some cases, such an engagement takes place in remote locations with very small populations, for example, case study CS.13, located in a municipality with only 60 residents.

The spatial reach and influence (Table 1) of the analysed civic initiatives (CS.01–CS.17) demonstrate a predominant focus on the local scale, underscoring their deep embeddedness within community contexts. All 17 initiatives primarily operate within their respective municipalities or regions, where they engage directly with residents, local authorities, and place-based environmental challenges. This local anchoring enables them to tailor interventions to specific socio-ecological contexts and to cultivate strong, trust-based relationships with stakeholders.

At the national level, $n = 6$ (35%) of the initiatives extend their activities beyond their immediate localities, contributing to broader environmental, educational, and policy impacts across Slovakia. For example, CS.01 organises a nationwide cultural and educational event (the Weekend of Open Parks and Gardens) that fosters public engagement in the conservation of historical parks and gardens. In parallel, it supports education and research through the Centre for Garden and Landscape Culture. CS.04 coordinates the national platform (Green to Green, Zelená zelení), which addresses climate change adaptation and mitigation while involving stakeholders from all Slovak regions. CS.05 operates nationally to protect and restore forests, meadows, and wetlands within Natura 2000 sites, with a particular emphasis on the Bratislava region and southwestern Slovakia. CS.14 contributes to environmental policy development by reviewing legislation and advocating for enhanced civic participation, while also being an active member of the Ekofórum national network, which fosters collaboration among Slovak environmental NGOs. CS.16 is frequently invited by municipalities across the country to share expertise in participatory planning, especially in contexts where local capacity is limited.

At the international level, $n = 4$ (24%) of the initiatives engage in transnational collaborations, EU-funded projects, and cross-border partnerships. CS.01 and CS.05 jointly participate in the Cities. Gardens. Diversity—Bratislava and Vienna Go Green Together INTERREG project, which strengthens green infrastructure and biodiversity. CS.01 also leads the “Wise Trees” project in partnership with Hungarian organisations, focusing on ancient tree conservation along the Slovak–Hungarian border. CS.05 is involved in multiple EU-funded environmental initiatives, including Resilient Trees, which promotes the conservation of old-growth forests and veteran trees across six European countries, and LIFE Resistance, a transboundary restoration project targeting Danube floodplain habitats through innovative methods such as satellite monitoring and traditional grazing. Furthermore, the WILDisland project, part of the broader DANUBEPARKS network, unites 15 partners from nine countries to revitalise Danube islands and preserve floodplain forests. CS.06 cooperates with Austrian partners on the City Nature project, enhancing urban biodiversity in Bratislava and Vienna, while also contributing to invasive species management strategies across Slovak and Czech territories. CS.14 hosted VUELA 2024, a Spanish–Slovak collaboration that engaged university students in hands-on environmental restoration in the Slatina River valley. CS.16 participated in the Slovak–Norwegian Cultural Matching initiative, which promoted civic engagement and cultural exchange through digital events focused on co-creation in urban planning, participatory democracy, and digital citizenship.

3.2. Activities of Civic Initiatives' Engaging in Nature-Based Solutions

According to Colding [51], active citizenship contributes to urban GI creation and maintenance, as well as activates the local communities by enhancing social cohesion and environmental awareness [52,53]. Citizen and stakeholder participation in NBS has been reported as crucial for the success of those solutions. Such participation usually involves people and organised groups that can influence the decision-making processes [42]. The study analyses the activities (Figure A1) of 17 case studies engaging in NBSs (Figure A2).

3.2.1. Blue Infrastructure

Within the scope of NBSs, blue infrastructure represents 41% of all identified civic-led interventions (Table 2).

Table 2. Analysis of studied NBSs—blue infrastructure.

Nature-Based Solutions	Activities	Civic Initiatives
Blue infrastructure (<i>n</i> = 7)	Protection and restoration of natural ecosystems (<i>n</i> = 7)	CS.05, CS.06, CS.07, CS.09, CS.10, CS.14, CS.17
	Transformation of previously derelict areas (<i>n</i> = 1)	CS.07
	Monitoring and maintenance of habitats (<i>n</i> = 3)	CS.05, CS.09, CS.14
	Improved governance of green and blue areas (<i>n</i> = 3)	CS.05, CS.06, CS.07
	Knowledge creation and awareness-raising (<i>n</i> = 5)	CS.05, CS.06, CS.07, CS.09, CS.14
	Strategy, planning, policy development (<i>n</i> = 4)	CS.05, CS.06, CS.07, CS.14

Activity: Protection and restoration of natural ecosystems

Across seven case studies (CS.05, CS.06, CS.07, CS.09, CS.10, CS.14, CS.17), initiatives address mainly the protection and restoration of freshwater ecosystems, ranging from large riverine landscapes to small urban wetlands and sustainable management. Notably, CS.05 restored over 1000 ha of wetlands and 1200 ha of improved water dynamics, as well as the reconnection of eight Danube River side arms. Their project Living Rivers spans multiple river basins (Danube, Hron, Ipeľ, Belá), aiming to improve the ecological status of 344 km of watercourses through hydro-morphological interventions, floodplain forest restoration, and the removal of migration barriers for fish. CIs have shown substantial engagement by enhancing water retention and improving biodiversity. CS.06 applies NBSs for climate adaptation through the LIFE WILL project, which promotes water retention and landscape resilience. In Šterusy, pilot measures include small-scale wetland restoration and rainwater retention. CS.09 focuses on wetlands around Dubnica nad Váhom, improving ecological conditions through habitat management, while CS.10 and CS.17 implement community-based revitalisation of water bodies and neglected riverbanks into accessible green–blue public spaces. CS.14 has notably contributed to the long-term protection of the Slatina River, receiving national recognition for its advocacy work.

Activity: Knowledge creation and awareness-raising

Education and knowledge dissemination are integral to civic engagement. CS.05 conducts extensive outreach through field visits, documentary films, and educational programs to communicate the ecological value of floodplain systems (Natura 200). CS.06 creates local knowledge on small-scale water management, while CS.07 integrates environmental

learning into public infrastructure, such as nature trails and observation piers in floodplain forest for blending environmental, cultural, and recreational goals.

CS.09 developed educational trails focused on wetlands, and CS.14 used public walks and local eco-branding (Riekoles) to foster environmental stewardship.

Activity: Strategy, planning, policy development

Strategic planning underpins the long-term success of civic NBS efforts. CS.05 contributes to formal forest management plans at the state level, integrating floodplain restoration into official planning frameworks. CS.06 applies participatory methodologies involving residents in decision-making from analysis to implementation. CS.07 developed detailed architectural and ecological plans for riverbank restoration, securing nearly €1 million in funding. CS.14 actively comments on national environmental legislation and empowers citizen participation in policy processes.

Activity: Monitoring and maintenance of habitats

Long-term sustainability of NBSs requires continuous monitoring and adaptive management. The Danube floodplain habitat restoration initiative CS.05 establishes pilot demonstration sites in the region as living laboratories to assess the effectiveness of nature-based solutions. In collaboration with universities and research institutes, it conducts monitoring and applied research to inform best practices in ecological restoration and green infrastructure planning. CS.09 implemented a restoration management plan for wetland Abrod, once home to valuable *Molinia* meadows, and CS.14 mobilises volunteers to identify biodiversity-supportive interventions in the Slatina River valley. Similarly, CS.09 and CS.14 contribute to biodiversity monitoring by managing neglected wetlands and mapping restoration opportunities along river valleys, respectively.

Activity: Improved governance of green or blue areas

Participatory governance is a core principle in the successful implementation of NBSs. CS.05 leads a multi-stakeholder steering committee under the LIFE RESISTANCE project, facilitating collaboration among farmers, foresters, researchers, and water managers. Within the DANUBEPARKS-connected initiative, bio-corridors have been enhanced through the introduction of floodplain dike grazing and coordinated habitat management, undertaken in partnership with local farmers, volunteers, and municipal stakeholders. This approach represents a governance model that integrates ecological objectives with community-based stewardship, thereby strengthening the resilience and long-term sustainability of riparian and floodplain ecosystems. For CS.06, through collaborative policy recommendations with public authorities, the initiative influences the governance and planning of protected and ecologically valuable areas, actively revitalising degraded green spaces by planting native vegetation and removing invasive species. CS.07 aligns its ecological restoration with municipal strategies, enhancing governance of the Natura 2000 site through co-developed projects.

Activity: Transformation of previously derelict areas

Derelict and abandoned riverine spaces are being transformed into multifunctional blue-green areas. CS.07 exemplifies community-led environmental revitalisation in a rural municipality, successfully removing a riverbank dump in the Natura 2000-protected Little Danube area through land regeneration and environmental stewardship. Its key achievement is an award-winning wooden promenade and lookout tower designed to blend with nature and host cultural events. Additional projects include a footbridge, floating pontoon, floodplain reforestation, and nature trails, integrating ecological, cultural, and recreational goals.

3.2.2. Community, Allotment Gardens, Nature Gardens

Allotment and community gardens have a longstanding tradition in Czech and Slovak society, even rooted in the spatial planning policies of the socialist era, when such spaces

were promoted as essential components of urban and peri-urban life. However, since the early 2000s, many of these gardens have been lost to real estate development and infrastructure expansion [54]. Recently, public interest in urban gardening has resurged, leading to a rise in CIs creating community and nature gardens as multifunctional spaces that blend food production, education, and social engagement. In total, 17% of the analysed NBS activities are dedicated to this category (Table 3).

Table 3. Analysis of studied NBSs—community gardens.

Nature-Based Solutions	Activities	Civic Initiatives
Community gardens, nature gardens (<i>n</i> = 6)	Food production (<i>n</i> = 6)	CS.02, CS.03, CS.08, CS.09, CS.13, CS.15
	Transformation of previously derelict areas (<i>n</i> = 4)	CS.02, CS.03, CS.08, CS.15
	Knowledge creation and awareness-raising (<i>n</i> = 5)	CS.02, CS.03, CS.08, CS.13, CS.15
	Strategy, planning, policy development (<i>n</i> = 4)	CS.02, CS.08, CS.13, CS.15

Activity: Food production

CS.02 operates a mobile network of temporary gardens that activate underutilised urban land. The project, led by architects and planners, fosters community building and civic engagement by creating semi-public spaces equipped for small-scale cultivation, social interaction, and cultural activities. CS.03 transformed a disused children’s playground into a permaculture-based community garden, emphasising ecological principles like composting, green manuring, and pesticide-free food production. The site includes a composting facility and is designed to enhance neighbourhood relations through shared work and intergenerational collaboration. CS.08 developed a certified nature garden used for environmental education. The initiative runs outdoor learning programs and permaculture workshops for schools and the wider public, promoting hands-on sustainability practices. CS.13 revitalised the depopulated village of Brdárka by restoring traditional cherry orchards and establishing a permaculture nature garden. The initiative focuses on ecological farming, biodiversity conservation, and cultural heritage preservation, supported by the influx of new residents committed to rural sustainability. CS.15 successfully prevented the conversion of a derelict urban courtyard into a parking lot by proposing and implementing a community garden instead. Through a participatory design process involving residents and municipal authorities, the initiative created a multifunctional space featuring raised beds, a pergola with a terrace, and a rain garden—demonstrating the potential of grassroots activism to reshape urban planning outcomes.

Activity: Knowledge creation and awareness-raising

Several CIs significantly contribute to public understanding of sustainability, biodiversity, and urban environmental challenges through innovative educational programs, participatory tools, and awareness campaigns. CS.02 raises awareness about the potential reuse of vacant urban land and buildings—often located just meters away from residents’ homes. By highlighting the untapped value of these underutilised spaces, the initiative promotes environmental literacy and introduces sustainability concepts into everyday urban life. Through spatial interventions and public communication, it encourages new perspectives on urban regeneration and civic engagement. CS.08 established an eco-centre that serves as an educational hub offering hands-on environmental learning opportunities, including workshops, exhibitions, and school programs. Its certified nature garden supports outdoor education, showcasing permaculture methods and promoting a harmonious relationship between people and nature. CS.13 fosters permaculture education and community

resilience through workshops in a certified nature garden and the restoration of traditional orchards and architecture. Its educational focus is integrated with cultural programming, traditional craft preservation, and community events that deepen connections between ecological practices and local identity. CS.15 organises planning meetings, workshops, and participatory events involving residents and local authorities. The initiative educates participants about urban ecology, inclusive public space design, and sustainable living. Its community garden includes tactile maps for visually impaired users and informative signage about plant species, supporting environmental accessibility and awareness.

Activity: Transformation of previously derelict areas

Several CIs have targeted the transformation of derelict urban spaces, reactivated neglected land, and redefined its role in the community through NBSs. These interventions serve not only environmental goals but also act as catalysts for social innovation, public dialogue, and spatial justice. CS.02 implemented the project DIERY (“Holes”) to integrate overlooked and underutilised urban plots into Bratislava’s mental and spatial landscape. These fragmented urban voids—relics of disinvestment or stalled development—were temporarily activated through “production fields,” conceptual pop-up spaces that emphasised public value over private speculation. The initiative uses these ephemeral interventions to challenge dominant land-use models, promote public discourse, and test low-cost, scalable models for reclaiming abandoned spaces. CS.08 converted an abandoned agricultural cooperative, including a disused granary, into the E.K.O. Centre, a multifunctional environmental and educational hub. The surrounding two-hectare site was transformed into a certified nature garden that supports biodiversity, hosts educational programs, and serves as a welcoming space for community gatherings and ecotourism. CS.15 successfully prevented the conversion of a derelict urban courtyard into a parking lot by proposing and implementing a community garden instead.

Activity: Strategy, planning, policy development

Some initiatives extend their influence beyond site-based interventions by contributing to policy development and long-term planning frameworks that shape sustainable urban governance. CS.02 plays a pioneering role in rethinking vacant land not as marginal but as sites of urban opportunity. Its strategic concept emphasises tripartism [55], fostering collaboration among non-profits, municipalities, and private actors. Through this model, CS.02 facilitated socially inclusive, economically sustainable reuses of urban voids—mobilising property owners, public authorities, and sponsors to co-create temporary but impactful solutions. Its advocacy efforts helped institutionalise community gardens at the municipal level in Bratislava. As the city took over support for new CGs, the initiative gradually phased out, having successfully fulfilled its mission. CS.15 exemplifies strategic civic participation in governance, with members taking seats in the municipal council to embed their values into local decision-making. The initiative created the CHANGING KOŠICE platform to support bottom-up urban stewardship by offering guidance, resources, and inspiration for residents interested in transforming their neighbourhoods. It fosters the replication of successful interventions and helps integrate community-driven planning into formal urban policy [56].

3.2.3. Green Areas for Stormwater Management

Green infrastructure for stormwater management accounts for approximately 23.5% of NBSs identified across the studied CIs (Table 4). These interventions aim to reduce surface runoff, enhance local water retention, and mitigate urban heat island effects while improving ecological quality and liveability in built-up areas.

Table 4. Analysis of studied NBSs—green areas for stormwater management.

Nature-Based Solutions	Activities	Civic Initiatives
Green areas for stormwater management (<i>n</i> = 4)	Creation of new green areas (<i>n</i> = 4)	CS.05, CS.08, CS.14, CS.15

A notable example is CS.05, which implemented rainwater management systems in partnership with municipal authorities in the Bratislava city district of Karlova Ves. Measures include the collection of rainwater from school and kindergarten buildings in both aboveground and underground retention tanks, used for flushing toilets and irrigating adjacent green spaces. In the kindergarten’s inner courtyard, vegetated climate ponds help to cool the space. A model rainwater-harvesting and reuse solution was introduced in a nearby residential courtyard, which also includes two rain gardens to facilitate infiltration and biodiversity enhancement. The nature garden of CS.08 incorporates a rainwater retention system via an irrigation pond and constructed wetland, supporting educational and ecological functions. Similarly, CS.15 applies rain garden infiltration methods and harvests stormwater for use in its community garden.

CS.14 participated in the Green Lungs of the City—Revitalisation of ÚSPECH Park project in Trenčín, where ecological principles—particularly sustainable stormwater management—were integrated into urban planning to increase the city’s climate adaptability.

3.2.4. Grey Infrastructure Integrating Green

CS.10 and CS.12 represent 11.7% of the studied cases that integrate green elements directly into grey infrastructure (Table 5). This relatively low occurrence may be attributed to the higher technical and design demands associated with such interventions, as well as the need for strong cooperation with municipalities and urban planners. CS.12 developed and implemented a planting plan for a residential car parking area, incorporating trees, hedges, and perennial beds. Additionally, the initiative planted an alley of trees along an adjacent road, aiming to mitigate the urban heat island effect and enhance the aesthetic and ecological quality of transport infrastructure. Similarly, CS.10 participated in the planning and execution of tree planting and perennial bed installations along streets in Galanta, working in close partnership with the municipal government to humanise and green mobility corridors.

Table 5. Analysis of studied NBSs—grey infrastructure integrating green.

Nature-Based Solutions	Activities	Civic Initiatives
Grey infrastructure integrating green (<i>n</i> = 2)	Creation of new green areas (<i>n</i> = 2)	CS.10, CS.12

3.2.5. Parks and Other Green Spaces

Green infrastructure represents 70% of all identified NBSs, making it the most common area of intervention by CIs (Table 6). Activities range from the protection and restoration of existing green spaces to the creation of new parks and the transformation of derelict or underutilised sites. These efforts contribute significantly to urban and rural climate resilience, biodiversity enhancement, and community well-being.

Table 6. Analysis of studied NBSs—parks and other green spaces.

Nature-Based Solutions	Activities	Civic Initiatives
Parks and other green spaces (<i>n</i> = 12)	Creation of new green areas (<i>n</i> = 9)	CS.05, CS.06, CS.07, CS.10, CS.11, CS.12, CS.14, CS.16, CS.17
	Maintenance and management of green spaces (<i>n</i> = 10)	CS.01, CS.04, CS.05, CS.07, CS.10, CS.11, CS.12, CS.14, CS.15, CS.17
	Protection and restoration of natural ecosystems (<i>n</i> = 8)	CS.05, CS.06, CS.07, CS.09, CS.10, CS.13, CS.14, CS.17
	Transformation of previously derelict areas (<i>n</i> = 8)	CS.01, CS.02, CS.03, CS.04, CS.07, CS.08, CS.15, CS.16
	Knowledge creation and awareness-raising (<i>n</i> = 12)	CS.01, CS.04, CS.05, CS.06, CS.07, CS.10, CS.11, CS.12, CS.14, CS.15, CS.16, CS.17
	Strategy, planning, policy development (<i>n</i> = 12)	CS.01, CS.04, CS.05, CS.06, CS.07, CS.10, CS.11, CS.12, CS.14, CS.15, CS.16, CS.17
	Improved governance of green and blue areas (<i>n</i> = 12)	CS.01, CS.04, CS.05, CS.06, CS.07, CS.10, CS.11, CS.12, CS.14, CS.15, CS.16, CS.17
	Monitoring and maintenance of habitats (<i>n</i> = 6)	CS.01, CS.05, CS.06, CS.07, CS.09, CS.14

Activity: Creation of new green areas

Several initiatives are involved in creating new green spaces in both urban and rural settings. CS.07, CS.10, CS.11, and CS.12 emphasise community involvement in greening activities, such as tree planting, creating perennial beds, and building small-scale infrastructure. CS.05 collaborates with the Bratislava city district of Karlova Ves on the *Life DELIVER* project, planting 100 trees, 400 shrubs, and establishing meadows to enhance urban climate resilience.

In Šterusy, CS.06 pilots innovative land and water management strategies that combine rainwater retention and landscape restoration. CS.07 implemented fruit tree planting along the planned bicycle trail and planting native trees in riparian forests. CS.10 develops nature-based urban interventions, such as establishing meadows (653 m²), extensive perennial beds (443 m²), and small infrastructure elements (benches, fences) to enrich public green areas. CS.11, operating in the rural village of Tvrdšovce, created a community park within a kindergarten, with plans to expand to other public spaces. CS.12 and CS.16 emphasise participatory design, engaging residents directly in planning and implementing green spaces through workshops and collaborative planning.

Activity: Maintenance and management of green spaces

Most initiatives have a significant impact on the management and maintenance of green spaces in settlements. CS.01 focuses on the maintenance of greenery in historic parks and gardens through volunteer brigades. In rescuing and restoring parks, it helps administrators find long-term solutions with volunteers, as well as educating them on appropriate maintenance practices for managing green spaces. CS.04 initiates and helps to rescue the Mičurin botanical site in Bratislava city. CS.05 collaborates with municipal governments to enhance sustainable management practices within urban environments; for example, the regulation of lawn mowing intensity. CS.07, CS.10, CS.11, and CS.12 are actively involved in maintaining green spaces. This includes activities such as watering, pruning, and trimming trees. They also influence the frequency and intensity of lawn mowing to promote biodiversity. CS.14 organises clean-up brigades along the natural sites in Lanice Park, Zvolen. CS.17 is involved in the management and development of the green

area around the local stream, which in a short time has become a place of recreation and relaxation for residents.

Activity: Protection and restoration of natural ecosystems and built-up green spaces

Several initiatives actively protect existing green infrastructure and prevent its degradation. CS.01 focuses on conserving Slovakia's cultural and natural heritage, with particular emphasis on the long-term care of historical parks and gardens. CS.04, CS.10, and CS.12 are engaged in safeguarding urban green spaces from unsustainable development, including tree protection and replanting efforts. CS.05, CS.06, and CS.14 are dedicated to the ecological restoration of habitats, such as meadows, forests, and urban green areas. These initiatives promote biodiversity and provide accessible spaces for recreation and health, often in partnership with municipal administrations.

Activity: Transformation of previously derelict areas

CIs are transforming formerly neglected or underused spaces into vibrant green infrastructure while creating public cultural, environmental, and social hubs (CS.07, CS.08). CS.04 is restoring the derelict site of the Mičurín National Cultural Monument in Bratislava into a space for public environmental education, echoing its historical function during the socialist era. CS.15 successfully prevented the conversion of a derelict urban courtyard into a parking lot by proposing and implementing a community garden instead. CS.16 has led a comprehensive urban revitalisation project in Košice, converting neglected residential areas into inclusive, climate-resilient public spaces. The project space (P'ac) functions as a community garden and social gathering space. The initiative also engaged residents in envisioning future uses for a former military barracks in Nitra, promoting participatory and sustainable reuse strategies.

Activity: Knowledge creation and awareness-raising

Environmental education and civic engagement are central to many initiatives to share responsibility for the condition and quality of green spaces. These efforts include the establishment of environmental centres (CS.05, CS.06, CS.07, CS.08). CS.01 promotes the protection of historical and aesthetic values of green spaces through public involvement in conservation. CS.04 advances citizen participation in green space management and climate policy. CS.05 and the Karlova Ves municipality created the CoCliBEC community centre to raise awareness about climate resilience and biodiversity in residential areas. CS.06 leads public campaigns (Meadows for People, Wetlands for Life) and a citizen science initiative (LiveAbleBratislava), encouraging residents to explore and monitor urban nature. CS.10, CS.11, and CS.12 include the public in the co-creation and maintenance of green spaces, such as the correct agro-technical timing for planting and the maintenance of trees, perennial beds, and lawns. This includes mulching techniques for both flower beds and trees to reduce maintenance intensity. CS.14 focuses on informal education, like engaging children and youth through school-based ecological programming and hands-on trail maintenance. An activity called ECO COUNSELING "GREEN POINT" provides support for active people who want to protect the environment and participate in decision-making on projects and documents with an impact on their environment (including discussions, educational activities for citizens). CS.16 actively involves citizens and stakeholders in planning and design processes, aiming to increase public awareness of land-use planning and support citizen participation in the city's new master plan. The "Never Never School and Citylove" lecture series promotes deeper reflection on urban planning, care, and local identity. CS.17 promotes locals with hands-on experience in the transformation of riverbanks into usable and attractive public spaces. An often-used technique is the organisation of citizen science programmes (CS.05, CS.06), public lectures, and the creation of informal learning platforms (CS.01, CS.04, CS.15).

Activity: Improved governance of green areas

Governance models vary across initiatives, from informal stewardship to structured collaboration with municipalities. CS.01 collaborates on the restoration of neglected parks through co-planning with local governments. CS.04 systematically monitors urban greenery, participates in public consultations, and comments on strategic planning documents. CS.05 co-implements Life DELIVER with Karlova Ves, planting 100 trees, 400 shrubs, and establishing meadows to increase urban resilience. CS.06 engages in policy development and habitat restoration, aligning with municipal planning objectives. Due to low volunteer engagement, CS.10 depends on the city of Galanta (technical services) for maintenance but retains decision-making authority over management methods and intensity. CS.11, CS.12, and CS.14 engage volunteers in maintaining and enhancing planted areas and nature trails, often negotiating adaptive mowing regimes to support biodiversity.

Activity: Monitoring and maintenance of habitats

Ongoing care and monitoring are vital for sustaining green infrastructure. Some associations, CS.05, CS.06, CS.09, CS.14, are involved in the ecological monitoring of protected habitats, often as part of cross-border or EU-funded projects. They focus on data collection, policy development, and community-based habitat stewardship in both urban and rural settings. Monitoring and maintenance of habitats are pivotal for long-term ecological outcomes. CS.05 participates in the Resilient Trees project to protect veteran trees and promote old-growth forest policies. The same CS developed a model for “close-to-nature” forest and wetland management, including inventorying native genetic resources, applying site-specific practices, and establishing living labs for adaptive restoration. Collaborative research with universities strengthens evidence-based NBS implementation. CS.06 contributes to the EU Habitats Directive by developing standardised habitat monitoring guidelines. CS.10 presents a model of shared maintenance responsibilities with the Galanta municipality. This division of roles ensures continuity of ecological intent while leveraging municipal resources.

Several initiatives, CS.04, CS.10, CS.12, address the problem of land-use pressure by participation in tree-felling procedures, monitoring, and commenting on the compliance of proposed developments within spatial planning documentation. CS.14 maintains green areas in both rural and urban contexts, including Lanice Park in Zvolen, balancing ecological integrity with community access.

Activity: Strategy, planning, policy development

Strategic planning and policy development form a crucial component of civic-led NBSs, enabling systemic change that extends beyond individual projects. Across multiple case studies, CIs in Slovakia have demonstrated a growing capacity to co-develop, influence, and implement long-term planning frameworks, climate adaptation strategies, and participatory policy processes that integrate environmental, social, and urban development objectives. CS.04 developed an innovative online platform “Green to Green” (Zelená zeleni) focused on public policies for green space management in built-up areas. The initiative organised four national conferences on the role of green spaces in climate change adaptation, alongside eight regional seminars for citizens and eight regional training sessions for public administration staff. These capacity-building efforts aimed to foster civic engagement and improve the competence of local governments in green infrastructure policy, with an emphasis on public participation and ecological resilience. CS.05, in partnership with the Bratislava city district of Karlova Ves, co-developed the Life DELIVER project aimed at enhancing the climate resilience of residential areas. One of the key outcomes was the “Climate Action Plan for Bratislava-Karlova Ves 2020–2030”, which outlines a strategic vision for climate adaptation and mitigation at the district level. This includes specific goals for sustainable energy use, CO₂ emissions reduction, and the integration of green infras-

structure. The strategy is supported by a Catalogue of Adaptation and Mitigation Measures and a diagnostic tool—Klimasken, designed to assess climate resilience at multiple spatial scales (urban district, building, household, <https://www.klimasken.sk/en/>, accessed on 30 August 2025). In addition, the establishment of the Community Climate and Biodiversity Educational Centre (CoCliBEC) helped institutionalise long-term climate education and engagement. CS.06 has contributed to several cross-border and thematic strategies. Through the Interreg cooperation program, the initiative is developing a strategy for invasive species management. This includes mapping invasive species and implementing eradication measures, particularly in protected areas, with active community participation. The organisation is also involved in the REACH Project (Research-based Education for Advancing Children in Hardship), which supports inclusive, inquiry-based learning methods for marginalised groups, thereby addressing social equity as part of broader environmental literacy and resilience-building efforts. Through projects like CITY NATURE, in collaboration with Bratislava City Forests and Austrian partners, CS.06 provides management guidelines for biodiverse urban meadows. These methods include mowing regimes and maintenance strategies to foster species-rich grasslands in cities.

CS.10 initiated its activities by drafting a strategic concept document outlining ten proposals for enhancing public and green spaces in the town of Galanta. The concept incorporates sustainable stormwater management and ecological design principles. Alongside CS.11 and CS.12, the association also prepares expert plans and funding applications to help municipalities secure external resources for project implementation. These initiatives combine technical expertise with community-based action, involving residents in planting and maintenance activities and educating both public officials and citizens on sustainable urban greening practices. CS.15 contributes to institutional change by offering a replicable model (e.g., CHANGING KOŠICE informative platform) of transferable strategies for civic empowerment and nature-based urban transformation. CS.16 positions itself as a thought leader in participatory architecture and sustainable urbanism, promoting inclusive, climate-resilient planning in Košice and beyond. The initiative contributed to the “Plan for Košice City”, advocating for transparent land-use planning and broader civic engagement in the city’s master planning process. In Veľký Šariš, the organisation facilitated the development of Slovakia’s first participatory Local Territorial System of Ecological Stability (MÚSES, 2022). This strategic document integrates ecological protection, spatial development, tourism, and cultural heritage into a cohesive planning framework that reflects the lived experiences and aspirations of residents. The participatory and cross-disciplinary approach exemplifies contemporary trends in landscape governance, emphasising multi-functionality, inclusiveness, and socio-ecological resilience.

3.2.6. Intentionally Unmanaged Areas

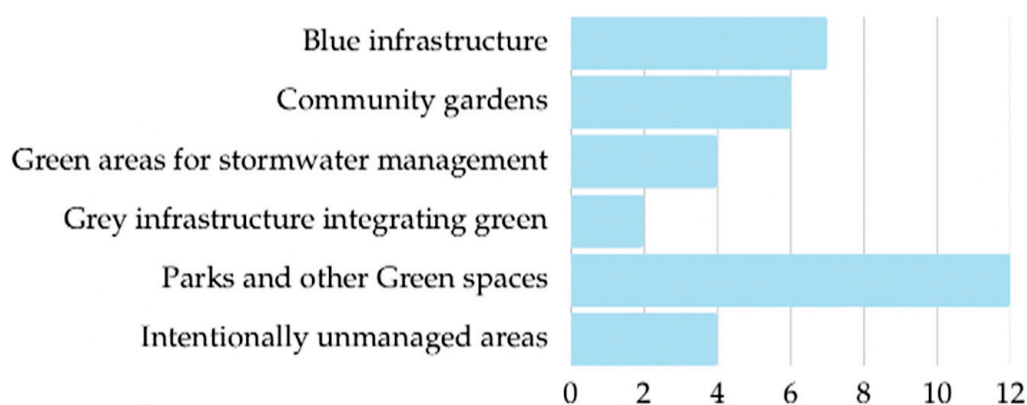
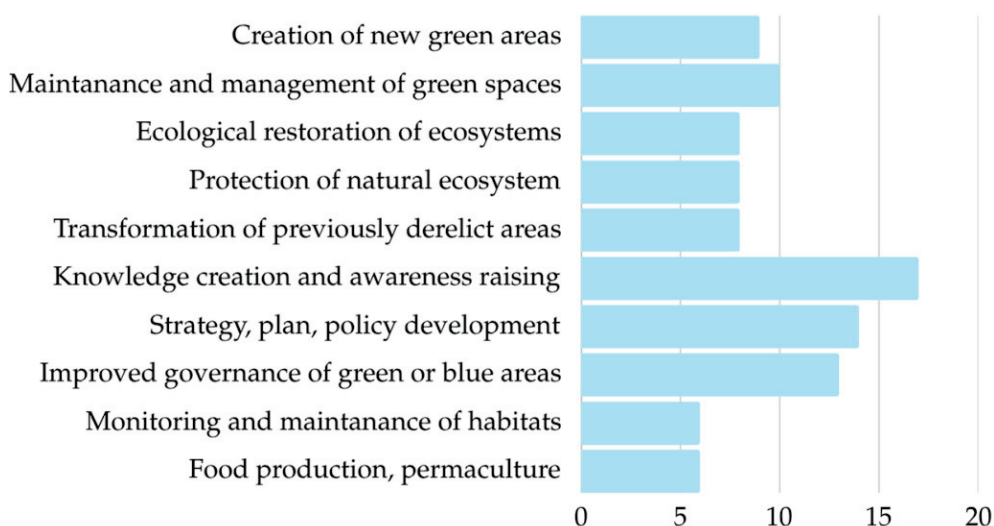
Intentionally unmanaged areas account for 23.5% of the NBSs implemented by CIs, notably by CS.05, CS.06, CS.09, and CS.14 (Table 7). These organisations promote the conservation of natural habitats by allowing certain green areas—often within urban or peri-urban settings—to develop without intensive maintenance. This approach is supported by policy advocacy and cooperation with public authorities. It includes the removal of invasive species, the revitalisation of degraded spaces using native vegetation, and the designation of specific zones to remain unmanaged. By minimising human intervention, these areas maintain ecological processes, support habitat heterogeneity, and enhance conditions for native flora and fauna.

Table 7. Analysis of studied NBSs—intentionally unmanaged areas.

Nature-Based Solutions	Activities	Civic Initiatives
Intentionally unmanaged areas (<i>n</i> = 4)	Monitoring and maintenance of habitats (<i>n</i> = 4)	CS.05, CS.06, CS.09, CS.14

3.3. Summary of Civic Initiatives' Engagement in Nature-Based Solutions

The analysed Slovak case studies (CS.01–CS.17) provided evidence of active CI implementation of NBSs (Figure 2) within their activities (Figure 3). The results of the analysis indicate that the most frequently implemented NBSs are related to activities within green (*n* = 12, 70%) and blue (*n* = 7, 41%) infrastructure. Community gardens represent *n* = 6, 35%; green areas for stormwater management amount to *n* = 4, 23.5%; and intentionally unmanaged areas belong to *n* = 4, 23.5% of solutions. The grey infrastructure integrating green represents *n* = 2, 11.7%, and is the least common CI solution implemented.

**Figure 2.** Results of the implemented nature-based solutions by civic initiatives.**Figure 3.** Results of the implemented activities of NBSs by civic initiatives.

The comparison of NBSs and associated activities across CSs reveals significant variation in scope and focus. CS.07 emerges as the most diversified initiative, engaging in almost all activity categories except food production within community gardens. Other initiatives, such as CS.09 and CS.14, stand out for implementing four distinct NBS types, demonstrating a balance between ecological and social functions.

NBSs are applied in a wide spectrum of contexts. In built-up environments, interventions include school grounds: $n = 5$, 29% (CS.02, CS.05, CS.11, CS.12, CS.16); residential areas: $n = 9$, 53% (CS.02, CS.03, CS.04, CS.05, CS.09, CS.10, CS.14, CS.15, CS.16); parks: $n = 5$, 29% (CS.06, CS.10, CS.12, CS.14, CS.17); streetscapes: $n = 2$, 12% (CS.10, CS.12); riverbanks: $n = 7$, 41% (CS.05, CS.06, CS.07, CS.10, CS.11, CS.14, CS.17); and historic parks: $n = 1$, 6% (CS.01). Adaptive reuse of derelict spaces includes former agricultural cooperatives: $n = 1$, 6% (CS.08); and vacant lots: $n = 5$, 29% (CS.02, CS.03, CS.04, CS.07, CS.15). At the other end of the spectrum, a significant number of CIs focus on ecologically valuable sites—including meadows, wetlands, and riparian and urban forests: $n = 5$, 29% (CS.05, CS.06, CS.07, CS.09, CS.14)—where biodiversity restoration and habitat protection dominate the activity portfolio.

The human resource base is a key determinant of NBS implementation quality. A majority of initiatives benefit from in-house professional expertise in natural sciences: $n = 7$, 41% (CS.01, CS.04, CS.05, CS.06, CS.09, CS.13, CS.14); urban planning and architecture: $n = 4$, 24% (CS.02, CS.07, CS.15, CS.16); or green space design and management: $n = 4$, 24% (CS.08, CS.10, CS.11, CS.12). Where internal capacity is lacking— $n = 2$, 12% (CS.03, CS.17)—CIs compensate by engaging external professionals to provide specialist input. This reliance on professional knowledge—whether internal or external—appears to be a critical success factor in ensuring that solutions are well-adapted, technically sound, and maintainable over time.

From the activity perspective, knowledge creation and awareness-raising are universal (17/17 CS), highlighting the strong social dimension of NBS work. A notable aspect of these initiatives is their contribution to planning and policy frameworks (14/17 CS, 82%). They act as knowledge brokers, offering expertise to municipalities and enhancing participatory governance and delivering landscape and climate action plans, local adaptation strategies, territorial plans of ecological stability, or participatory urban spatial plans. Transformation of previously derelict areas (8/17CS, 47%) and creation of new green areas (9/17 CS, 53%) emerge as key strategies for linking ecological benefits with community revitalisation. More specialised actions, such as monitoring and habitat maintenance (6/17CS, 35%), tend to be concentrated among initiatives with higher environmental expertise. Food production/permaculture (6/17CS, 35%) reveal the enduring cultural legacy of allotment gardening in the post-socialist context, while simultaneously reflecting new paradigms of multifunctional public space that combine food production, education, and social innovation.

4. Discussion

Overall, the Slovak cases demonstrate that civic initiatives serve as critical agents in bridging ecological restoration, community participation, and governance innovation. Across these domains, they co-design new green areas, steward maintenance through volunteer brigades and adaptive regimes, convert derelict land into multifunctional hubs, institutionalise governance via partnerships with municipalities, and mainstream monitoring through living labs and citizen science. This repertoire not only aligns with but also extends contemporary European knowledge by demonstrating how Slovak civic actors can translate NBS principles into site-specific, durable arrangements that might have added value to planning, maintenance, governance, and monitoring of green and blue spaces, Figure 4.

In this way, our research complements other [1,47,57] studies by showing how civic actors in transitional governance systems simultaneously address ecological, social, and institutional deficits, thereby advancing sustainability transitions under conditions of weak state capacity and fragmented planning systems.

All 17 initiatives operate primarily within their respective municipalities or regions, engaging directly with residents, local authorities, and place-specific environmental challenges. This strong local anchoring enables interventions to be tailored to distinct socio-ecological contexts while fostering trust-based relationships with stakeholders.

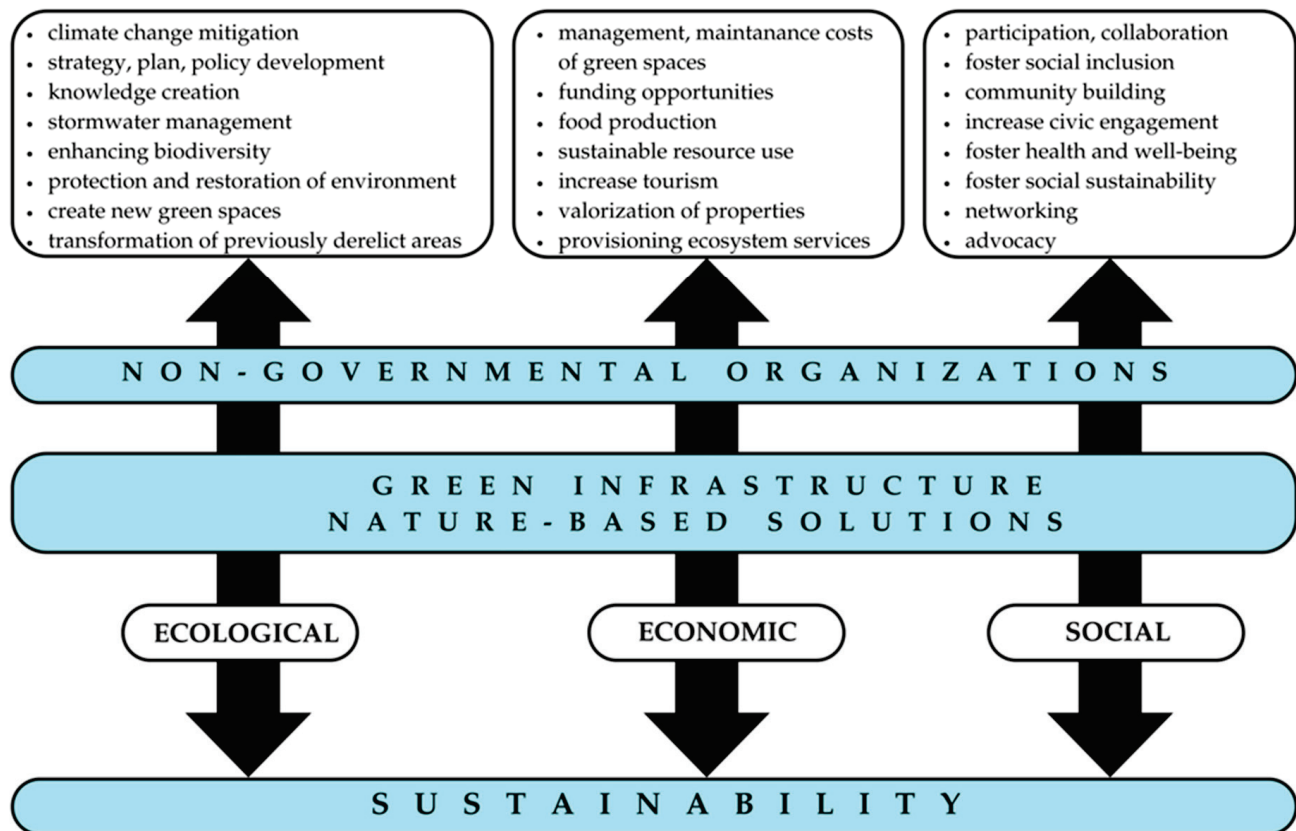


Figure 4. Conceptual understanding of civic initiatives contributing to the 3 pillars of sustainable green and blue space development.

The observed reliance on professional expertise—either internal or contracted—underscores the technical competence underpinning successful implementation, aligning with Galan et al. [58], who emphasise that adaptive planning depends on local networks and the co-creation processes enriched by specialised knowledge. For example, CS.07 initiated the revitalisation of the Little Danube riverbank in the village. Due to the architectural expertise of the initiative’s leader, the group was able to plan, apply for, and obtain external funding to implement the wooden promenade project. In line with Kabisch et al. [59], our findings suggest that the infusion of professional knowledge into civic-led initiatives not only improves technical outcomes but also institutionalises participatory governance, strengthens local decision-making capacity, and fosters long-term stewardship of green and blue infrastructures.

4.1. Comparative Perspective with Mosaic Governance

Furthermore, the observed multi-level engagement of some initiatives—combining local action with contributions to regional, national, and even international projects—echoes the “mosaic governance” model described by Buijs et al. [23,42], in which diverse governance actors operate at different scales, creating complementary capacities and adaptive governance networks that enhance the resilience of urban and rural landscapes. However, in contrast to the mosaic governance perspective, where municipalities often act as key partners in scaling and sustaining such initiatives, the Slovak cases demonstrate

a more uneven institutional landscape. Civic initiatives here often shoulder a heavier share of initiation and maintenance responsibilities (CS.11, CS.12, CS.17), compensating for institutional gaps while also experimenting with innovative governance practices. This reflects a post-socialist planning legacy marked by weaker formal integration of civic actors into spatial decision-making, necessitating more grassroots-driven mobilisation to reclaim and repurpose land. Another divergence concerns scaling pathways. In Buijs et al.'s mosaic governance model, upscaling is often achieved through formal institutionalisation of grassroots practices—local governments adopting, funding, or replicating community-led interventions. In the Slovak context, while there are examples of this (e.g., CS.02 influencing Bratislava's municipal policy on community gardens, or CS.16 facilitating the development of Slovakia's first participatory Local Territorial System of Ecological Stability (MÚSES, 2022)), upscaling more often occurs through horizontal diffusion between civic networks rather than vertical incorporation into municipal programs. This suggests that in contexts with limited policy continuity or resource allocation for NBSs, peer-to-peer exchange and replication may be a more viable scaling mechanism.

The study identified several cases that could be “scaled-out” (the horizontal diffusion) to other communities, like repurposing of derelict sites into eco- and socio-cultural hubs (CS. 07, CS.08, CS.13) or community gardens (CS.02, CS.03, CS.15). Furthermore, keeping intentionally unmanaged areas (CS.05, CS.06, CS.09, CS.14) in urban environments is essential for enhancing the biodiversity and resilience of built-up environments. For upscaling to be sustainable, supportive policy frameworks and long-term municipal partnerships, as advocated by Buijs et al., would be essential. Yet, the Slovak cases also illustrate that in less enabling environments, civic-led adaptive networks can still drive significant ecological and social transformation, albeit through more decentralised and grassroots-centric pathways.

These governance frictions underscore the need for conflict-resolution mechanisms that bring together governmental, civic, and business actors—reflecting the collective problem-solving ethos outlined by Galan et al. [58], where adaptive planning depends on multiple civic capacities recognising and addressing shared challenges. In line with Kabisch et al. [59], our findings suggest that for NBSs to function as proactive investments, they must be embedded in sustained policy–society–science dialogues, ensuring that bottom-up innovations are not only piloted but institutionalised.

4.2. Alignment with Participatory Integrated Processes

While van der Jagt et al. [4] emphasise participatory assessment frameworks, the Slovak cases illustrate that participation extends beyond evaluation into long-term stewardship—such as biodiversity monitoring (CS.05, CS.09) and adaptive wetland management (CS.14). Similarly, although EU-funded projects often highlight multifunctionality [48], Slovak initiatives stand out for their bottom-up approach, filling governance and resource gaps through community mobilisation and activism, particularly in post-socialist settings where municipal capacities remain limited.

Compared with Ferreira et al. [42], who find stakeholder engagement often limited to consultation, our cases demonstrate structurally embedded co-governance: community gardens institutionalised in urban planning (CS.02, CS.15) and civic actors acting as knowledge brokers in policy-making (CS.05, CS.06, CS.14, CS.16). Moreover, while Mahmoud et al. [60] stress the interplay between governance and participation, Slovak initiatives highlight an integrated model where governance innovation and ecological restoration advance simultaneously.

While the national-level study of Vaňo et al. [40] documented structured, municipality-led co-planning processes, our findings reveal more bottom-up mobilisation, with CIs frequently initiating projects in the absence of formal planning frameworks. This shift from formal integration to grassroots leadership highlights the adaptability of participatory principles in less institutionally supportive settings, demonstrating that civic actors can still deliver coherent, place-sensitive UGI despite limited municipal coordination. Framed through Watson et al. [61]’s distinction between collaboration and co-production, several initiatives (e.g., CS.10, CS.15) illustrate co-production, where authority and responsibility are redistributed between civic and municipal actors. This suggests that Slovak CIs not only complement institutional planning but actively reshape governance systems and ecological practices, offering transferable models for NBS implementation in both post-socialist and broader European contexts.

4.3. Challenges and Future Developments

In the current climate of Slovak institutional distrust and regional development stagnation, there is a pressing need to transition from hierarchical governance to inclusive, multi-actor models. Such approaches require cooperation among citizens, NGOs, municipalities, businesses, and local communities—acknowledging their mutual interdependence and pooling resources to co-develop innovative responses to complex policy challenges [62].

However, the uneven cooperation with municipalities echoes earlier observations of tension between civic innovation and formal governance structures, suggesting that transformation requires not only local capacity but also institutional receptivity. Addressing these tensions requires recognising that complex community problems demand not only governmental engagement but also multiple civic capacities capable of identifying shared challenges and fostering collective solutions [63]. Building stronger links between local government and grassroots initiatives is essential to achieve synergies and lasting outcomes. The study thus underscores that scaling NBS through civic action depends on enabling frameworks that value citizen expertise, secure long-term stewardship arrangements, and reconcile the flexibility of bottom-up action with the stability of public administration.

Such collaboration ensures that activities are informed by domain-specific expertise, thereby enhancing the effectiveness, scalability, and credibility of nature-based solutions. This finding aligns with previous research [59,64] highlighting that the integration of professional expertise in civic-led environmental projects not only improves technical outcomes but also strengthens participatory governance and long-term stewardship [65,66].

Future research could examine the long-term ecological, social, and governance performance of civic-led NBSs. Identify effective capacity-building pathways for initiatives lacking in-house expertise or assess the role of policy frameworks and municipal cooperation in enabling or constraining particular NBS types and undertake comparative analyses with other post-socialist urban contexts to test the transferability of observed patterns.

5. Conclusions

This study demonstrates that civic initiatives in Slovakia function as hybrid governance actors, simultaneously filling service gaps, experimenting with ecological practices, and bringing innovation in policy-relevant domains. Their activities span multiple scales—from neighbourhood-level interventions and the adaptive reuse of derelict land to contributions in national policy and international knowledge exchange—showcasing their versatility and multi-dimensional value in advancing NBSs. By moving beyond consultation towards co-production, co-management, and even co-governance, these initiatives embed ecological, social, cultural, and political benefits into both urban and rural landscapes. The Slovak experience also illustrates the distinctive role of civic actors in

post-socialist contexts, where isolated institutions and ownership changes have generated a niche for grassroots innovation, experimental governance, and the reclamation of abandoned land. Importantly, these initiatives reveal how bottom-up actors can drive sustainability transitions, not only by delivering tangible environmental improvements but also by co-developing monitoring frameworks, policy tools, and participatory planning processes. Yet, their long-term transformative potential depends on supportive policy frameworks, stable funding, and institutionalised partnerships that enable them to complement rather than compensate for municipal capacities. Future research should therefore explore pathways for scaling up these grassroots practices, examine their potential integration into formal governance architectures, and assess their transferability to other post-socialist and resource-constrained settings. Overall, Slovak civic initiatives provide vital lessons on how civil society can act as a catalyst for an inclusive, adaptive, and resilient green–blue infrastructure governance.

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Abbreviations

The following abbreviations are used in this manuscript:

CA	Civic association
CI	Civic initiative
CS	Case study/studies
ES	Ecosystem services
GI	Green infrastructure
KCAR	Knowledge creation and awareness-raising
NBS	Nature-based solutions
NGO	Non-governmental organisation
NPO	Non-profit organisation
SGRs	Self-governing regions
UNA	Urban nature atlas
UN SDGs	United Nations Sustainable Development Goals

Appendix A

Table A1. Legal forms of non-governmental organisations in Slovakia.

Name of the NGO	Dated from	Location Within Slovakia	Legal Form	Objective of the Civic Initiative	Contact, Accessed on 30 August 2025
01. Národný trust—The National Trust of Slovakia	2006	Bratislava	NPO	Creation, development, protection, restoration and presentation of spiritual and cultural values of Slovakia	www.nt.sk/en www.facebook.com/NarodnyTrust
02. Vnútroblok	2012	Bratislava	CA	Public spaces, public engagement and consultations, Social and Spatial mapping	www.facebook_MobilneZahrady
03. KoZa v Háji	2018	Bratislava	CA	Environmental and community engagement, environmental education, public greenery protection	www.kozavhaji.eu www.facebook.com/kozavhaji
04. Hrad—Slavín	2006	Bratislava	CA	Environmental protection and education, spatial and cultural conservation of the old town Bratislava, spatial plan consultations	Občianske Združenie Hrad-Slavín— www.ozhradslavin.sk Facebook_hradslavin
05. BROZ—Regional Association for Nature Conservation and Sustainable Development	1997	Bratislava	CA	Environmental protection and education, environmental strategies and planning	BROZ—ochranárske združenie—BROZ www.facebook.com/broz.ba
06. DAPHNE—Institute of Applied Ecology	1997	Bratislava	CA	Environmental protection and education, environmental strategies and planning	www.daphne.sk www.facebook.com/daphne.institut
07. Naše Zálesiečko	2013	Zálesie	CA	Environmental protection and education, community engagement, cultural activities and events, public space	www.facebook.com/nasezalesicko www.nasezalesicko.sk
08. ŽiTo v SÝPKE	2018	Moravské Lieskové	CA	Environmental protection and education, community engagement, cultural activities and events	www.facebook.com/ZITOVSYPKKE www.zitovsypke.sk
09. eDeN v meste	2022	Nová Dubnica	CA	Environment	www.facebook.com/edenvmeste
10. Zelený plán	2018	Galanta	CA	Protection and restoration of environment, maintenance of green spaces, community engagement, green space planning	Zelenyplan.sk www.facebook.com/zelenyplan
11. ViZia—Rural Green Infrastructure	2020	Tvrdošovce	CA	Protection and restoration of environment, maintenance of green spaces, community engagement	www.facebook_ViZia
12. Strom darom	2017	Nové Zámky	Informal CI /Project	Protection of green public spaces, maintenance of green spaces, community engagement	www.facebook.com/stromdarom
13. Alter Nativa	2002	Brdárka	CA	Environment, biodiversity protection and creation, permaculture, protection of cultural heritage	www.alter-nativa.sk www.facebook.com/Alter.Nativa.Brdarka
14. Pod' na dvor	2020	Košice	CA	Environment, public space, civic engagement, culture community development	www.podnadvor.sk www.facebook.com/podnadvor
15. Spolka	2016	Košice	CA	Urban planning, strategies, consultations, public engagement, culture	www.spolka.cc
16. Združenie Slatinka	1993	Zvolen	CA	Environmental protection, ecological restoration, and public engagement in environmental decision-making	www.slatinka.sk
17. Živý priestor	2022	Námestovo	CA	Environment	Facebook_zivypriestor

Appendix B

Table A2. Legal form of civic initiatives in Slovakia.

Type of Organisation	Civic Association	Non-Profit Organisation	Foundation
Legal basis	Act No. 83/1990	Act No. 213/1997	Act No. 34/2002
Purpose	Common interests, Activities can include public-benefit services or business activities related to their goals	Public-benefit services: like healthcare, education, social assistance, and environmental protection	Grant-making and public-benefit purposes for environmental protection
Membership	Requires at least three founders; has members	Does not have members. Operates through mandatory governing bodies such as an executive board, director, and auditor. At least five individuals are required to establish these bodies	No members; they are established through a founding deed signed by one or more founders
Structure	Flexible, the structure is defined by the association’s statutes	Mandatory governing bodies	Defined in founding charter
Funding Administration	It can be financed through membership fees, donations, grants, or business activities. Profits can be reinvested into the association’s activities	Profits cannot be distributed among founders or employees; they must be used exclusively for public-benefit purposes. Sources include grants, subsidies, donations, and sponsorships	Relies on endowments or property contributions from founders. Assets are used to support charitable projects or causes outlined in the founding charter
Administration	Less administratively demanding compared to other non-profit entities.	Higher administrative requirements and annual reports are required.	Stricter guidelines

Appendix C

Table A3. Civic initiatives spatial and impact delimitations.

Spatial Delimitation, Impact	Characteristics
Local	Activities of NGO that are place-based interventions, localised within towns, districts, community projects.
National	Activities with influence across a whole country, including collaboration with governmental bodies or national networks.
International	Activities that cross borders, engage with international networks, or influence global discussions. Addressing transboundary environmental issues.

Appendix D

Table A4. Civic initiatives and nature-based solutions.

Nature-Based Solution (NBS)	Type of NBS
blue infrastructure	lakes, ponds, rivers, streams, wetlands, peatlands, swamps, moors, riverbank, lakeside greenery
food production	nature gardens, allotments, community garden
green areas for stormwater management	rain gardens, swales, retention areas
grey infrastructure integrating green	alley or street trees, street vegetation, green parking lots
parks and other green spaces	urban parks, forests, pocket parks, neighbourhood green space, institutional green, school grounds, playgrounds
intentionally unmanaged areas	spaces that are deliberately left to natural succession and ecological processes without active maintenance or design interventions; abandoned spaces with growth of wilderness through a low-input, nature-led approach

Appendix E

Table A5. Civic initiative focus.

Focus	Description of Main Activities
Creation of new green areas	Establishment of new vegetated spaces such as parks, green corridors, gardens, or forests in urban or peri-urban environments. This can include both small-scale (e.g., pocket parks) and large-scale (e.g., urban forests) interventions that increase green cover.
Maintenance and management of green spaces	Activities focused on the management of green spaces. This includes watering, pruning, planting.
Ecological restoration of ecosystems	Focuses on returning degraded or damaged ecosystems to a more natural, biodiverse, and resilient state. Restoration may involve soil improvement, reforestation, removal of invasive species, or reintroduction of native flora and fauna (e.g., wetland rehabilitation, riverbank restoration, meadow creation).
Protection of natural ecosystem	Includes legal, physical, or participatory actions to safeguard existing natural environments from degradation, urban development, or climate impacts. Often tied to conservation policies or local activism.
Transformation of previously derelict areas	Describes the conversion of abandoned or underutilised spaces—such as brownfields, vacant lots, or former industrial areas—into functional green infrastructure that offers ecological and social benefits.
Knowledge creation and awareness-raising	Creating eco-centres, environmental and cultural events, organising thematic workshops for schools and public, educational walks in ecologically valuable areas, participatory planning, co-creation.
Strategy, planning, policy development	Refers to initiatives that can deliver or participate in developing landscape architecture planning, spatial planning, climate adaptation strategy, urban greening strategies.
Improved governance of green or blue areas	Enhancing decision-making, coordination, and accountability in the management of green (vegetation) and blue (water) spaces through inclusive, transparent governance structures.
Monitoring and maintenance of habitats	Systematic observation and technical upkeep of natural or semi-natural habitats to ensure long-term biodiversity and ecological health. Wildlife monitoring in restored wetlands, invasive species control.
Food production, permaculture	Green infrastructure used for growing food through sustainable and regenerative practices, enhancing urban food security. Community gardens, edible landscapes, permaculture gardens.

	Self-governing region	Case study_no_Name	Nature-based solutions					
			blue infrastructure	community gardens, nature gardens, allotments	green areas for stormwater management	grey infrastructure integrating green	parks and other green spaces	intentionally unmanaged areas
CASE STUDIES	BA	CS.01_Národný trust - The National Trust of Slovakia					*	
	BA	CS.02_Vnútroblok		*				
	BA	CS.03_KoZa v Háji		*				
	BA	CS.04_Hrad - Slavín					*	
	BA	CS.05_BROZ - Regional association for Nature conservation and Sustainable development	*		*		*	*
	TN	CS.06_DAPHNE -Institute of applied ecology	*				*	*
	TN	CS.07_Naše Zálesičko	*				*	
	TN	CS.08_ŽiTo v SYPKE		*	*			
	TN	CS.09_eDeN v meste	*	*			*	*
	TT	CS.10_Zelený plán	*			*	*	
	NR	CS.11_ViZia - Rural Green Infrastructure					*	
	NR	CS.12_Strom darom				*	*	
	BB	CS.13_Alter Nativa		*				
	BB	CS.14_Združenie Slatinka	*		*		*	*
	KE	CS.15_Poď na dvor		*	*			
	KE	CS.16_Spolka					*	
	ZA	CS.17_Živý priestor	*				*	
			7	6	4	2	12	4

Figure A1. Nature-based solutions implemented by civic initiatives. The asterisk marks the NBS implemented by respective case studies.

	Self-governing region	Case study_no_Name	ACTIVITIES									
			creation of new green areas	maintenance and management of green spaces	restoration of ecological ecosystems	protection of natural ecosystem	transformation of previously derelict areas	knowledge creation and awareness raising	strategy, plan, policy development	improved governance of green or blue areas	monitoring and maintenance of habitats	food production, permaculture
C A S E S T U D I E S	BA	CS.01_Národný trust - The National Trust of Slovakia		*			*	*	*	*	*	
	BA	CS.02_Vnútroblok					*	*	*			*
	BA	CS.03_KoZa v Háji					*	*				*
	BA	CS.04_Hrad - Slavín		*			*	*		*		
	BA	CS.05_BROZ - Regional association for Nature conservation and Sustainable development	*	*	*	*		*	*	*	*	
	TN	CS.06_DAPHNE -Institute of applied ecology	*		*	*		*	*	*	*	
	TN	CS.07_Naše Zálesičko	*	*	*	*	*	*	*	*	*	
	TN	CS.08_ŽiTo v SÝPKE					*	*	*			*
	TN	CS.09_eDeN v meste			*	*		*		*	*	*
	TT	CS.10_Zelený plán	*	*	*	*		*	*	*		
	NR	CS.11_ViZia - Rural Green Infrastructure	*	*				*	*	*		
	NR	CS.12_Strom darom	*	*				*	*	*		
	BB	CS.13_Alter Nativá			*			*	*			*
	BB	CS.14_Združenie Slatinka	*	*	*	**		*	*	*	*	
	KE	CS.15_Poď na dvor		*			*	*	*	*		*
	KE	CS.16_Spolka	*				*	*	*	*		
	ZA	CS.17_Živý priestor	*	*	*	*		*	*	*		
			9	10	8	8	8	17	14	13	6	6

Figure A2. List of activities civic initiatives focus on. The asterisk marks the main activities conducted by respective case studies.

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Article

A Methodological Proposal for Implementing Dark Infrastructure Within the Ecological Network of an Urban Forest

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Abstract

Ecological continuity cannot be limited to spatial surfaces and corridors without consideration of the day–night cycle. This integration is achieved through the implementation of dark infrastructure, a field that remains comparatively understudied. The present article proposes a methodological approach for implementing dark infrastructure within an urban forest near Liège (Belgium), where the ecological network has recently been characterised, but nocturnal landscape-specificities are not included. Several sources of information were combined, including satellite imagery, a point-light map and the existing ecological network. The research seeks to illustrate conflicts between ecological requirements and human activities, with particular emphasis on public, and private lighting. In the discussion, the paper identifies methodological limitations, characterises the nature of light pollution, and lists planning issues for the cohabitation of human activities and nocturnal species' habitats.

Keywords: dark infrastructure; ecological network; urban forest; planning; day-night cycle; artificial light at night (ALAN)

1. Introduction

Biodiversity conservation can no longer be addressed independently of human influences. Increasing levels of anthropisation have generated numerous obstacles to species movement [1–3], necessitating measures to protect and restore habitats that underpin biodiversity. One strategy involves establishing ecological networks, partially underpinned by the principles of island biogeography outlined by MacArthur and Wilson [4]. According to this theory, species richness within a given territory depends on available area, degree of isolation, and interspecific competition. Consequently, it is feasible to estimate a dynamic equilibrium influenced by the extinction rate, which is correlated with habitat area, and the immigration rate, which is dependent on isolation [5]. As a result, natural habitat fragmentation is widely incorporated into biodiversity conservation strategies and should be systematically integrated into urban planning and land-use management. The significance of this approach is further reinforced by metapopulation theory [6], which posits that population dynamics are governed on the one hand the ability to recolonise vacant habitat patches and on the other hand local extinction rates. The ecological network concept thus represents a conservation strategy designed to maintain a coherent spatial structure conducive to species movement at the landscape scale [7].

An ecological network is structured into thematic sub-networks to facilitate the management of groups of habitats with shared characteristics. The goal is to ensure ecological

continuity between biodiversity reservoirs via appropriate corridors [8]. Both urban and rural landscapes are linked to ecological networks based on infrastructural logic, connecting natural, semi-natural, and anthropogenic environments [9]. This strategy enables the integration of ecosystem service provision into conservation objectives. The best-known forms are green and blue infrastructure, corresponding to terrestrial and aquatic environments, respectively. These aim to secure ecological continuity by drawing upon principles from landscape ecology [10]. Additional infrastructure types are also described in the literature: Tiwary and Kumar [11] define grey infrastructure as artificial structures shaping the urban environment, while others highlight soil connectivity through brown infrastructure [12].

However, ecological continuity cannot be limited to spatial surfaces and corridors without consideration of the day–night cycle. The nocturnal landscape is subject to additional disturbances at night that are not apparent during the day. It is therefore essential to integrate this temporal dimension and the disruptions resulting from artificial lighting into conventional green or blue infrastructure frameworks. This integration is achieved through the implementation of dark infrastructure, a field that remains comparatively understudied. Nearly 30% of vertebrates and more than 60% of invertebrates are nocturnal, highlighting the need to address light pollution [13]. The present article proposes a methodological approach for implementing dark infrastructure within an urban forest, where the ecological network has recently been characterised, but nocturnal landscape-specificities are not included. The research seeks to illustrate conflicts between ecological requirements and human activities, with particular emphasis on public and private lighting.

To this end, a brief review of relevant literature regarding light pollution and dark infrastructure precedes the presentation of the Sart-Tilman site context and the relevant datasets. In light of this case study, the objectives are to delineate the spatial extent of light pollution, identify areas of conflict between the ecological network and artificial light at night (ALAN), and evaluate the appropriateness of implementing dark infrastructure within the study area.

2. Literature Review

The concept of light pollution first appeared in the 1970s [14]. Research interest in this topic has grown [15], especially in highly urbanised countries such as the United States, China, and the United Kingdom. On a global scale, the loss of ecosystem services from light pollution is estimated at 3.4 trillion US dollars per year [16].

The designation of artificial light as pollution is predicated on its capacity to cause lasting disruptions to ecosystems when present or excessive in naturally dark environments [17–19]. If darkness at night is recognised as a form of natural capital, its degradation results in habitat impoverishment, notably through disturbances to movement patterns and foraging behaviour. As a result, measures such as reducing or adapting artificial lighting sources, as well as interventions such as reintroducing species into degraded environments, warrant consideration.

2.1. Biodiversity Challenges

Light pollution affects predation, reproduction, feeding, communication, migration, and competition [15,17,20–22]. Nocturnal species are more light-sensitive than humans and have different spectral sensitivities. This makes artificial light even more disruptive for them [17,20,23]. Most nocturnal activity depends on moonlight, a level of “biologically useful semidarkness” [23]. New artificial lights can mimic higher light intensities, leading species to stop performing essential survival activities.

Species generally display two distinct reactions to light: attraction or avoidance [17]. Nocturnal flying insects, for example, are attracted to light sources and may remain trapped

near them until exhaustion [17,22], leading to shifts in population spatial distribution [20]. Some predators subsequently adapt their hunting behaviour to remain near illuminated areas. Species that rely on bioluminescence to locate mates also become less able to find one another, resulting in population declines [23].

These mechanisms lead to changes in activity patterns among nocturnal, diurnal, and crepuscular species. Artificial lighting allows diurnal and crepuscular species to extend their activity time, while nocturnal species reduce their activity and experience habitat degradation [17,23,24]. However, artificial light alone may not suffice for diurnal and crepuscular species to exploit nocturnal ecological niches, as lower nighttime temperatures can limit their activity [24]. Species inhabiting wetlands or aquatic environments are likewise affected in their movement and reproduction [22], with some becoming less selective in mate choice under increased light levels, a behaviour influenced by heightened predation risk and favouring rapid mate choice [17].

Bats are a key nocturnal group and are highly vulnerable, though vulnerability differs by species. Slow-flying, gleaners like *Myotis* and *Rhinolophus* spp. avoid light because they hunt by following prey until it stops [13,25]. Fast-flying hawkers such as *Pipistrellus* and *Nyctalus* spp. may use lit areas for foraging [13,25]. For light-averse bats, light worsens fragmentation and reduces prey [17,24,26]. Still, fast-flying species suffer too as reduced dark areas cut connectivity and suitable breeding sites [25].

2.2. Human Challenges

Humans are a diurnal species and, consequently, have sought to make darkness visible as soon as technology permitted it. Night-time lighting aims to provide protection by allowing individuals to see and be seen. Fear of darkness and its associated dangers have been a decisive factor in the development of lighting systems [27]. From the outset, illuminating the night has been linked to social needs and values [14] as well as to the idea of progress [28]. With the development of electric lighting, motorised transport, and the road network, the nocturnal landscape has undergone profound transformations at large spatial scales [17,20]. According to Falchi et al. [29], 83% of the world's population lives under a sky polluted by artificial light, defined as an increase of at least 8% above natural brightness levels, hindering the observation of stars and other celestial bodies. Globally, light pollution increases by an average of 6% per year [30]. The challenge, therefore, is to regulate the installation of lighting points, as their provision often exceeds actual needs [22].

Night-time lighting particularly impacts the circadian cycle [15,22,31], as melatonin production is stimulated by darkness. The presence of artificial light, especially blue-rich light, suppresses melatonin synthesis [23,32] and disrupts sleep [19,21]. Some studies also associate exposure to artificial light with diabetes and some cancers [33]. However, impacts on human health and on biodiversity more broadly remain insufficiently quantified [15]. Figure 1 summarises the main causes and consequences of ALAN.

2.3. Observation of ALAN Using Remote-Sensing Imagery

Current approaches to observing ALAN remain constrained by several methodological limitations. Although the spatial resolution of nocturnal observations has progressively improved, from DMSP/OLS in 1976 with resolutions of 2.7 km and later 1 km [21,31] to the Suomi-NPP VIIRS sensor, which provides a spatial resolution of 750 m for the panchromatic DNB band [21,31], this resolution remains too coarse for local-scale analyses. Since the early 2000s, the emergence of commercial satellites has further refined the spatial resolution of nocturnal imagery. EROS-B was the first commercial satellite to provide imagery with a spatial resolution below 1 m using a panchromatic sensor. Subsequently, in 2017 and 2018, the Jilin-1-03 and Luojia-1 satellites were launched, offering spatial resolutions of

1 m and 130 m, respectively. Unlike EROS-B, these nocturnal images are multispectral [21], allowing the calculation of indices based on the red, green, and blue (RGB) bands, such as the melatonin suppression index or the potential of a light source to induce photosynthesis through the induced photosynthesis index [34].

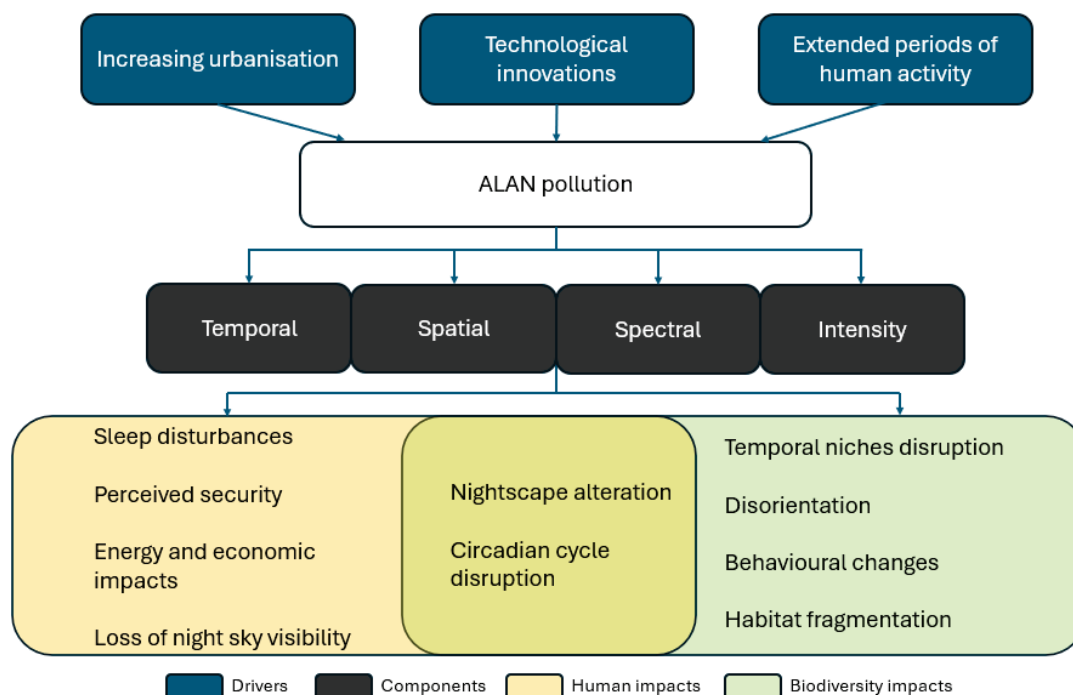


Figure 1. Schematic overview showing the general causes and impacts of ALAN pollution. Impacts shared by biodiversity and humans are presented in the central box of the impacts section.

Nevertheless, numerous challenges specific to satellite-based observation of nocturnal light pollution remain. First, observed scenes combine natural sources with very low radiance values and artificial sources that vary widely in intensity, orientation, and spectral signature. As a result, sensors must strike a balance between sufficiently broad spectral resolution and the finest possible spatial resolution. This challenge has become even more pronounced with the global transition towards LED lighting. The spectral output of LED lamps is broader than that of sodium lamps, for example, and, as mentioned above, the blue component is not captured by certain nocturnal satellite sensors. According to Bará et al. [35], the VIIRS sensor may even record a decrease in emissions in the DNB band while ground-based observations indicate the opposite trend. A comparison between Jilin1 imagery and drone-based measurements confirms this tendency [36], with the weakest correlation observed in the blue band compared to the red bands. In addition, the viewing angle strongly influences observations due to shading effects from buildings or vegetation, as well as emissions from façades or windows. Finally, temporal variability must also be considered. The Suomi-NPP and DMSP satellites are polar-orbiting and therefore operate at fixed overpass times, preventing the observation of nocturnal lighting dynamics throughout the night. This variability is partly driven by policy decisions that reduce or partially switch off lighting infrastructures. At the seasonal scale, snow also influences the captured luminance values [21].

2.4. Designing a Dark Infrastructure

The growing interest in light pollution has highlighted its importance for biodiversity and circadian rhythms. Consequently, implementing dark infrastructure requires preserving and restoring biodiversity reservoirs, as well as corridors that provide sufficient

darkness [37]. Reflecting upon and establishing dark infrastructure is a new challenge for spatial planning, particularly within and around urban areas.

Several approaches have been proposed in the literature for constructing a dark infrastructure [8,37]. The first is a general and operational approach based on identifying conflict zones between artificial lighting and areas of high biodiversity value. It acts as a decision-support tool for prioritising restoration actions or reducing light pollution, without truly designing a complete network. The second method builds a dark infrastructure by relying on an existing map of the ecological network. This deductive approach overlays a map of light pollution with a map of the existing network to highlight areas that offer sufficient darkness and fall within the ecological network. The third approach treats light pollution as a direct source of habitat fragmentation for each thematic subnetwork of the ecological network. Specific reservoirs are identified using indicator species and the light pollution map. Corridors are then defined by modelling optimal paths that incorporate darkness as a factor in ecological permeability. The different corridors and reservoirs are subsequently aggregated for each thematic subnetwork. This approach, described as integrative, follows the classical procedure for constructing an ecological network while incorporating the day-night cycle into its structuring elements [8,37]. However, this method may overlook important areas for diurnal biodiversity if they are excessively illuminated. The result may therefore be an ecological network that is potentially more restricted than a daytime network.

3. Materials and Methods

3.1. Study Area

The study site covers 14 km². It is located in Sart-Tilman, in the Province of Liège, Belgium, and hosts the main campus of the University of Liège (Figure 2). The site was selected as it lends itself well to the study of the impact of ALAN on the ecological network. University facilities and the university hospital (CHU) have expanded close to forest and heathland areas considered to be of high biological value, 240 ha of which are designated as an approved nature reserve. The site is currently structured by its road network and is mainly accessible by car and bus.

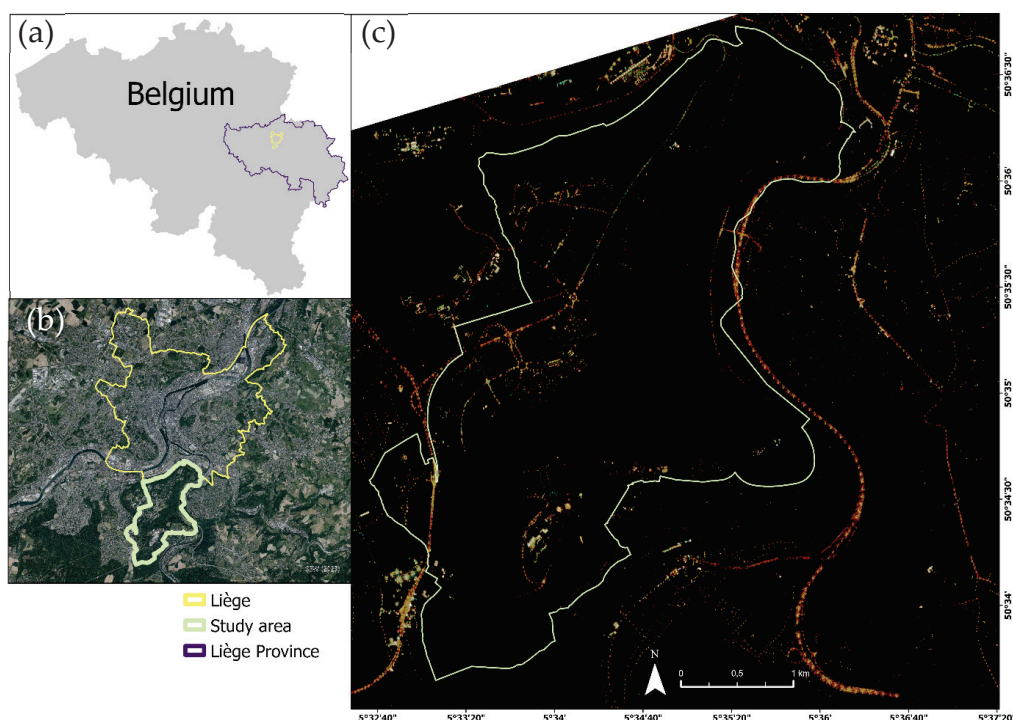


Figure 2. Location of the study area in Belgium (a) and within the city of Liège (b). JL1-7B image (c).

This site is of particular interest because it combines predominantly daytime human activities with extensive species-rich areas near an urban agglomeration of 500,000 inhabitants. In addition, it was recently the subject of ecological infrastructure mapping, though this prior work did not account for the site's nocturnal characteristics.

3.2. Data

To analyse the potential development of dark infrastructure at Sart-Tilman, several sources of information were combined, including satellite imagery, a point-light map, and the existing ecological network. Field surveys were also conducted to identify methodological limitations and characterise the nature of the light pollution.

3.2.1. Satellite Data

The primary data source is the commercial Chinese satellite Jilin-1 7B, operated by Chang-guang Satellite Technology Co., Ltd. (Changchun, China). Its multispectral sensor provides RGB imagery with a spatial resolution of 1.2 m and a radiometric resolution of 16 bits. The satellite is sensitive to low-level light emissions, which enables fine-scale analyses of the nocturnal landscape compared with NASA's Black Marble product derived from VIIRS/NPP data. The satellite flew over the study area on 25 March 2020 at 22:02 local time. The selected image has a signal-to-noise ratio (SNR) of 73 for the red band and 25 for both the green and blue bands. This indicates limited separation between the useful signal and noise in the green and blue bands, partly due to low nocturnal irradiance, which limits the amount of information captured. Moreover, shorter wavelengths, such as blue, are more strongly scattered by the atmosphere, further reducing the amount of light reaching the sensor. The use of a drone was considered but quickly ruled out due to the high risks associated with nocturnal navigation over a relatively large area that includes the hospital heliport.

3.2.2. Nighttime Photography

Field photographs were taken across the study site to document the visual impact of ground-level lighting and to compare it with the satellite-derived data. The photographs were captured between 23:00 and 00:30.

3.2.3. Light Points

The various light points within the site were obtained from the Real Estate Resources Administration of the University of Liège. These data were cross-checked with the regional road lighting network to obtain a more comprehensive dataset.

3.2.4. Land Cover

The land cover data used in this study are publicly available through a federal website (WalOnMap). The land cover layer is based on 2020 orthophotos and a Digital Elevation Model (DEM). Its original spatial resolution is 1 m. The raster was resampled (nearest neighbour method) to match the spatial resolution of the satellite data. Roads were categorised into three classes according to their relative importance within the road network. The final classification includes ten classes, which will be presented in the Section 4.

3.2.5. Ecological Network Mapping

The ecological network used in this study corresponds to the operational network. This network is derived from the functional ecological network, which represents the spatio-temporal dynamics of species within each thematic infrastructure [38]. At Sart-Tilman, the ecological network is divided into four thematic subnetworks [38]:

- Broadleaved forests, comprising habitats with at least 75% native species. They are divided into two subnetworks. The first includes broadleaved forests adapted to intermediate moisture levels, known as mesophilic forests. The model species for this infrastructure is the stag beetle (*Lucanus cervus*). The second consists of wet forests, which must include streams; the model species here is the fire salamander (*Salamandra salamandra*).
- Dry open habitats, which include dry grasslands and heathlands. The model species is the blue-winged grasshopper (*Oedipoda caerulea*).
- Grasslands, which are also open habitats but are mesophilic, with richer soils supporting denser herbaceous vegetation.
- Forest edges, forming a transition zone between forested areas and open habitats.

It should be noted that the stag beetle exhibits both diurnal and crepuscular activity. During the day, individuals walk and rest, while the crepuscular period is used for flight and dispersal over longer distances [39]. The fire salamander, by contrast, is a nocturnal species [40], whereas the blue-winged grasshopper is predominantly diurnal [41]. Consequently, assessing the impact of ALAN on the thematic infrastructures, and especially on the forest infrastructure, is highly relevant. In addition, several bat species are present within the study area.

3.3. Methodology

3.3.1. Satellite Image Preprocessing

The raw image was projected into the Belgian Lambert 2008 coordinate system. To preserve the original reflectance values, the nearest neighbour resampling method was selected. Once georeferencing was completed, a median filter was applied using a 3-by-3-pixel window around each pixel. A 3-by-3 window provides slight smoothing while preserving edges. The median value is preferred because it is less affected by extreme values than the mean. Using the gain and offset coefficients included in the metadata, the image underwent radiometric calibration. This processing converts Digital Numbers (DNs) ranging from 0 to 65,535 into spectral radiance values expressed in $\text{W}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}\cdot\mu\text{m}^{-1}$. However, this processing merges the three bands, preventing an RGB visualisation of the post-processed image. The mathematical relationship used is the following:

$$L\lambda = \text{Gain} \times \text{DN} + \text{Offset}$$

where $L\lambda$ represents the spectral radiance. The gain and offset values for the three wavelengths are provided in Table 1.

Table 1. Gain and offset coefficients for the red, green, and blue bands of the Jilin1-7B satellite image.

	Red	Green	Blue
Gain	0.000574	0.000644	0.000895
Offset	0.009202	0.009854	0.011851

The radiance values were combined into a single band by converting them to greyscale using the method developed by Grundland and Dodgson [42], as applied in the studies of Zheng et al. [43] and Xue et al. [44], which used satellite data from JL1 3 B. This technique preserves the correspondence between greyscale levels and radiance values while providing rapid visual understanding by maintaining contrast. Thus, pixels displaying the same

colour in the original image display the same shade of grey. The equation of the Grundland and Dodgson [42] method is the following:

$$\text{Brightness} = 0.2989 \times \text{Red} + 0.587 \times \text{Green} + 0.114 \times \text{Blue}$$

where the luminance represents the resulting greyscale value, and red, green and blue correspond to spectral radiance values.

The minimum value obtained after conversion was $85 \text{ nW} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1}$, which is similar to the values reported by Zheng et al. [43] and Xue et al. [44]. This value is treated as background, and pixels with higher values are considered illuminated. After processing, the image still contained several outlier pixels, and an additional filtering step was performed to remove them. Values exceeding $5000 \text{ nW} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1}$ were considered abnormally high, based on the maximum values reported in Zheng et al. [43] and Xue et al. [44]. As their studies focused on urban districts, values of $5000\text{--}9500 \text{ nW} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1}$ within the study area were deemed unrealistically elevated. For each pixel, the median of the neighbouring pixel values within a 5-by-5 window was calculated. This approach was preferred because the median reduces the influence of neighbouring outliers, and a 5-by-5 neighbourhood allows the removal of larger clusters while remaining within a range of high brightness values.

3.3.2. Spatial Description of the Illuminated Area

The land cover classes were differentiated using statistical analysis to identify those most affected by the observed ALAN footprint. For each land cover class, the mean, median, standard deviation and coefficient of variation (CV) of brightness were calculated, as well as a skewness index defined as follows:

$$\frac{1}{n} \sum_{i=1}^n \left(\frac{x_i - \bar{x}}{SD} \right)$$

where n represents the number of pixels in the land cover class, x_i represents the brightness value of a pixel, $\bar{x}$ is the mean brightness of the class, and SD represents the standard deviation.

The nocturnal photographs then enabled visualisation of the illuminated surfaces from a ground-level perspective. To ensure systematic tracking of the photographs, the QGIS extension QField 4.9.0 was used. The satellite-observed luminosity footprint was imported to visualise the results of satellite image processing. The photographs were taken with a Canon EOS 550D without a flash.

The images were also processed in GIMP 3.0.4 software. To enhance the distinction of illuminated areas within the photographs, the image colours were converted to grey-scale while preserving the human eye's perception of brightness. This step follows a logic similar to that used in processing the satellite image. GIMP performs this conversion using a different formula:

$$\text{Luminance} = (0.22 \times R) + (0.72 \times G) + (0.06 \times B)$$

where R , G and B correspond respectively to the pixel values in the red, green and blue channels of the original image. The luminance values were then inverted to transform bright areas into dark areas.

3.3.3. Light Infrastructure

The approach selected to assess the impact of light pollution is a deductive one, partially inspired by the work of Sordello [8] and Sordello et al. [10]. The observed spatial

structure of light pollution is integrated into the ecological network to identify potential conflict areas involving light infrastructure, which represents barriers to species movement. The brightness threshold considered corresponds to the minimum value obtained from the satellite image preprocessing. In the scientific literature, researchers agree that no normative minimum value exists to distinguish light-polluted areas. Thresholds depend on the sensor and the objectives of the study [8,24,29,33,37,45,46]. Consequently, any detected artificial light is considered to directly impact biodiversity in this study.

The dark infrastructure is constructed from the light infrastructure to highlight potential conflict areas with the ecological network described by Gillet et al. [38]. The light infrastructure is built on the footprint of observed brightness extracted from the satellite image, complemented by a set of light points available to us that are not all detected or detectable in the satellite image. Although purely theoretical, some light points present in the territory may not have been detected by the satellite for various reasons. This may occur if a lamp post has a device that reduces upward light emission, if the light intensity is too low to be detected, or if the light point is out of service. This extension was produced by intersecting the observed brightness with a fifteen-meter buffer around each lighting point. The buffer allows the intersection to be performed while mitigating positional biases caused by georeferencing and lighting-point positions, and is inspired by Angerand's [47] observations. Once the intersection was completed, a reverse selection was applied to retain lighting points that are not located near illuminated surfaces. A seven-meter buffer was then applied around these points, and the layer was rasterised.

The choice of these buffer values is based on measurements of light footprint conducted by Angerand [47] on standard road lighting systems in Wallonia. Ground level illumination values were observed beyond 15 m for both LED and sodium lamps. Regarding the 7 m raster, this value was selected based on the width of municipal roads as well as on field observations and photographic documentation collected on site. Furthermore, the final point raster constructed from the 7 m buffer represents a theoretical footprint, as the individual characteristics of each light source are not known.

3.3.4. Conflict Areas

The light infrastructure is then superimposed on the areas of the different thematic infrastructures of the ecological network to highlight and assess potential conflict zones. The same process is repeated on the existing corridors.

4. Results

4.1. Spatial Description of the Light Footprint

In the case of Sart-Tilman, the observed light pollution is mainly concentrated along road traffic axes and artificial surfaces, as shown in Figure 3. Although the intensity gradient is wide, ranging from 85 to 4956, most values fall near the lower end of this range. An inspection of the pixel histogram (Figure 4) shows that more than 35% of the pixels have a brightness value between 85 and 100 $\text{nW}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1}$.

The land cover analysis refines the spatial description. The Table 2 presents all results by land cover class. While all land cover classes display a minimum value close to 85, which is also the minimum detectable brightness threshold, maximum values vary considerably. Built-up areas show the highest value (4956), followed by municipal roads (4897) and forests (4781). The maximum value of the forest class originates from a few targeted points located near human activity areas, including the vicinity of a golf club building. The classes bare soil, grove and water body present much lower maximum values but also represent a small proportion of the illuminated surface.

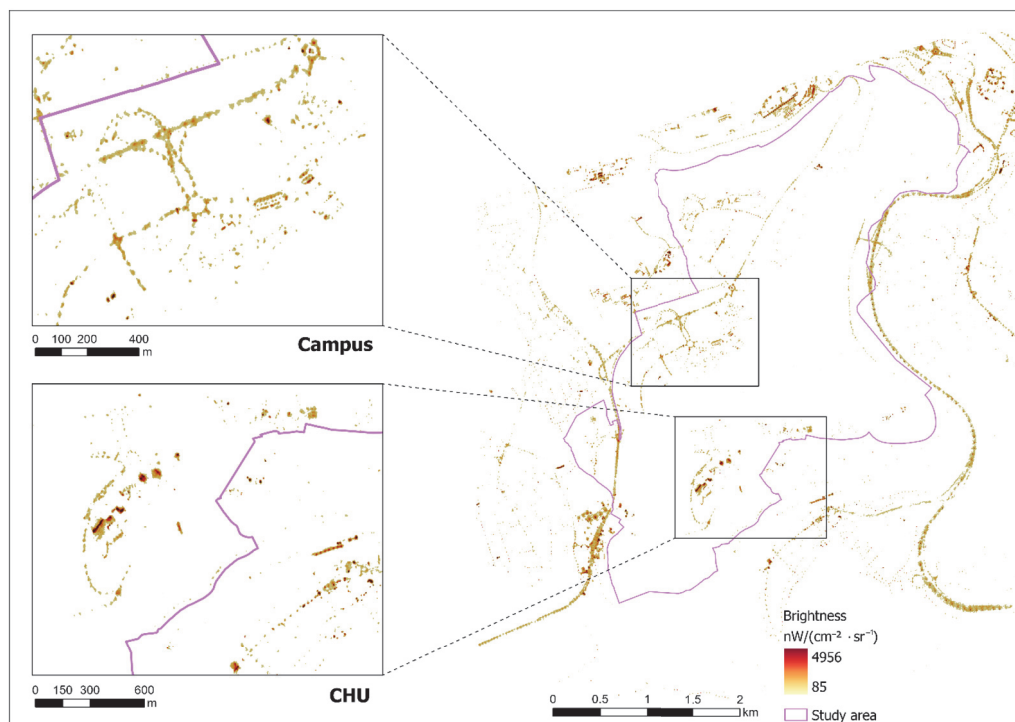


Figure 3. Cartographic representation of pixel brightness within the study site. Two detailed views are provided, focusing on the Sart-Tilman campus and the CHU, respectively.

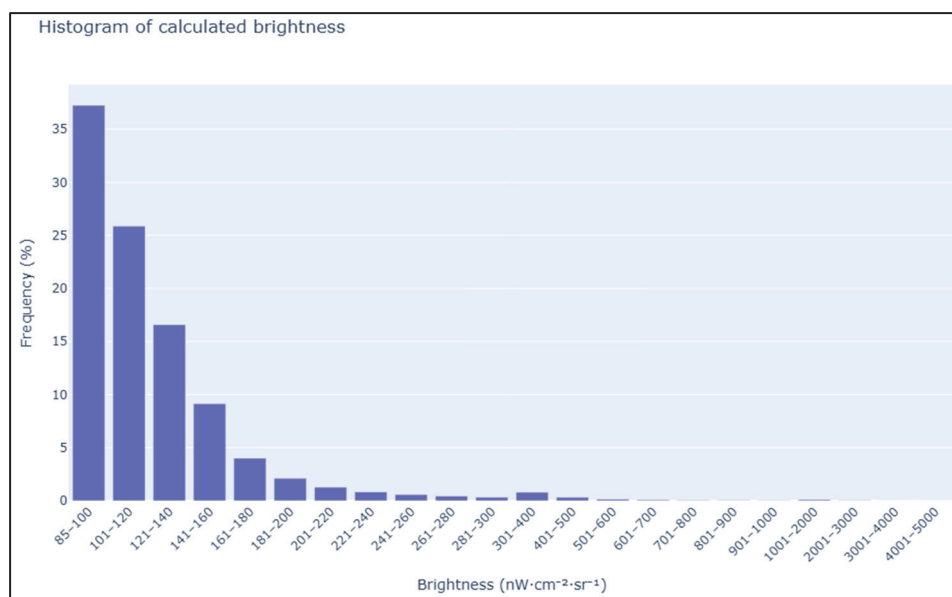


Figure 4. Histogram of the calculated brightness. The X-axis represents the different brightness values obtained. These values are grouped into classes of variable width based on the number of observations within each class. The Y-axis represents the number of pixels per brightness class as a frequency.

The standard deviation varies significantly across land cover classes. The classes built-up (144), forest (116), herbaceous cover (102) and municipal road (103) indicate high variability, whereas the classes path (40) and main road (48) show values clustered around the mean and are more homogeneous. The classes main road (42.5%) and municipal road (25.5%) represent a very large share of the total illuminated surface. Built-up areas (10.4%) and herbaceous cover (9.1%) are also significant.

Table 2. Distribution of observed brightness over the study site. The Min, Max, Mean, and Median columns respectively represent the minimum, maximum, mean, and median brightness values, expressed in $\text{nW}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1}$, for each land cover class. The percentage of illuminated surface corresponds to the proportion of the illuminated surface area of each land cover class relative to the total illuminated surface area.

Land Cover Classes	Min	Max	Mean	Median	SD	CV	Skewness	Surface (%)
Bare soil	86	254	132	118	43	0.33	1.1	0.1
Forest	85	4781	119	100	115.5	0.97	20.3	7
Grove	85	1078	121	106	58	0.48	8.2	1
Railway	85	817	137	121	62.6	0.46	3.6	3.9
Primary road	85	4371	118	106	48.2	0.41	21.8	42.5
Communal road	85	4897	133	112	103	0.78	17.4	25.5
Path	86	471	112	100	40	0.36	4.7	0.2
Water body	85	547	121	104	48.5	0.40	3.8	0.3
Herbaceous cover	85	3799	128	104	102.1	0.80	15.3	9.1
Built-up	85	4956	143	113	144.1	1.01	14.9	10.4

Already considered as an obstacle during the day, the road network also constitutes the main driver of fragmentation at night, creating discontinuities in nocturnal ecological continuity. Roads, therefore, act as barriers structuring the nightscape, complemented by built-up areas whose brightness is higher but more variable. Indeed, within the built-up area, the character of the light sources is more diverse, oscillating between decorative lighting and functional illumination. The design of the lighting directly influences the amount of light perceived, as illustrated in Figure 5, with the original photographs provided in the Appendix B.

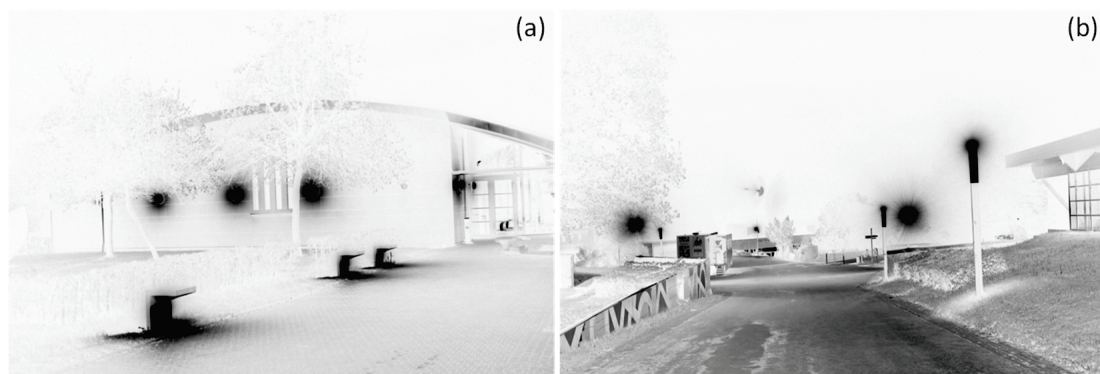


Figure 5. (a) photograph of a university building façade; (b) photograph of a campus pathway. The images were edited using the GIMP software, with white areas corresponding to dark zones and vice versa.

4.2. Light Infrastructure

The identified light infrastructure shown in Figure 6 corresponds to the light captured by the satellite, as referenced in Figure 3. The potential infrastructure includes lighting for secondary roads adjacent to the main road network and the surroundings of campus buildings. The Blanc Gravier sports centre, which combines parking and stadium lighting, appears to be a critical location which, although not illuminated throughout the night, may disturb certain species in its vicinity. The issue of hospital lighting, which is highly visible, is more problematic given the need for nighttime activity. Lastly, the mapping highlights

several municipal public lighting points that could be considered unnecessarily disruptive to nocturnal species.

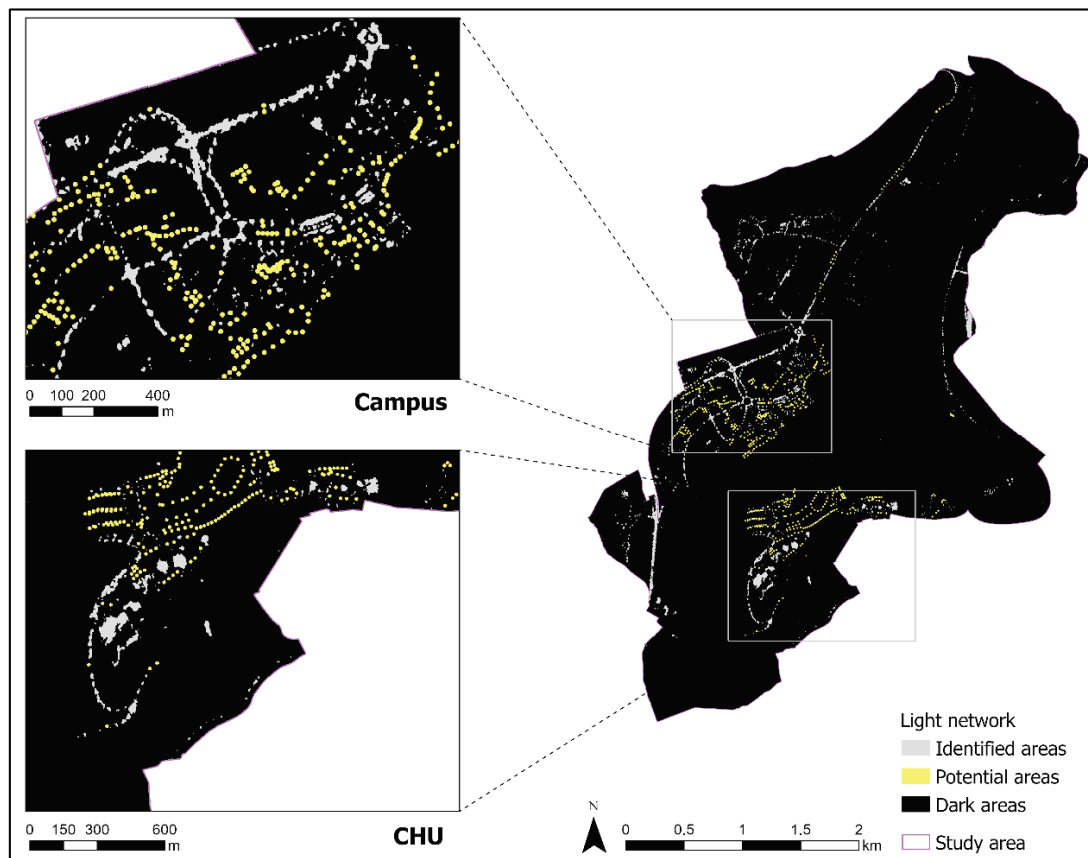


Figure 6. Cartographic representation of the identified light network and the potential light network on the Sart-Tilman site. The dark areas represent surfaces considered unlit according to the data used. Two detailed views are presented: one focusing on the Sart-Tilman campus and the other on the CHU and the Blanc-Gravier neighbourhood.

4.3. Conflict Zones

The results of the intersections between the light infrastructure and the different areas of the ecological network infrastructures (Figures 7 and 8) show that the impact is almost entirely located along the outer boundaries of the sites of core areas. The definitions of the ecological network components (core area, development area, and corridor) are provided in the Appendices A and B. The dry, open-habitat infrastructure is not affected because the sites are located in the very core of the nature reserve. Within the broadleaved forest infrastructure, light pollution identified in humid broadleaved forests primarily affects the core areas in direct contact with roads. Potential brightness affects mainly the development areas. The most important corridor zones are only slightly impacted. The mesophilic broadleaved forest sub-infrastructure is more strongly affected by the light infrastructure, particularly in corridor areas, some of which cross the campus and are directly fragmented by it. This is partly explained by the higher connectivity within the mesophilic forest sub-infrastructure. The forest-edge infrastructure covers limited areas but is affected at numerous locations directly adjacent to roads and university facilities. Finally, the grasslands infrastructure is the most affected by ALAN. Many areas of the operational network intersect the light infrastructure around the road network and within pedestrian zones on the campus. The impact is substantial because these areas have rectilinear and irregular shapes, which increases the contact surfaces.

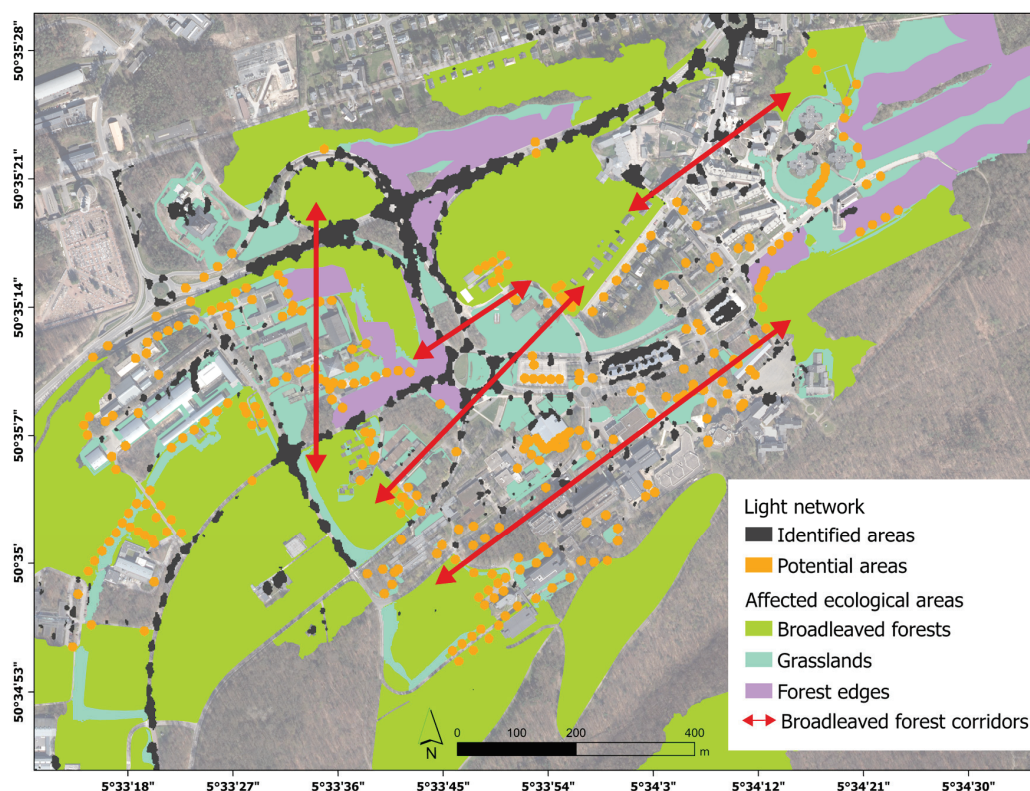


Figure 7. Cartographic representation of the light network's impact on the ecological network areas present on the campus (see detailed view in Figure 6). Only the affected surfaces are represented. The red arrows schematically represent the corridors of the broadleaved forest subnetwork.

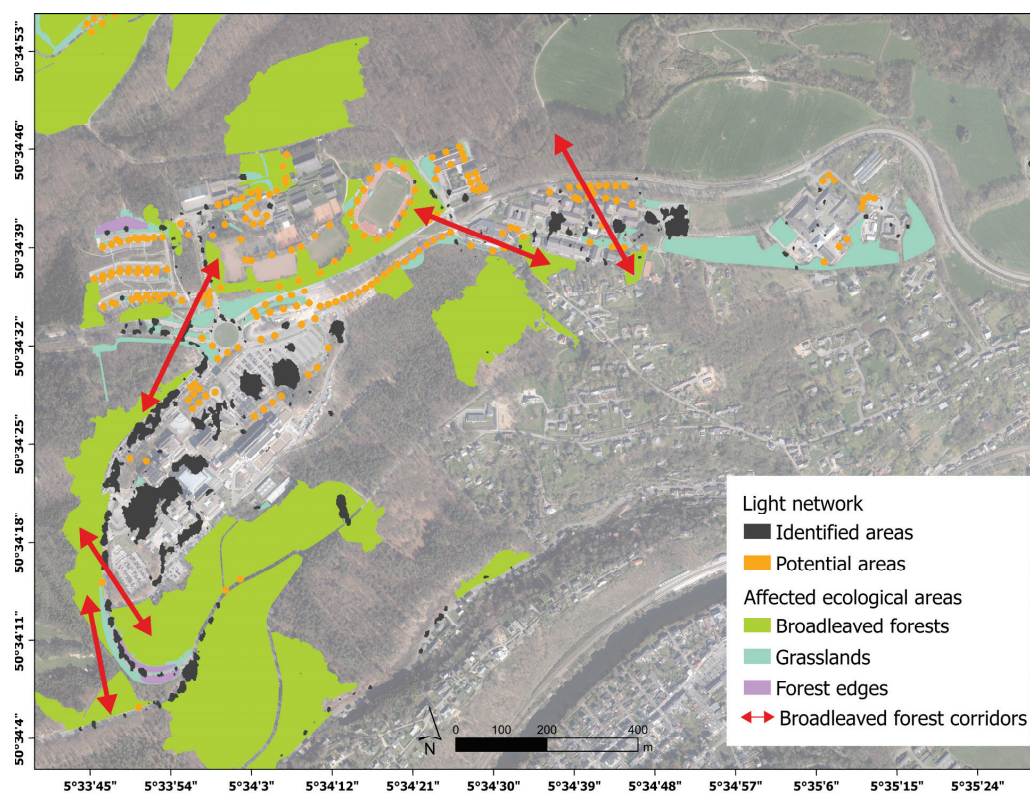


Figure 8. Cartographic representation of the light network's impact on the ecological network areas present on the CHU and Blanc Gravier (see detailed view in Figure 6). Only the affected surfaces are represented. The red arrows schematically represent the corridors of the broadleaved forest subnetwork.

On campus, some zones are isolated from the rest of the system due to the lighting footprint. Examples can be observed in Figure 7 along the road network and each ecological infrastructure is affected. The corridor zones of broadleaved forests crossing the campus are all impacted by the light infrastructure. Around the university hospital and the Blanc Gravier sports complex (Figure 8), contacts are less numerous but occur within core areas. The Blanc Gravier site is almost exclusively associated with the potential light infrastructure, whereas the hospital site is well integrated within the identified light infrastructure.

5. Discussion

5.1. The Footprint of ALAN on the Sart-Tilman

The spatial analysis of luminance data revealed the distribution of light pollution across the study area. The road network, which is the main barrier to the ecological network during daytime, strongly structures the nocturnal landscape, with more than 60% of illuminated pixels concentrated along primary and municipal roads. Roadside areas are also illuminated to varying degrees depending on the type of lighting. The overall lighting infrastructure forms an almost continuous luminous barrier, contributing to the fragmentation of corridor zones and wildlife habitat areas. Built-up areas are also illuminated. Quantitatively, the values are generally homogeneous, with more than 75% of illuminated pixels ranging between 85 and 140 $\text{nW}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1}$, including 35% between 85 and 100 $\text{nW}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1}$. However, the mean levels of light intensity per land cover class show that, despite locally high maxima, illuminated environments are mostly moderately bright. Variability indices (standard deviation, coefficient of variation and skewness) show that built-up areas and some municipal roads exhibit high heterogeneity in their values, whereas the main roads provide more homogeneous and sustained lighting. Still, some parts of the territory show higher light intensities than expected given their socio-economic context, suggesting oversized or poorly adapted lighting systems. Built-up areas exhibit the highest light intensities and greater variability than the road network. Conversely, forest zones are relatively dark, with most illumination observed near forest edges. High values within forests are very localised and related to human activities.

5.2. Relevance of Integrating a Dark Infrastructure

A dark infrastructure can be understood as an ecological network adapted to nocturnal conditions. This spatial framework is designed to preserve ecological continuity at night by explicitly integrating the characteristics of nocturnal space, including levels of darkness, unlit corridor zones, and the spectral and temporal properties of artificial lighting, in complement to existing diurnal infrastructures. Accordingly, dark infrastructure aims to identify and restore priority areas where artificial lighting fragments the nocturnal landscape by cross-referencing fine-scale mapping of the lightscape with ecological sub-infrastructures to target operational measures that maintain nocturnal ecological continuity and the coherence of the nocturnal landscape.

Within this conceptual framework, the Sart-Tilman territory appears particularly relevant. The study area is mostly forested, dominated by mesophilic broadleaved forest subinfrastructure (58%), followed by humid broadleaved forests (41%). These surfaces largely overlap and provide ecological continuity around the nature reserve, which serves as a core area for both forest sub-infrastructures. Forest edges, dry open habitats, and grassland infrastructure are less represented, often fragmented, poorly connected, and composed largely of restorable areas. Yet these infrastructures play an essential complementary role for overall biodiversity, especially since Sart-Tilman is a key node of the ecological network at the scale of the urban agglomeration, hosting many biologically important sites.

Including the potential pressure of nocturnal lighting in the assessment of the ecological network, therefore, appears relevant.

However, the intersections between the light infrastructure and the ecological network elements nuance the importance of integrating a dark infrastructure at the scale of the Sart-Tilman. On the one hand, the overall surface area affected by light is relatively limited, suggesting that a site-wide dark infrastructure is not strictly necessary. On the other hand, the spatial distribution of impacts reveals intersections with key elements of the operational ecological network, particularly within the mesophilic broadleaved forest sub-infrastructure, where corridor zones of medium and high centrality are strongly affected. Corridor zones crossing the campus, the Blanc Gravier sports complex, and the hospital surroundings are impacted, reducing movement capacity for certain species and diminishing connectivity among core areas across the ecological infrastructure. For the humid broadleaved forest sub-infrastructure, impacts appear to be limited compared to those in the mesophilic forest. However, the influence of light pollution on corridor zones is reduced by the road network's dominant weight in corridor modelling. When defining the ecological network, the movement cost assigned to urbanised and road surfaces was sufficiently high to force corridor zones to avoid illuminated areas. Protected areas, such as the nature reserve, also contributed to reducing the potential footprint of artificial light. The species used to model the broadleaved forest sub-infrastructures are nocturnal or crepuscular, making light pollution a critical factor in designing a functional network. Several bat species inhabit forest habitats and use forest edges as foraging ecotones, requiring special attention regarding ALAN. According to Azam et al. [25], artificial light at night has a greater negative impact on movement capacity than impermeable surfaces. Although individual light points may offer local foraging opportunities, they negatively affect bat activity at the landscape scale.

Therefore, even though the quantitative footprint of nocturnal lighting is limited, many authors have demonstrated the ecological disruptions caused by ALAN. The spatial distribution of lighting and its intersections with key corridor zones justify targeted actions to preserve ecological continuity. In least-cost path modelling, illuminated areas can be assigned a movement cost, just like any other land cover class. The cost can also be modulated according to light intensity, providing a flexible tool. Establishing a dark infrastructure, therefore, enables the integration of the temporal dimension of ecological processes into the design of a connected network of habitat cores and corridor zones.

5.3. Methodological Considerations

This study developed a method to identify light pollution on the site. Once the footprint was defined, the analysis profiled insights for the development of a dark infrastructure on Sart-Tilman. The work was based on satellite imagery and the existing ecological network mapping. The deductive method provides rapid results. However, light pollution is treated as a secondary criterion in the construction of the ecological network. This approach confines the dark infrastructure to the boundaries of the existing ecological network and may overlook other dark zones, making the results dependent on the initial ecological study.

Night-time satellite images capture only the upward light flux, i.e., the light passing through the atmosphere to reach the sensor. Viewing angle also greatly influences observations, as buildings and vegetation cast shadows. The presence of strong LEDs on the site adds complexity. Guk and Levin [36] showed that Jilin-1 images may detect reduced emissions even when ground measurements indicate the opposite, partly because the relatively low SNR of the green and blue bands reduces the amount of captured information. The images also offer only a single observation at a fixed time, preventing evaluation of

nighttime variations in intensity or colour temperature. In this case, the image was taken early at night, reflecting the maximum expected intensity.

Thus, the entirety of artificial light perceived by wildlife is not represented, particularly for species on the ground, in flight or in aquatic environments. Nonetheless, the images allow direct visualisation of upward light flux from both public and private lighting.

The threshold value of $85 \text{ nW}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1}$ was chosen to classify pixels as either illuminated or dark. This threshold corresponds to the lowest luminance observed, following Zheng et al. [43] and Xue et al. [44]. This implies that all illuminated pixels are considered, consistent with sensitivity thresholds for bat species present on the site, which are lower than $85 \text{ nW}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1}$ [13]. Light points not captured by the satellite were integrated into a potential light infrastructure. This addition provides a more precise representation of the potentially affected area, distinguishes observed and unobserved sources, and supports prioritisation for dark corridor planning. However, this potential infrastructure remains theoretical, based on an arbitrary buffer distance that does not differentiate lighting types.

Although the existing ecological network had previously been the subject of a dedicated study to ensure its validity, the model produced in this article was visually verified at several locations across the study site using field photographs and nocturnal survey routes. Satellite imagery alone does not capture the full extent of ecologically relevant light pollution, a limitation corroborated by field photographs. The observed light infrastructure footprint was imported into QField to assess the results of satellite image processing directly in the field. This qualitative approach aimed to document the diversity of lighting types presents across the study site and the reliability of the measurements. The limited representation of certain areas that are nevertheless illuminated reinforced the decision to implement a potential dark infrastructure. This step also highlighted one of the main limitations of exploiting satellite data. The proposed model could be further validated by measuring, for example, changes in bat movement patterns before and after the implementation of a dark corridor within the study site.

5.4. Contributions and Perspectives

This work proposes a reproducible protocol for analysing the characteristics of dark infrastructures. Through the identification of the light infrastructure and hotspot mapping, affected operational network zones and corridor zones are highlighted, allowing light pollution to be explicitly integrated into the design of an ecological network that accounts for diurnal, crepuscular and nocturnal species.

The method enables the identification of conflict areas between artificial lighting and ecological continuities, which constitutes a key basis for developing targeted action plans. The visual outputs facilitate communication with local decision makers and stakeholders, while providing operational guidance for prioritising mitigation measures, such as dimming strategies, luminaire redesign or the removal of unnecessary lighting, particularly along low-traffic road segments and near corridor zones. More broadly, the results support the protection of dark refuges and the integration of nocturnal ecological criteria into urban planning, land-use regulation and public lighting policies.

Beyond the Sart-Tilman case, the protocol is designed to be transferable to other territories, provided that a mapped ecological network and nighttime imagery with sufficiently fine spatial resolution are available. While high-resolution satellite data remain costly, the workflow can be adapted using drone-based imagery or by estimating the spatial extent of artificial lighting through ground-based measurements. These conditions make the approach applicable to a wide range of contexts, including peri-urban natural parks or municipalities engaged in dark sky or biodiversity policies.

In the case of Sart-Tilman, although the core areas of the ecological network are relatively little affected by artificial lighting, the main challenges concern corridor zones and the overall connectivity of the network. Some road segments classified as low-traffic or low-risk for road safety could therefore be dimmed or switched off. Ecological areas that become isolated at night remain a major concern, particularly along primary roads that are not locally managed and remain heavily used during nocturnal periods. Azam et al. [26] recommend a minimum distance of 50 m between ecological corridors and light sources for bats.

In the longer term, the method could be improved by integrating time series of nighttime images, ground-based radiometric measurements and a more complete inventory of light points. Discriminating lighting types using indices based on RGB channels, such as that developed by Sánchez de Miguel et al. [34], would further enhance the ecological relevance of the analysis.

6. Conclusions

This work provides an analytical and operational framework for assessing the footprint of artificial light at night. The methodology, designed and applied, combines several elements: the acquisition and processing of a night-time satellite image, the production of light-intensity data, and the creation of a light infrastructure integrating both observed light and potential light generated by existing light points. These data were spatially cross-referenced with land cover and the existing ecological network to identify conflict areas and the issues related to light pollution.

The methodology developed is reproducible and usable by local managers, although several methodological limitations must be considered. The satellite image alone cannot capture the full extent of ecological light pollution, but it provides a first estimate, albeit one that underestimates reality. This work opens operational perspectives by enabling landscape connectivity modelling that incorporates light intensity as a movement cost while accounting for seasonal variations. The dark infrastructure thus appears as an operational tool for reconciling human activities with the requirements of nocturnal conservation, to be integrated into green and blue infrastructures.

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Data Availability Statement: Data are available on request by the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ALAN Artificial Light at Night

Appendix A

Table A1. Glossary of landscape ecology and ecological network terminology.

Landscape matrix	The dominant land cover within which biodiversity nuclei (reservoirs) are embedded [6].
Core areas	Surfaces accommodating target species populations and biotopes within each thematic network. These sites require a protection status and are exclusively dedicated to nature conservation [38].
Development areas	Areas where socio-economic activities are permitted, provided they are compatible with the promotion of biodiversity development. Sites of known biodiversity interest but smaller than the minimum vital size required for the species are also considered development areas [38].
Corridors	Elements ensuring ecological continuity and connectivity between different biodiversity reservoirs within the landscape matrix. They correspond to the theoretical optimal paths that connect the reservoirs within the matrix.

Appendix B



Figure A1. Original photographs of Figure 5.

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Article

Urban Green Spaces and Their Role in Enhancing Liveability: Lessons from a Lisbon Neighbourhood During the COVID-19 Pandemic

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Abstract

Urban and population densification have resulted in deteriorating living conditions for populations and the loss of UGSs. The COVID-19 pandemic has exposed the social, economic and environmental vulnerabilities of our societies, but it has also demonstrated the importance of UGSs as intrinsic elements for maintaining the quality of life of the population and making urban spaces sustainable. Due to its considerable area of UGS, the district of Benfica in Lisbon, Portugal, is the object of study. The study focuses on understanding how the proximity of UGS influences the practice of leisure activities for different publics, and how they are reflected in the populations' lives, exploring the context during the COVID-19 pandemic. It develops a methodology with a mixed-methods approach: (1) literature review, policies, and urban planning; (2) observation methods, mapping and spatial analysis of UGS types; and (3) surveys. The empirical results indicate the importance of proximity to improve the frequency, namely for the elderly and children. The results also demonstrate that the quality (infrastructure and equipment) of UGS, despite having less walking proximity, is an important element to attract people to use the UGS. A general conclusion is that the proximity and accessibility (walking or public transport) are interlinked in both profiles of UGS, demonstrating a relationship between the place of residence, easy access and frequency of UGS in the practice of activities and the self-assessed physical and mental health benefits.

Keywords: community liveability; urban green spaces (UGSs); proximity; healthy city; COVID-19; well-being; urban planning; Benfica (Lisbon)

1. Introduction

A city is the consequence of a complex combination of features, serving as the backdrop for the daily lives of its inhabitants [1]. The swift expansion of urban areas coupled with the escalating population density, often attributed to industrialisation, has precipitated a decline in the living standards of urban populations [2–4]. This phenomenon is closely intertwined with poverty, socio-economic disparities, and the degradation of environmental integrity due to excessive resource exploitation, water and air contamination,

waste accumulation, and a reduction in green spaces [5–7]. Consequently, these factors have engendered health disparities within local communities, leading to a surge in both non-communicable and communicable diseases, as exemplified by the global health crisis of COVID-19 [8,9].

The COVID-19 pandemic has disproportionately affected vulnerable populations, such as older people and children, impacting their health, well-being, and education [7]. During this period, urban well-being became inextricably linked to what may be seen as a “new lifestyle”, characterised by quarantine measures and a shift towards remote work and education at home [5]. The lockdowns precipitated substantial alterations in individual behaviours and routines [10], amplifying the significance of domestic environments and proximity to green spaces [11].

This increased awareness of the critical role of nearby green public spaces, which emerged as intrinsic elements akin to a “space vaccine”, conferring physical and psychological benefits and enhancing urban well-being and sustainability [4,12]. Studies conducted during the COVID-19 pandemic revealed a propensity among individuals to frequent nearby green spaces, underscoring their importance.

While the World Health Organization (WHO) declared the end of the COVID-19 global health emergency on 5 May 2023 [13], the enduring threat underlines the urgency for policymakers of adopting transformative measures to mitigate the spread of infectious diseases, especially in urban green spaces (UGSs). Insights into the quality, demand dynamics, and utilisation trends of UGSs, both before and during the crisis, are indispensable for devising strategies to enhance the spatial and social functionality, foster social inclusion, and promote physical and mental health, thereby cultivating healthier, more inclusive, and integrated urban environments [14]. In the European Union member states, socio-economic and demographic nuances are reviewed in order to moderate the health and green space relationship [15] and to ensure equitable access to high-quality urban environments, including green and leisure spaces, irrespective of residential location.

Hence, the first research question is related to the assumption that green spaces contribute to the liveability of populations. In this paper, we understand “liveability” as the capacity of urban environments to support healthy, safe, inclusive and environmentally sustainable everyday life, combining physical, social and economic dimensions [15,16]. This aligns with international frameworks such as the New Leipzig Charter and the WHO Healthy Cities approach, which emphasise access to high-quality public and green spaces as core components of liveable cities [16,17]. A complementary research question is based in the assumption that the proximity of green spaces is more relevant than the quality (in terms of infrastructure and amenities) of these spaces, improving their use. The empirical verification contributes to a better understanding of, and further recommendations for, how these spaces can foster healthier and more inclusive urban environments.

While a growing body of literature has analysed the relationship between COVID-19, urban green spaces and well-being—often using large-scale datasets, mobility data or single-method approaches—there is still limited evidence from neighbourhood-scale, applied studies that integrate the spatial structure, proximity, perceived quality and everyday patterns of use in a consolidated urban context. This paper addresses this gap by providing an empirical case study from a Southern European neighbourhood, combining spatial analysis, field observation and user perceptions. By focusing on Benfica, a district characterised by a diverse green structure and a pronounced ageing profile, the study contributes planning-oriented insights into how proximity and quality jointly support liveability and well-being during and beyond the COVID-19 pandemic.

This article comprises six parts, with the first being the introduction, followed by a literature review focusing on green spaces and their relationship with a healthy environ-

ment and COVID-19. Section 3 addresses urban green spaces in Lisbon. Section 4 details the study area and methods, while Section 5 presents and discusses the results based on observations and surveys conducted in Benfica's green spaces. Section 6 presents the conclusions and recommendations.

2. Green Spaces as Health Promoters

Urbanisation and increasing population density exacerbate the challenge of access to recreational areas, contributing to physical inactivity, which is responsible for approximately 3.2 million deaths annually worldwide [17]. The availability and quality of UGSs correlate with variations in both physical and mental outcomes. Research indicates that increased access to nearby green areas significantly mitigates the mortality risk and the prevalence of chronic diseases such as stroke, asthma, diabetes, obesity, and coronary heart disease [18,19]. Moreover, exposure to green spaces, whether physical or visual (including mere contemplation through a window), is associated with improved mental health, including reduced anxiety, depression, and stress, along with enhanced cognitive functioning, attention, creativity, mood, and overall psychological well-being [18–20].

Notably, children, particularly females, benefit from the utilisation of nearby green spaces, exhibiting better concentration, discipline, and functional performance in daily activities. The positive effects of physical activity extend beyond the physical–functional domains, encompassing mental and social dimensions, thereby bolstering individual resilience against physiological and psychological stressors. Conversely, the absence of contact with natural spaces heightens the risk of mental disorders [21].

Children and older adults particularly benefit from regular use of nearby UGSs, showing better functional performance and resilience to stressors, whereas lack of contact with nature has been associated with an increased risk of mental disorders [21].

Theoretical Framework: Restorative Theories and Well-Being

The conceptual foundation of this research builds on two complementary models that explain the restorative potential of contact with nature: the Attention Restoration Theory (ART) by Kaplan and Kaplan (1995) [22] and the Stress Recovery Theory (SRT) by Ulrich (1983) [23]. Both describe how natural environments help restore depleted cognitive and emotional resources, thereby contributing to mental well-being [24].

According to the ART, daily exposure to stressors such as traffic, crowding, or noise leads to attentional fatigue, which can be alleviated by experiences of “soft fascination” in nature that effortlessly capture attention and allow mental recovery [18]. Brief exposure—sometimes under ten minutes—has been shown to improve concentration and reduce mental fatigue [25].

In this study, these theories provide the interpretive basis for understanding users' perceptions of well-being and health improvement. The reported benefits—especially stress reduction, mood improvement, and cognitive relaxation—observed among survey respondents confirm that proximity to green spaces fosters restoration processes consistent with the ART and SRT assumptions.

The SRT, on the other hand, focuses on emotional and physiological responses [22], showing that visual and sensory contact with vegetation, water, and natural light can reduce stress indicators and promote positive affect. Ulrich does not specifically detail the spatial configurations of a restorative environment but reinforces the increasing importance of exposure to natural environments—given the innate human inclination towards such [26]—given the impacts of disruptive events and adversity imposed by daily life on modern humans [27]. Recent studies have expanded these theoretical perspectives, confirming

that biodiversity, multisensory experiences, and micro-scale green areas can significantly enhance mental restoration and stress recovery in urban contexts [28].

Beyond these general mechanisms, evidence suggests that the degree of naturalness and management of urban green spaces (UGSs) shapes their restorative value. More “natural” spaces tend to foster attentional restoration and stress recovery, whereas more “managed” parks enhance the perceived safety, routine use, and social interaction—both supporting well-being through complementary pathways.

The efficacy of UGSs in promoting health depends on the exposure frequency, duration, and intensity, which are contingent on UGS availability and disposition [29]. Exposure can be measured in three ways: frequency (i.e., how often one visits an UGS), duration (i.e., how long a visit to an UGS lasts), and intensity (i.e., what activity can be performed during a visit). The provision of UGSs can also be measured in three ways: quantity (i.e., how many UGSs exist in each geographical area), quality (i.e., how qualitatively attractive an UGS is), and accessibility (i.e., access to the UGS, free or paid, and geographically close or far from where people live) [30].

Beyond the quantity and accessibility, several authors have operationalised UGS quality through attributes such as the safety, cleanliness, maintenance, aesthetics, comfort, lighting, and availability of facilities. These perceived quality dimensions strongly influence both the frequency of visits and the magnitude of physical and mental health benefits associated with UGS use, particularly for stress reduction, social interaction, and perceived safety among vulnerable groups. These indicators are widely used in international UGS quality frameworks and public health assessments [19,31,32]. In this study, these dimensions provide the conceptual basis for the empirical evaluation of Benfica’s UGSs.

3. The Concept of Urban Green Space and Its Association with the Portuguese Context

The concept of UGS has presented changes throughout history, essentially associated with the evolution of the city. These spaces are then located within the urban boundary and are defined as open spaces of public or private domain, covered by permeable surfaces, soil [31,33] or referring to all forms of vegetation. These spaces play a crucial role in shaping liveable cities, denoting environments that are safe, clean, aesthetically pleasing, economically vibrant, accessible to diverse populations, efficiently managed, and imbued with a sense of community. UGSs encompass a diverse array of areas, including formal parks, green roofs, woodlands, community gardens, lawns, sports fields, shrubbery, and ornamental plant arrangements. Additionally, they can encompass more informal and seemingly neglected areas such as vacant lots, spaces along highways and railways, pavements, and abandoned properties [14,31,34].

UGSs assume varied characteristics and dimensions, as well as a variety of uses and functions. A set of dimensions can characterise them: localisation, size, function, quality and safety, distance from users and intended publics, besides being related to the landscape quality and user perception [18]. Green land uses in urban areas have been studied extensively for their contributions to urban quality of life [35], as part of the urban green infrastructure [31].

The green structure of urban areas comprises main and secondary substructures. The main structure comprises spaces with varying densities of vegetation, offering a multitude of services and amenities to attract users from different social and age groups. This structure includes a diverse range of typologies, such as gardens, parks, sports areas, urban gardens, and specialised enclosures like zoos and exhibition parks. Conversely, the secondary green structure consists of public spaces adjacent to residential, service, and economic

areas, forming smaller, neighbourhood-oriented spaces (called proximity or neighbourhood UGSs) catering to the local population within a walking distance of up to 400 m [36].

In Lisbon, the Municipal Master Plan of 2020 delineates the Municipal Ecological Structure, which includes the Fundamental Ecological Structure at the metropolitan level and the Integrated Ecological Structure at the municipal level. The former includes corridors and wetland systems, while the latter features green spaces. These spaces are categorised as follows:

- Recreation and production: Permeable areas designated for urban agriculture and recreational activities, including collective amenities and infrastructure for leisure and tourism.
- Protection and conservation: Areas dedicated to conserving ecosystems, habitats, and valuable vegetation, with restrictions on construction except for recreational support and fire-control infrastructure.
- Road infrastructure frames: Spaces under different levels of restriction that only allow support facilities.
- Riverside spaces: Areas providing ecological balance and recreational opportunities, ensuring pedestrian access to riverbanks and landscape enjoyment.

In Lisbon, UGSs such as parks and gardens are recognised in the city's Municipal Master Plan (PDM/Plano Diretor Municipal) [37] as essential for improving the quality of life of residents and supporting environmental sustainability. These spaces contribute to urban resilience by improving air quality, promoting biodiversity, and providing areas for recreation. Ensuring equitable access to these areas is a priority outlined in the PDM, reflecting Lisbon's commitment to creating a more sustainable and liveable urban environment.

Furthermore, Lisbon's Plano Verde (Green Plan, 2020) [38] and the Urban Biodiversity Strategy reinforce the PDM's objectives by establishing a continuous ecological network that integrates the main and secondary green structures. These instruments promote connectivity between parks, gardens, and neighbourhood green corridors, following the principles of the Healthy Cities initiative and the European Green Capital 2020 programme. In Benfica, this policy framework guides the requalification of local parks such as Silva Porto and Quinta da Granja, ensuring equitable access to safe, inclusive, and multifunctional spaces. By embedding ecological and social functions into spatial planning, Lisbon aims to enhance the physical and mental well-being of residents and contribute to climate resilience at the neighbourhood scale. Lisbon's green planning strategy aligns with transdisciplinary approaches that integrate ecological, social, and health dimensions of urban infrastructure [39]. In recent years, several municipal and community-led initiatives have contributed to the diversification and improvement of Lisbon's green infrastructure. Examples include Agrofloresta de Campolide—Bela Flor Respira, which transformed a degraded hillside into an agroforestry park through community participation, and Vale do Casal Vitoso Urban Forest, a reforestation project that promoted biodiversity and climate resilience. In addition, the Green Corridor of Monsanto has been extended to improve the pedestrian and ecological connections across the city. These initiatives illustrate Lisbon's ongoing commitment to expanding and regenerating its green spaces in response to the climate crisis [38,40,41].

4. Study Area and Methodology

This study focuses on Benfica, a district in the municipality of Lisbon, and examines the impact of its UGSs on residents' quality of life. Covering 8.02 km², Benfica constitutes 9.5% of Lisbon's total area and is part of the city's Northwest Zone (Figure 1).

Originally a rural village connected by a suburban railway, Benfica has evolved into a densely populated district with significant socio-spatial diversity, community engagement, and potential for urban centrality.

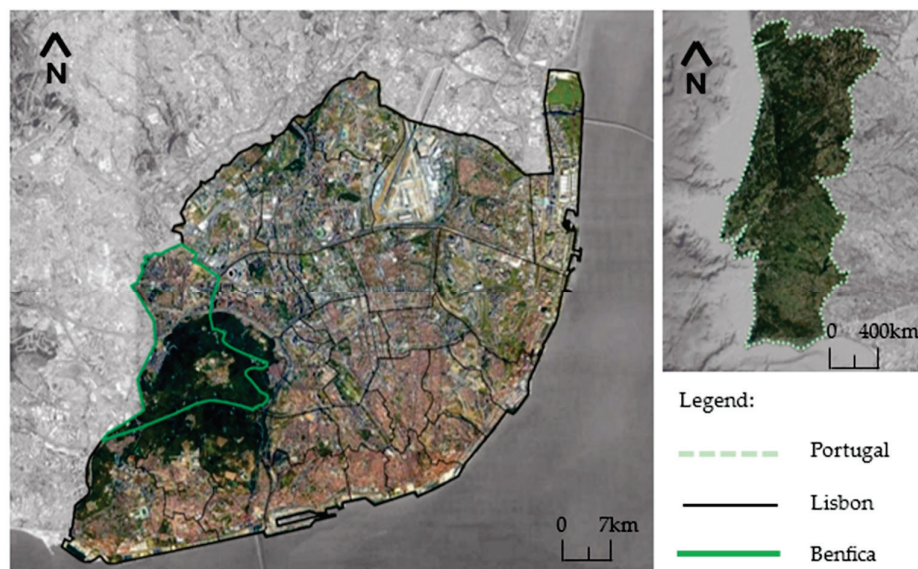


Figure 1. Geographic framing of the study area. Location of the municipality of Lisbon with all the districts. Benfica is highlighted in dark grey. Source: [5].

Aligned with European and Portuguese demographics, Benfica has experienced a population decline over the past decade. In 2021, Benfica had a population density of 4409.2 inhabitants/km², compared to 5455.2 inhabitants/km² in Lisbon. Between 2011 and 2021, Benfica's population decreased by about 4%, accompanied by clear signs of ageing. The share of residents aged 75 and older rose from 13.6% to 17.2%, while the working-age group slightly declined. Women remain the majority (55.3%), particularly among the older age groups. These demographic shifts underline the growing importance of accessible and inclusive urban green spaces for elderly residents (Tables 1 and 2).

Table 1. Demographic characterisation of Portugal, Lisbon, and Benfica. Source: [42,43].

Data Reference Period	Place of Residence	Total Resident Population N. °	Population Change 2011–2021 %	Population Density (Inhab./km ²)	Youth Dependency Ratio N. °	Elderly Dependency Ratio N. °
2011	Portugal	10,562,178	−2.03	114.5	22.5	28.8
	Lisbon	547,733	−0.53	6448.2	20.4	37.8
	Benfica	36,821	−4.19	4639.5	18.4	48.2
2021	Portugal	10,347,892	-	112.2	not available	
	Lisbon	544,851	-	5455.23		
	Benfica	35,362	-	4409.23		

Table 2. Population living in Benfica by age group and gender. Source: [44,45].

Data Reference Period	Age Groups	Number of Residents			%	Gender	
		Inhabitants	Gender Male	Female		Male	Female
2011	0 to 14 years	4062	2097	1965	11%	5.70%	5.34%
	15 to 24 years	3380	1687	1693	9.18%	4.58%	4.60%
	25 to 64 years	18,725	8496	10,229	50.85%	23.07%	27.78%
	65 to 74 years	5633	2349	3284	15.30%	6.38%	8.92%
	75 and older	5021	1858	3163	13.64%	5.05%	8.59%
	Total	36,821	16,487	20,334	100%	44.78%	55.22%

Table 2. Cont.

Data Reference Period	Age Groups	Number of Residents			%		
		Inhabitants	Gender Male	Female	Inhabitants	Gender Male	Female
2021	0 to 14 years	4101	2115	1986	11.6%	6.00%	5.60%
	15 to 24 years	3193	1579	1614	9.0%	4.50%	4.60%
	25 to 64 years	17,593	8170	9423	49.8%	23.10%	26.60%
	65 to 74 years	4399	1719	2680	12.4%	4.90%	7.60%
	75 and older	6076	2225	3851	17.2%	6.30%	10.90%
	Total	35,362	15,808	19,554	100%	44.70%	55.30%

This demographic shift has been accompanied by a significant increase in the ageing population, with the elderly dependency ratio reaching 48.2 (Table 1).

This study employed a mixed-methods approach, combining quantitative and qualitative techniques to assess the UGSs in Benfica. The methodology included the following:

- Cartographic observation: Mapping of UGSs using geographic information systems (GISs) to identify the spatial distribution and typologies.
- Quantitative surveys: Structured surveys were conducted with UGS users to collect data on demographics, usage patterns, and health impacts. The survey included 80% closed questions on the frequency of use, reasons for visiting, and perceived health benefits. A total of 120 surveys were conducted from August to September 2021, via on-site intercept sampling with voluntary participation, across different locations, days, and time periods. Approximately 20 surveys were conducted in each of the six analysed urban green spaces, ensuring balanced representation across different locations within Benfica.
- The questionnaire comprised 25 questions divided into three thematic blocks: (1) users' socio-demographic profile; (2) patterns of use—frequency, duration, activities, and travel modes; and (3) self-perceived health and well-being before, during, and after the COVID-19 restrictions. Although the questionnaire did not ask for the exact home-to-UGS distance, proximity was indirectly captured through respondents' reported mode of access (predominantly walking) and travel time to each park. These indicators are commonly used as proxies for walkable proximity in urban green space studies. A five-point Likert scale was applied to evaluate the perceived quality attributes, such as cleanliness, safety, maintenance, comfort, lighting, and diversity of facilities. These quality indicators were not defined arbitrarily; rather, they were adapted from established frameworks in the literature that identify the perceived safety, cleanliness, maintenance, comfort, lighting, and availability of facilities as core determinants of UGS quality and restorativeness. These parameters have been shown to influence usage patterns, perceived well-being, and the likelihood of experiencing restorative benefits in urban green environments [18,19,31]. Accordingly, our survey grid translated these theoretically grounded quality dimensions into an operational tool adapted to the Benfica context. Surveys were conducted in six UGSs across Benfica on weekdays and the weekends between them, covering different times of the day. Although the sampling strategy was designed as simple random sampling, participation relied on voluntary availability, which is consistent with an on-site intercept sampling approach commonly used in neighbourhood-scale exploratory studies. Although participation was voluntary, on-site observation revealed that most respondents were habitual users of the selected UGSs, regularly visiting these spaces before, during and after the COVID-19 restrictions. This constraint limits the application of inferential statistical tests; however, the approach remains methodologically robust and appropriate for an exploratory, neighbourhood-scale case study focused on usage patterns

and user perceptions rather than statistical generalisation. This reduces the likelihood that the survey captured only occasional or COVID-19-specific visitors. Nevertheless, the diversity of sites and schedules ensured representativeness across age and gender groups, enabling reliable characterisation of the usage patterns. Similar post-lockdown studies have confirmed that the frequency of visits to nearby green areas is closely related to psychological recovery and life satisfaction across user groups [46,47].

- Qualitative observations: On-site observations of UGSs were conducted to evaluate the accessibility, infrastructure, and variety of activities offered. This involved examining both internal and external access, maintenance quality, and user interactions. The qualitative observations were based on a grid that traduced these aspects, as translated into Tables 3 and 4.

Table 3. Summary of the urban green structure in Benfica. Source: [5,36].

Definition of Existing Typologies in Benfica		Identification of Spaces Under Study	Area	Size	Base Pop. (inhab.)	Diversity of Uses	Types of Vegetation
MGS	Free Sports	-	≥ 5 inha	20 m ² /inab.	10,000	Sectors of leisure and recreation	Not applicable
	Urban Park and Garden	Silva Porto Park; Quinta da Granja Urban Park; Eucaliptal Garden; Baldaya Palace Garden;	≥ 3 inha		10,000	Sectors for leisure, rest, and recreation (playgrounds, cultural activities); isolated from noise ³	Diversified, long-lasting, forest, vegetation, natural. Clumps of bushes, meadows, and lawns.
	Garden Park	Quinta da Granja Urban Park	200 m ² /each		10,000	Sectors of leisure and rest; secluded from noise ³	Diversified, plants, vegetables, fruit trees, intuitive.
	Picnic Park	Silva Porto Park	-		-	Sectors of leisure and recreation ³	Varied, landscaped, shade trees.
	Urban Green Corridors	-	-	-	-	-	Diversified, long-lasting, forest, vegetation, natural, clumps of bushes, meadow, lawns.
SGS	Proximity Green spaces ¹	Charquinho's Garden	Variable	10 m ² /inab.	2500	Sectors for leisure, recreation, and rest; isolated from noise ³	Diversified long-lasting, garden, shrubs, lawns, shady trees.
	Proximity Green spaces ²	Maria's Garden			-	Sectors for leisure, recreation, and rest; isolated from noise ³	Varied, hard-wearing, garden, vegetables, fruit trees, intuitive.

Notes: ¹ located up to 400 m; ² located up to 100 m; ³ does not allow car circulation. MGS—main green structure; SGS—secondary green structure.

While Benfica includes a significant portion of the Monsanto Forest Park, the primary focus of this study was on urban parks such as Silva Porto Park, Quinta da Granja Urban Park, Baldaya Palace Gardens, Maria's Garden, Eucaliptal Garden, and Charquinho's Garden (Figure 2).

This district represents a particularly unique area within Lisbon's green infrastructure, as part of its territory is occupied by the extensive Monsanto Forest Park—the largest green area in the city—which establishes physical and ecological continuity with the neighbouring parish of São Domingos de Benfica and the adjacent municipality of Amadora. This connection functions as a metropolitan green corridor, linking Benfica's local urban parks to the wider ecological and recreational network of Lisbon. These inter-district linkages enhance accessibility to green spaces and reinforce Benfica's strategic role in the city's green structure.

Table 4. Accessibility and mobility parameters of the analysed UGSs in Benfica, based on field observation and user surveys. Source: [5].

Accessibility and Mobility	Silva Porto Park		Quinta da Granja Urban Park		Eucaliptal Garden		Baldaya Palace Gardens		Charquinho's Garden		Maria's Garden	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Free access	x		x		x		x		x		x	
Paid access		x		x		x		x		x		x
Easy access to the park	x		x		x		x		x		x	
Internal accessibility		x	x			x	x		x		x	
Lifts		x		x		x		x		x		x
Lifting platform		x		x		x		x		x		x
High traffic intensity on surrounding roads		x	x		x		x			x	x	
Nearby access/stops												
Bus	x		x		x		x			x	x	
Bicycle use is allowed		x	x			x	x		x			x
Easy access on foot		x	x		x		x		x		x	
Areas for pedestrian walks	x		x		x		x		x		x	

Note 1: “x” indicates the presence or availability of the corresponding accessibility or mobility feature. Note 2: Accessibility refers to physical access (paths, slopes, internal routes) and user mobility within each UGS.

**Figure 2.** Examples of the analysed urban green spaces (UGSs) in Benfica: Silva Porto Park, Quinta da Granja Urban Park, and Baldaya Palace Garden. Source: [5].

5. Results and Discussion

Benfica stands out from most of the residential neighbourhoods in Lisbon in terms of the value, number, and diversity of UGSs, including historical areas such as Quinta da Granja, smaller public spaces, and heritage sites like the Baldaya Palace Garden and Monsanto Forest Park. The latter, the largest UGS, covers approximately 1000 ha citywide and 400 ha within Benfica. Cartographic observation reveals that Benfica's existing green space structure comprises a diverse set of urban green space typologies, classified into main and secondary green structures and detailed according to specific functional categories, as shown in Figure 3 and Table 3.

The analysis of Benfica's UGSs included (i) spatial identification and classification of green spaces by typology and green structure (Figure 3) and (ii) assessment of the minimum green area requirements per inhabitant (Table 3).

The cartographic analysis reveals that Benfica's green space structure covers approximately 4.5 km², representing 56% of the urban surface. The per capita green area is 127.55 m², reinforcing the effectiveness of UGSs in providing public health benefits. Most of this area is attributed to Monsanto Forest Park. Comparative analysis with other studies shows that Benfica's UGSs provide a high per capita green area relative to other European urban areas. However, the distribution of UGSs shows discrepancies between the northern and southern parts of the district, indicating the need for equitable urban planning to maximise access to UGSs.

Table 3 provides a detailed description of the different UGS types in the study area, based on a grid.

Benfica features a diverse network of urban green corridors, including tree-lined pavements and central separators that connect the urban fabric. Gardens and smaller landscaped spaces enhance the green continuum principle, whilst parks, being large, continuous green spaces, support urban landscapes and improve the quality of public space. Comparable patterns were identified in international studies, where pocket parks, greenways and multifunctional spaces played complementary roles in enhancing well-being during and after the COVID-19 pandemic [48,49].

The application of the chosen methodology matches the research purpose, as Benfica's green structure was analysed in order to understand the interaction between individuals and green public spaces. The parameters examined include "accessibility and mobility" and the "activities available" at each site.

Public spaces in Portugal are freely open to community use, as are UGSs (Table 4). In Benfica, they can be accessed by various modes (walking, soft mobility, private vehicle, or public transport), except for Charquinho's Garden, which is primarily accessible on foot. Benfica benefits from the proximity of the Sintra railway line, which strengthens the interconnection between locations.

Accessibility was assessed by parameters such as the ease of access, proximity, and internal accessibility. Internal accessibility issues were noted in parks such as Silva Porto Park and Eucaliptal Garden, where age-related challenges and lack of ramps impact usability, indicating a critical need to improve access and ensure equitable use. Silva Porto Park and Eucaliptal Garden also exhibit negative aspects owing to age-related challenges and steep slopes lacking ramps, handrails, and tactile paving.

It was observed that the Eucaliptal Garden's playground could be improved by repairing the pavement or even its substitution by a softer material. These findings align with those of various research studies, which also emphasise the importance of accessibility in ensuring equitable use of urban green spaces. Recommendations include improving infrastructure to enhance accessibility and maintenance. Ensuring accessibility enhances inclusion and quality of life, which should be considered in future improvements.

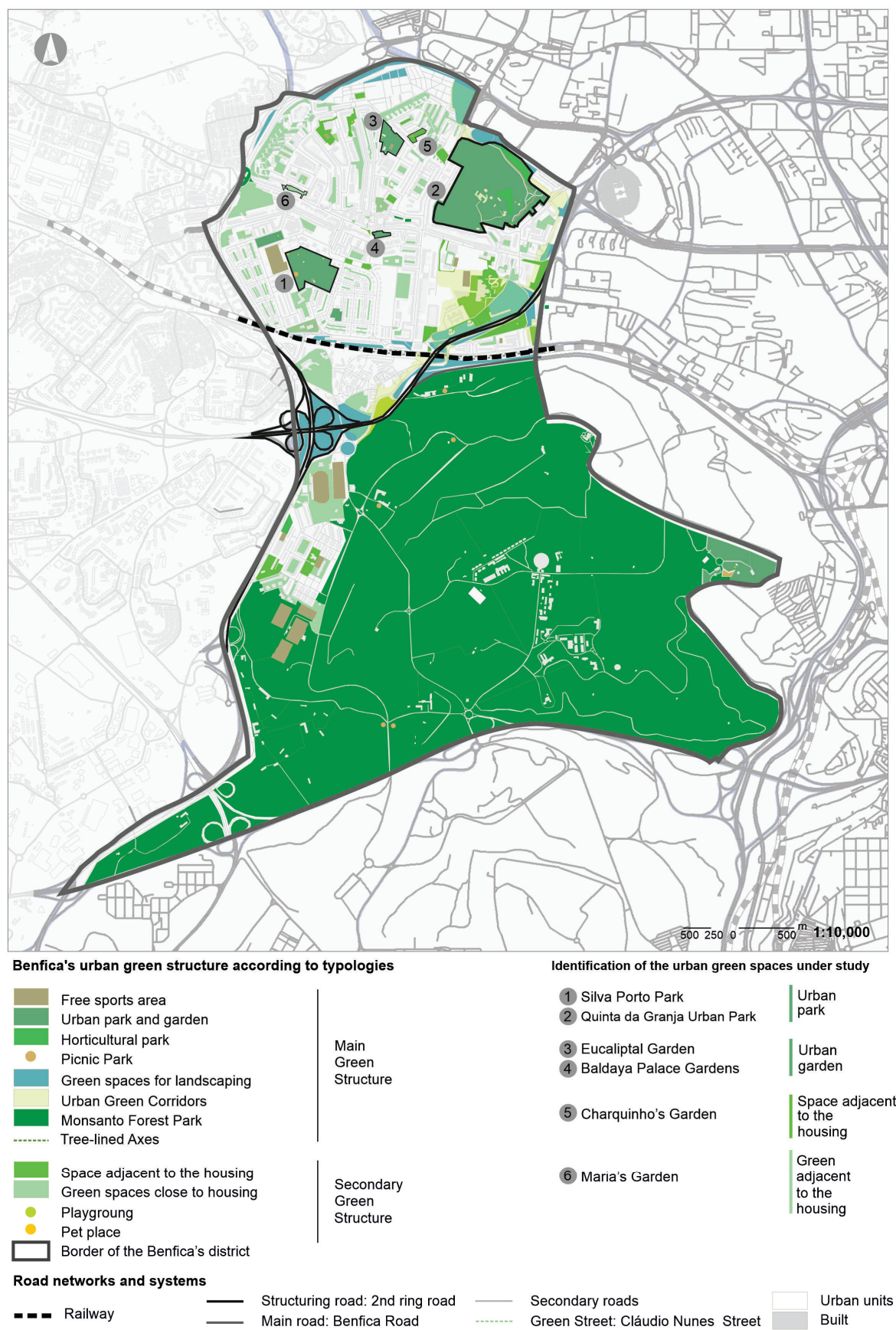


Figure 3. Typology of Benfica's UGSs and identification of the UGSs under study. Source: [5].

The diversity of amenities offered in Benfica's UGSs is linked to the available infrastructure and equipment. Thus, all the UGSs include pedestrian spaces, with Silva Porto Park and Quinta da Granja Urban Park offering the highest variety of activities, although they lack specific amenities like cycling spaces and pet-friendly areas (Table 5).

Table 5. Activities that can be carried out in UGSs in Benfica. Source: [5].

Activities that Can Be Conducted	Silva Porto Park		Quinta da Granja Urban Park		Eucaliptal Garden		Baldaya Palace Gardens		Charquinho's Garden		Maria's Garden	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Space for hiking	x		x		x		x		x		x	
Cycling space		x	x			x		x		x		x
Space for sports practice	x		x		x			x	x			x
Activities organised for groups	x		x		x		x		x			x
Playground	x		x		x			x		x		x
Pet-friendly spaces	x			x		x		x		x		x

Note 1: An "x" indicates the presence or availability of the corresponding activity in each urban green space, as identified through field observation. Note 2: The diversity of activities complements perceived quality attributes such as comfort, maintenance, and safety.

The activities listed in Table 5, combined with the accessibility and quality parameters, formed the basis for the subsequent evaluation of user satisfaction and perceived well-being. Eucaliptal Garden lacks cycling and pet spaces but features a popular playground, in contrast to Charquinho Garden, which includes sports facilities but lacks a playground. Meanwhile, Baldaya Palace Garden and Maria's Garden are both unsuitable for sports and primarily serve pedestrian use. Users seek stimulating and pleasant spaces that are easily navigable and well-integrated. The quality indicators assessed in this study reflect internationally recognised dimensions of UGS quality, such as safety, cleanliness, comfort, lighting, maintenance, and diversity of facilities. These attributes correspond to established frameworks demonstrating that perceived safety and adequate infrastructure are prerequisites for users to experience restorative and health benefits in urban green settings [18,19,31]. The consistency between users' satisfaction scores and these theoretical dimensions reinforces the relevance of evaluating UGS quality as a multidimensional concept. Benfica's UGSs offer diverse possibilities, catering to various user needs and providing physical and mental health benefits, whilst the urban structure of Benfica also supports a range of recreational options, contributing to overall well-being and social interaction.

The survey complemented the observation grid by examining user demographics, usage patterns, and health impacts. The analysis focused on the (i) age distribution of UGS users, (ii) frequency of UGS utilisation and reasons for selecting these spaces, and (iii) health impact of UGS usage before and after the COVID-19 pandemic.

Most respondents were working-age adults (76.7%), with a notable presence of individuals aged 25 to 34 years (25.83%) and 35 to 44 years (20%). In contrast, younger age groups (18–24 years) and children (under 18) were less represented (11.67% and 1.67%, respectively). The user demographics reflect the general trends of the district, with UGSs typically frequented by nearby residents. Most respondents accessed the UGSs on foot, indicating short travel distances between their homes and the green areas. This functional proximity, inferred from the mode of access and frequency of visits, supports the interpretation that accessible UGSs contribute to residents' perceived well-being. The survey results indicate that working-age adults (76.7%) are the primary users of UGSs, with a high frequency of daily visits to spaces such as Quinta da Granja Urban Park and Eucaliptal Garden. The usage patterns reflect the proximity of UGSs to users' residences, with frequent visitors

typically spending shorter periods in their local spaces. Comparison of these findings with studies that show that proximity and accessibility influence green space usage highlights the need for improved integration of UGSs into daily life to maximise their health benefits.

The frequency of UGS use (Figure 4) data show that most respondents visited daily, with Quinta da Granja Urban Park, Eucaliptal Garden, Baldaya Palace Garden, Charquinho Garden, and Maria's Garden each reporting high daily visit rates. Weekly visits were reported by 41% of respondents, notably at Silva Porto Park (50%).

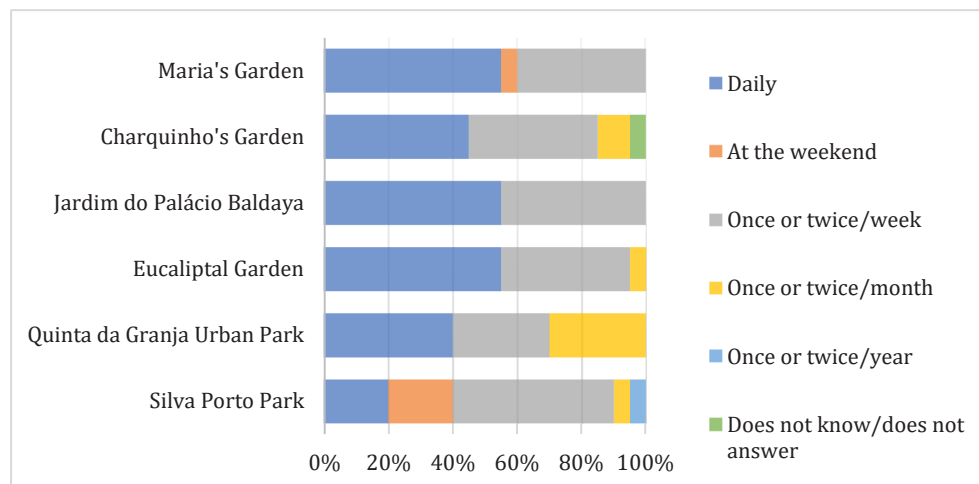


Figure 4. Frequency of use of UGSs in Benfica. Source: [5].

With regard to the age range (Figure 5), older groups tend to use UGSs every day, whereas individuals aged 25 to 44 visit these spaces once or twice a week, probably on their free days or weekends. This is likely due to differences in time availability.

A significant number of visitors (40%) spend almost an hour in Silva Porto Park, while the urban agricultural activities of Quinta da Granja result in 35% of users spending over 120 min there. Visitors to the Eucaliptal Garden show varied usage patterns, with significant time spent on both physical and non-physical activities. Users were concentrated in three categories—between 20 and 40 min (25%), based on sports activities; between 61 and 90 min (25%); and between 91 and 120 min (25%), spent on both non-physical recreational activities such as reading and playing cards and using the restaurant infrastructure. A similar situation was observed in the Baldaya Palace Garden, which also has a café and restaurant that encourage people to stay for 41–60 min (25%) and 61–90 min (25%), respectively.

The diverse uses of UGSs cater to various user interests. Notably, the category “other”, encompassing activities such as socialising with friends, reading or studying, and engaging in sports, was prominently represented at Quinta da Granja Urban Park, accounting for 31%. This category is particularly associated with activities unique to this park, including the vegetable garden and cycling facilities.

Although many studies mention the benefits of UGSs for physical health through participation in physical activities, this study reveals that the frequency and reasons why visitors like these spaces are related, in the case of most UGSs, to low-physical-intensity activities (Figures 5 and 6). Thus, it is not only the number of UGSs that appears to be important but also their location (proximity) and accessibility as well as the diversity of available activities that allow users to enjoy moments of leisure and well-being and obtain the associated health benefits.

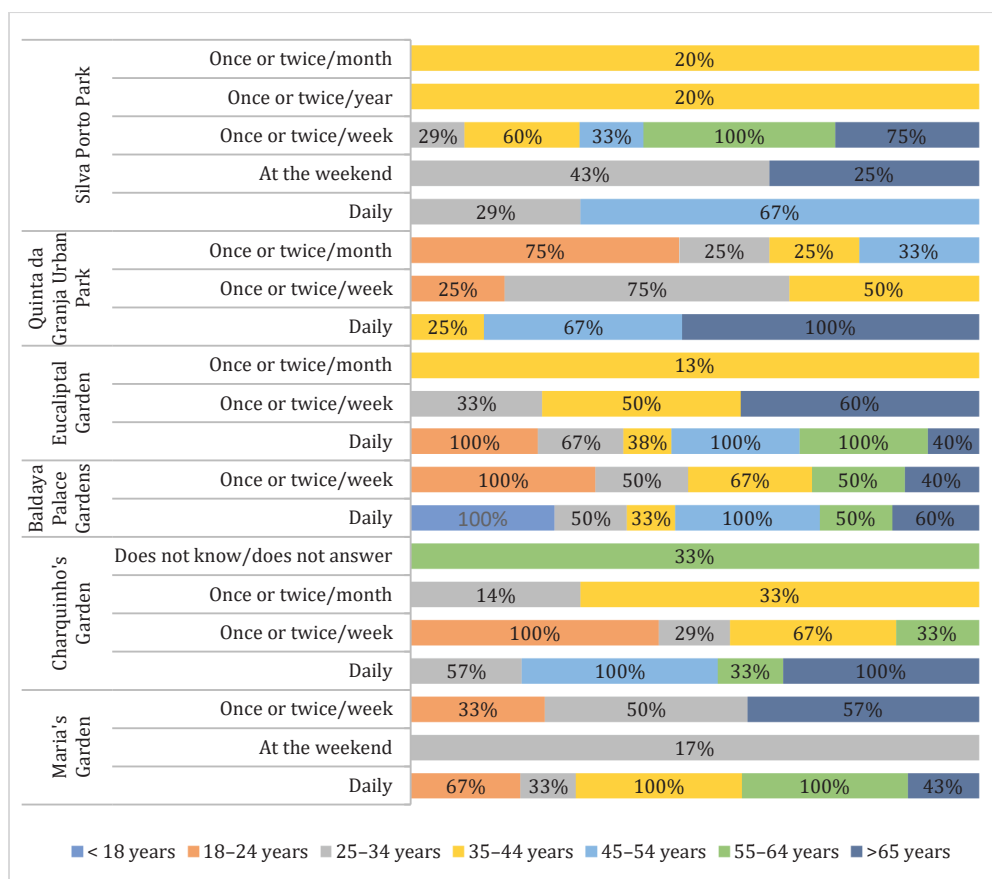


Figure 5. Frequency of UGS use by age in Benfica. Source: [5].

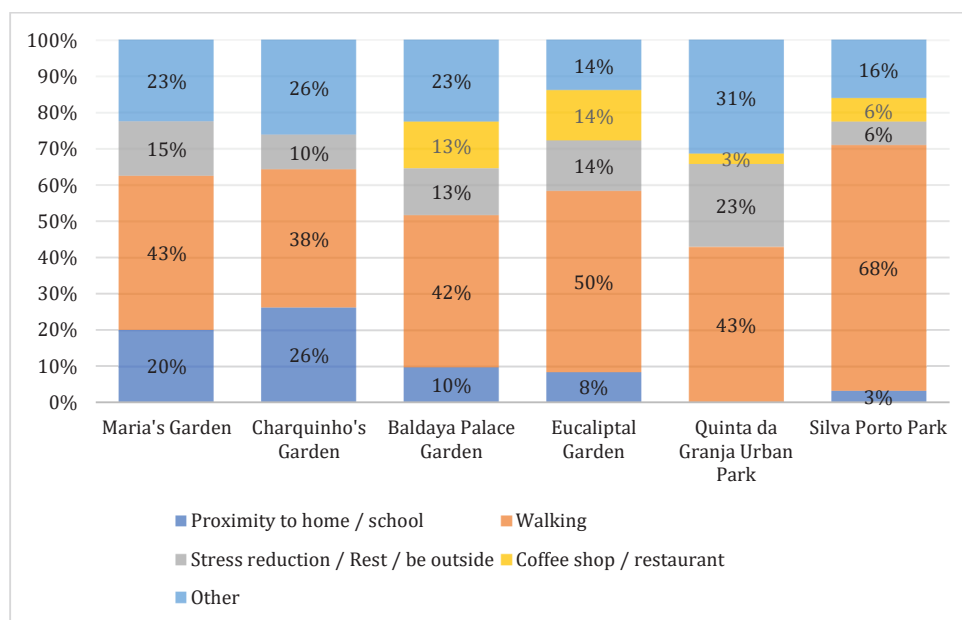


Figure 6. Main reasons for choosing to visit UGSs in Benfica. Source: [5].

Since several authors have demonstrated that UGSs play a crucial role in promoting a good quality of life [38,50], users were also asked to self-assess the impact of UGSs on their health, particularly during and after the COVID-19 pandemic. During the pandemic, UGSs provided essential physical and mental health benefits, especially for the elderly. While some spaces, such as Silva Porto Park and Baldaya Palace Garden, were closed

during the period of confinement, many users reported an increase in visits to UGSs once the restrictions were lifted, accompanied by high satisfaction scores regarding the impact of UGSs on their physical and mental health (Figure 7). Hence, this study confirms that UGSs contributed significantly to both physical and mental health, particularly post-pandemic, as users continued to value their benefits for their overall well-being even after the lockdown. These findings can also be interpreted through the lens of restorative theories. The frequent motivations of “stress reduction”, “rest” and “being outside” correspond to the emotional and psychophysiological mechanisms described by the Stress Recovery Theory (SRT), where natural environments reduce stress responses and promote emotional regulation. Simultaneously, the predominance of low-intensity activities such as walking, contemplation, reading or sitting aligns with the Attention Restoration Theory (ART), as these activities involve “soft fascination” and support cognitive restoration. The reported improvements in mood, relaxation, and concentration—particularly among elderly and frequent users—demonstrate that Benfca’s UGSs enable both stress recovery and attention restoration in everyday conditions. Thus, residents’ behaviours and feelings empirically confirm the key assumptions of these theoretical models in a post-pandemic Southern European context.

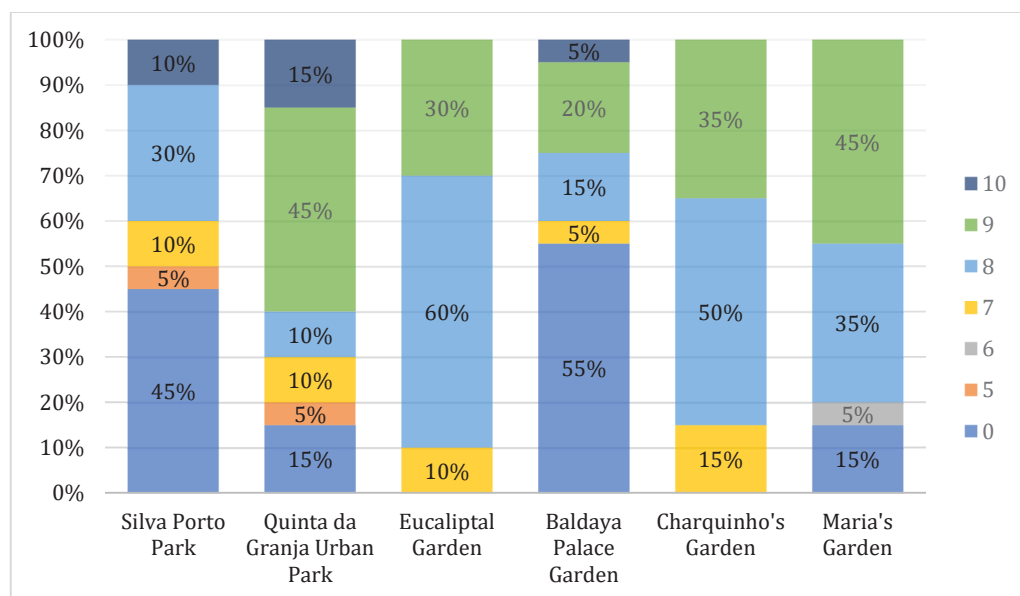


Figure 7. Evaluation of Benfca’s UGSs’ contributions to users’ physical and mental health during the COVID-19 confinement period, in percentages. Source: [5].

Additionally, the overall assessment indicates that UGSs are crucial for mental health, benefiting all age groups. Generally, the local UGSs were deemed sufficient, while community-driven UGS initiatives, such as in Maria’s Garden, received more positive feedback and could be expanded to other areas.

While Benfca’s UGSs have a positive impact on residents, evolving community needs should be addressed when making adjustments or during maintenance. Thus, enhancements are proposed to improve usage, foster interpersonal and intergenerational relationships, and enhance the district’s “healthy” and “human” dimensions. To effectively manage UGSs in the post-pandemic context, it is crucial to adopt an integrated, participatory approach involving community stakeholders [51]. UGSs are key to the Healthy City framework, which supports both physical and social environments to maximise human potential. The proposed interventions include reinforcing the green network, creating new UGSs, and enhancing existing ones, whilst the recommendations aim to address coverage

gaps, increase the green space per inhabitant, and expand vegetation in underutilised areas or those negatively impacting the urban fabric, particularly in response to the challenges posed by the COVID-19 pandemic (Table 6).

Table 6. Proposals for enhancing UGSs in Benfica. Source: [5].

Main Theme/ Sub-Recommendation	Objective/ Expected Effect	Source of Evidence
1. Repair and reinforce the quality of UGSs		
1.1 Increase vegetation cover in Quinta da Granja, Charquinho's Garden, Maria's Garden and Eucaliptal Garden	Strengthen green and blue resources; improve ecological resilience	Field observation: low vegetation density and limited biodiversity in these UGSs.
1.2 Implement "scented trails" and herb/vegetable beds in Eucaliptal and Charquinho's Gardens	Enhance sensory experience and biodiversity	Survey: users value relaxing, multisensory experiences (stress reduction, rest); observation: underused peripheral areas suitable for sensory planting and literature review.
1.3 Utilise water mirrors and rainwater systems in selected UGSs	Promote biodiversity and climate adaptation	Observation: lack of shade and water elements; survey: users associate freshness and tranquillity with comfort.
2. Promote social interaction through nature-based activities	Organise community days and horticulture workshops to foster inclusion and well-being	Survey high interest in social and collective activities; observation: few organised events currently available and literature review.
3. Establish green pedestrian routes between buildings and UGSs	Create continuous walkable links; enhance accessibility and integration	Survey: predominance of elderly users and walkers; observation: discontinuous or steep access paths.
4. Expand UGSs by integrating adjacent buildings	Reuse disused buildings (e.g., Eucaliptal and Baldaya Palace Gardens) for community purposes	Field observation: presence of underused facilities near UGSs; survey: demand for indoor meeting or cultural spaces and literature review.
5. Improve accessibility	Ensure all residents can easily reach and enjoy UGSs	Survey: elderly users report mobility difficulties; observation: barriers such as slopes and missing ramps.
6. Enhance safety and quality	Improve lighting, comfort, maintenance, and cleanliness to create a welcoming environment	Survey: lower scores for lighting and maintenance; observation: uneven surfaces and worn furniture.
7. Explore and connect infrastructure and culture		
7.1 Promote sports and sociocultural activities (e.g., fitness classes in Eucaliptal Garden)	Encourage community engagement and healthy lifestyles	Survey: strong interest in physical activity and cultural events; observation: existing open areas suitable for classes.
7.2 Enable integration of domestic animals (e.g., dog parks in Quinta da Granja and Eucaliptal Garden)	Improve inclusiveness for pet owners and reduce conflicts of use	Survey: demand for pet-friendly areas; observation: absence of designated spaces.
8. Increase diversity of equipment and services	Introduce cafés, kiosks, and small commerce to enhance user experience and satisfaction	Survey: users highlight cafés and rest areas as important quality attributes; observation: limited-service offer and literature review

The timing of the data collection, in the late phase of the COVID-19 pandemic (August–September 2021), influenced users' behaviour and perception. Many respondents reported an increased need for outdoor recreation after prolonged confinement, associating green spaces with emotional relief and social reconnection. This contextual factor partly explains the higher visitation rates recorded among the elderly and families with children. The findings suggest that proximity to safe and well-maintained UGSs was crucial for psychological resilience during and immediately after the lockdown periods, reaffirming their role as public health infrastructures.

6. Conclusions

Urban environments are in a constant process of transformation to meet the physical and psychological needs of their inhabitants, increasingly emphasising the creation of healthy spaces that enhance overall well-being. Urban green spaces (UGSs) are vital to this endeavour, serving as indicators of environmental, economic, and social quality, thereby contributing to quality of life.

The reduction in natural areas within urban settings has fostered a disconnect between people and nature, reinforcing the need to promote access to UGSs as a public health priority. In contrast, exposure to nature provides numerous benefits for human well-being, underscoring the necessity of interventions that promote access to UGSs as a public health priority. The COVID-19 pandemic has amplified awareness of social and environmental issues, further underscoring the importance of UGSs during times of confinement. The pandemic has significantly altered behaviours and perceptions, highlighting the necessity of understanding how users evaluate the quality and quantity of UGSs.

This study focused on the impact of proximity to UGSs on activities across various demographic groups and its influence on the overall well-being of the population, specifically in the Benfca District of Lisbon, Portugal. Utilising a mixed-methods approach that integrated qualitative and quantitative techniques with cartographic analysis, the research provided a thorough examination of UGSs from the sociocultural and environmental perspectives. The findings reveal that UGSs in Benfca significantly enhance urban quality of life, improving aesthetics and offering recreational and sports opportunities. These spaces facilitate meaningful connections with nature, thereby positively impacting residents' well-being.

Beyond confirming the relevance of urban green spaces for health and well-being during and after the COVID-19 pandemic, this study offers an applied contribution at the neighbourhood scale, responding to the need for place-based evidence in urban planning research. By integrating spatial analysis, field observation and user perceptions within a single local green structure, the findings provide insights that complement large-scale or method-specific studies, supporting planning and design decisions oriented towards liveability in ageing urban contexts.

The findings of this pilot study indicate that proximity and quality jointly influence how urban green spaces support liveability and health. While exact home-to-UGS distances were not measured, our usage patterns by mode of access (predominantly on foot) and self-reported travel time are consistent with previous research showing that closer walking catchments are associated with higher visit frequency and greater perceived physical and mental benefits, whereas parks offering better maintenance, safety and amenities tend to attract users from a wider area. This duality—proximity as enabler and quality as motivator—suggests that accessibility (safe, short walking access) and environmental quality (well-maintained, multifunctional settings) work together to encourage regular use and restorative experiences. Consequently, interventions should prioritise easy pedestrian

access, maintenance quality, safety, and diversity of activities to engage user groups who traditionally underutilise these spaces.

Despite the evident benefits provided by UGSs in Benfica, certain limitations are noted. The study's geographic focus on the Benfica District may not represent other urban contexts, and the reliance on self-reported data could introduce bias, potentially affecting the conclusions regarding the perceived benefits of UGSs. Consequently, this research should be viewed as a pilot study, with potential applicability to other districts.

Furthermore, the survey was conducted between August and September 2021, during the late phase of the COVID-19 pandemic. This timing may have influenced respondents' perceptions, as reliance on and appreciation of urban green spaces were likely heightened following periods of confinement. Consequently, the reported benefits of UGSs might partially reflect this contextual sensitivity, reinforcing the importance of maintaining access to such spaces in times of social or health crises. Additionally, this study acknowledges that the sample size, although adequate for a pilot study at the neighbourhood scale, may limit the generalisability of the findings. However, field observation showed that the respondents were largely regular and habitual users of Benfica's UGSs, which mitigates—though it does not fully eliminate—the risk of atypical or pandemic-specific usage patterns influencing the results. Thus, the behavioural tendencies observed are likely representative of routine interactions with these spaces, even beyond the COVID-19 period.

Although the UGSs in Benfica offer substantial benefits, there remains room for improvement, particularly in terms of accessibility, infrastructure, and maintenance. Tailored interventions that ensure ease of access, safety, diverse activities, and promotional initiatives can effectively engage users who typically do not utilise these spaces.

Integrating user feedback into nature-based health interventions and urban planning is crucial for developing inclusive and effective green infrastructure. Future research should investigate the barriers to accessing and utilising UGSs across various socio-economic contexts and employ longitudinal methodologies to assess the long-term effects of these spaces on public health. Furthermore, it is essential to explore the implementation of policies aimed at enhancing the quality and accessibility of UGSs, paying particular attention to vulnerable communities. These conclusions align with the One Health perspective (an integrated framework connecting human, animal, and environmental health), highlighting that accessible and biodiverse urban green networks can enhance both human and environmental well-being [39,52].

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Article

Spatial Justice and Accessibility: Optimizing Sports Facility Allocation in Tehran

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Abstract: The optimal allocation of sport facilities is crucial for urban management, as it enhances public health and improves citizens' quality of life. This study proposed a novel decision-making approach for optimizing the allocation of sports facilities in a megacity in which accessibility to sports facilities is a major challenge. To achieve this, 23 criteria in three categories of compatibility, environmental, and infrastructural criteria were analyzed. The analytical hierarchy process (AHP) method determined the criterion weights, while the weighted linear combination (WLC) method integrated them. The results showed that the current spatial distribution of sports facilities in Tehran follows a clustered pattern, and the compatibility criterion, with a weight of 0.45, has the greatest impact on the sports facility location selection process. A spatial analysis identified 48.58 km² as being highly suitable for facility development, mainly in central and southern Tehran. These findings can assist urban managers and planners in improving spatial justice, increasing accessibility to sports facilities, and promoting sustainable urban development.

Keywords: sports facilities management; location-allocation; GIS; SMCDA; Tehran

1. Introduction

In contemporary urban planning and public health discourse, equitable access to sports facilities is increasingly recognized as a cornerstone of sustainable and just cities. Numerous studies have shown that the presence and proper distribution of such facilities plays a crucial role in enhancing physical and mental well-being, promoting social cohesion, and improving the overall quality of life for urban populations [1]. As cities continue to grow in scale and complexity, especially in the Global South, ensuring spatial justice in the allocation of urban services including sports infrastructure has emerged as a pressing policy concern.

A key challenge faced by many urban regions is the imbalance in the spatial distribution of sports facilities, which can exacerbate health disparities and social inequalities [2]. While some areas enjoy sufficient access, others remain underserved, leading to unequal opportunities for physical activity and community engagement. International benchmarks suggest that a minimum per capita sports space of 2 m² is desirable in urban contexts [3]. However, this standard is seldom met in many cities of developing countries, where infrastructure development has often lagged behind population growth and urban sprawl.

In this regard, the combination of geographic information system (GIS) and spatial multi-criteria decision analysis (SMCDA) methods has gained attention as an innovative tool in urban management. The GIS method, with its capability to analyze spatial data and provide a comprehensive view of distribution patterns, enables the identification of areas in need of sports facilities [4]. On the other hand, SMCDA methods, considering multiple criteria such as the population density, accessibility, implementation costs, and environmental considerations, facilitate the decision-making process [5]. This combination not only provides optimal solutions for the location–allocation of sports facilities but also enhances spatial equity.

Despite this growing body of knowledge, there remains a need for context-specific models that adapt these methodologies to the unique socio-spatial challenges of particular cities. In this context, Tehran, a megacity with notable demographic and geographical complexities, provides a compelling case for applying a GIS-SMCDA-based approach to sports facility planning. The city is characterized by significant spatial inequalities; while the northern districts are relatively well-served, the southern areas suffer from acute under-provision of sports infrastructure. For instance, the per capita sports space in Tehran is estimated at less than 0.5 m² overall, and even lower in districts such as district 18, which also lack proximity to natural recreational spaces such as the Alborz Mountains. This unequal distribution not only impairs public health contributing to the rise of non-communicable diseases such as diabetes, hypertension, and cardiovascular issues [6] but also undermines social justice by deepening existing socio-economic disparities [7]. Studies by organizations such as the Centers for Disease Control and Prevention (CDC) have shown that better access to sports facilities can increase public participation in physical activity by up to 25% [8].

Previous studies indicate that this approach is highly effective in the optimal location of infrastructure in various fields such as healthcare [9,10], culture and education [11,12], accessibility and public services [13,14], shopping centers [15,16], energy [17,18], and crisis management [19,20]. In this regard, several studies [21,22] have emphasized that easy and convenient access to sports facilities, such as sports fields, stadiums, and parks, can increase individuals' willingness to engage in physical activity. Additionally, the research by Ahmadi et al. [23], Giles-Corti and Donovan [24], and Hallmann et al. [25] has shown that the increase in sports facilities, easy access to these centers, and better proximity to other urban uses can lead to greater participation in physical activities and improved life satisfaction among community members. Furthermore, the studies by McGrath et al. [26] and Zohrevandian et al. [27] have also emphasized the importance of the proper distribution and optimal location of sports facilities. Based on this, it can be concluded that easy access for citizens to these facilities plays a crucial role in achieving a healthy and sustainable society. In this study, the term sports facilities refers to both public and private facilities, as all types contribute to the overall spatial accessibility and support the goal of improving public health and social equity.

Tehran, as the capital of Iran, with its unique geographical, economic, and demographic characteristics, requires more precise planning in the development of sports infrastructure. The population density, air pollution, spatial limitations, and unequal distribution of facilities are challenges that make this issue even more critical. The southern areas of the city, due to their higher population and infrastructure limitations, suffer the most from the disproportionate distribution of sports facilities. Meanwhile, the northern areas, despite having a smaller population, have more facilities. Therefore, the main goal of this research is to propose a novel approach for the optimal allocation of sports facilities in Tehran. This approach, utilizing a combination of GIS and SMCDA methods, aims to identify suitable areas for the establishment or development of sports facilities. The innovation of this re-

search lies in the simultaneous use of a spatial analysis and multi-criteria decision-making techniques to address a multi-dimensional problem in the allocation of sports facilities. This method can also serve as a model for other metropolitan cities in the country.

The remainder of this paper is structured as follows. Section 2 describes the materials and methods used in the study. Section 3 presents the results. Section 4 provides a discussion of the findings, and Section 5 concludes the paper with final remarks and implications.

2. Materials and Methods

2.1. Study Area

Tehran, the capital of Iran and the largest city in the country, is situated on the southern foothills of the Alborz Mountain range and the northern edge of the Central Plateau of Iran. With a population of 9,259,009 people and an area of 613 km², Tehran is considered one of the largest and most important metropolises in the world [28]. Geographically located between 51°17' to 51°33' E and 35°36' to 35°44' N (Figure 1), the city is bordered to the north by mountainous regions and to the south by desert areas. The elevation of Tehran varies significantly across the city, ranging from 1800 m in the northern areas to 1050 m in the southern parts. This elevation difference has a noticeable impact on the climate of different regions, with the northern areas experiencing a cold and dry climate, while the southern areas have a warmer and drier climate. Tehran consists of 22 districts, 134 neighborhoods, and 376 sub-neighborhoods, holding special economic, social, and political significance. The city's share in Iran's gross domestic product (GDP) is around 27%, and it houses more than half of the country's industries. Moreover, Tehran plays a key role in Iran's economy, contributing 38% of the services sector and 24% of the industrial sector's value added. Due to its specific economic and demographic characteristics, Tehran is one of the busiest cities in the world, with a daily influx and outflux of people, pushing its daily population to over 20 million. The city holds a distinguished position globally, ranking as the 37th most populous city in the world.

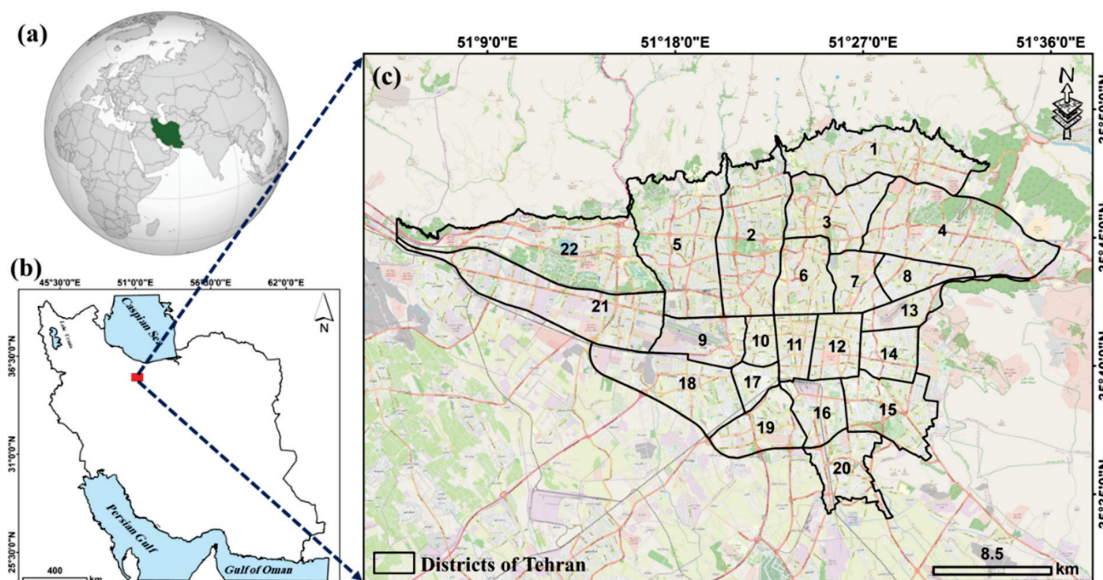


Figure 1. Map of the geographical location of the study area, (a) Iran's position in the world, (b) location of Tehran in Iran, (c) 22 district of Tehran (numbers indicate location of each district).

2.2. Data Used

In the present study, geographical datasets were used to achieve the desired objective. To identify areas with high potential, the data were categorized into three groups—

compatibility criteria, environmental criteria, and infrastructural criteria. The compatibility criteria included cultural centers, educational centers, commercial centers, entertainment centers, industrial areas, existing sports centers, residential areas, and the population density; the environmental criteria included the earthquake risk, flood risk, slope, and water bodies; the infrastructural criteria included fire stations, police stations, medical centers, pharmacies, fuel stations, parking, public transportation stations, highways, airports, and main streets. The characteristics of the data used are shown in Table 1. After gathering the initial data, the capabilities of ArcGIS 10.8 software were employed for a spatial analysis and the generation of criteria maps at various stages. Additionally, TerrSet 19.0 software was used to produce the sports facility potential maps.

Table 1. Specifications of the data used in this study.

Data	Format	Resolution/Scale	Source
Highways	Shapefile (polyline)	1:2000	https://www.mrud.ir/ (accessed on 20 December 2024)
Public transport stations	Shapefile (point)	1:2000	http://www.ncc.org.ir/ (accessed on 20 December 2024)
Existing sports centers	Shapefile (point)	1:2000	https://www.tehran.ir/ (accessed on 28 December 2024)
Industrial areas	Shapefile (polygon)	1:2000	https://gis.isipo.ir/ (accessed on 18 December 2024)
Entertainment centers	Shapefile (point)	1:2000	https://www.tehran.ir/ (accessed on 9 December 2024)
Residential areas	Shapefile (polygon)	1:2000	http://www.ncc.org.ir/ (accessed on 20 October 2024)
Slope	Raster	30 m	https://www.aw3d.jp/en/products/standard/ (accessed on 20 October 2024)
Main streets	Shapefile (polyline)	1:2000	https://www.mrud.ir/ (accessed on 20 October 2024)
Airport	Shapefile (point)	1:2000	https://en.caa.gov.ir/ (accessed on 20 October 2024)
Water bodies	Shapefile (polygon)	1:2000	http://www.ncc.org.ir/ (accessed on 20 October 2024)
Fire stations	Shapefile (point)	1:2000	https://www.tehran.ir/ (accessed on 9 December 2024)
Police stations	Shapefile (point)	1:2000	https://www.tehran.ir/ (accessed on 9 December 2024)
Medical centers	Shapefile (point)	1:2000	https://www.tehran.ir/ (accessed on 9 December 2024)
Pharmacies	Shapefile (point)	1:2000	https://www.tehran.ir/ (accessed on 9 December 2024)
Fuel stations	Shapefile (point)	1:2000	https://www.tehran.ir/ (accessed on 9 December 2024)
Parking	Shapefile (point)	1:2000	https://www.tehran.ir/ (accessed on 9 December 2024)
Earthquake risk	Raster	30 m	https://gsi.ir/ (accessed on 9 December 2024)
Population density	Raster	30 m	https://www.tehran.ir/ (accessed on 9 December 2024)
Flood risk	Raster	30 m	https://frw.ir/ (accessed on 14 December 2024)
Cultural centers	Shapefile (point)	1:2000	http://www.ncc.org.ir/ (accessed on 20 December 2024)
Educational centers	Shapefile (point)	1:2000	http://www.ncc.org.ir/ (accessed on 20 December 2024)
Commercial centers	Shapefile (point)	1:2000	http://www.ncc.org.ir/ (accessed on 20 December 2024)

2.3. Research Methodology

Based on the flowchart presented in Figure 2, the research methodology of this study consisted of six main stages. In the first stage, the study area was defined, and the key criteria influencing the optimal location–allocation of sports facilities were identified and selected. In the second stage, the current distribution of sports facilities was analyzed using the average nearest neighbor (ANN) statistical method. In the third stage, spatial data and GIS-based spatial analyses were employed to generate maps for the selected criteria.

In the fourth stage, the analytical hierarchy process (AHP) and pairwise comparison matrices were used to determine the relative importance of each criterion. In the fifth stage, the criteria were standardized using the min–max standardization method to ensure uniform scaling. Finally, in the sixth stage, the standardized criteria and calculated weights were integrated using the weighted linear combination (WLC) method, generating the final potential development map for sports facilities. In this stage, model validation was performed through field visits and a satellite imagery analysis. This comprehensive process enables the optimal location of sports facilities and assists urban planners in making efficient decisions.

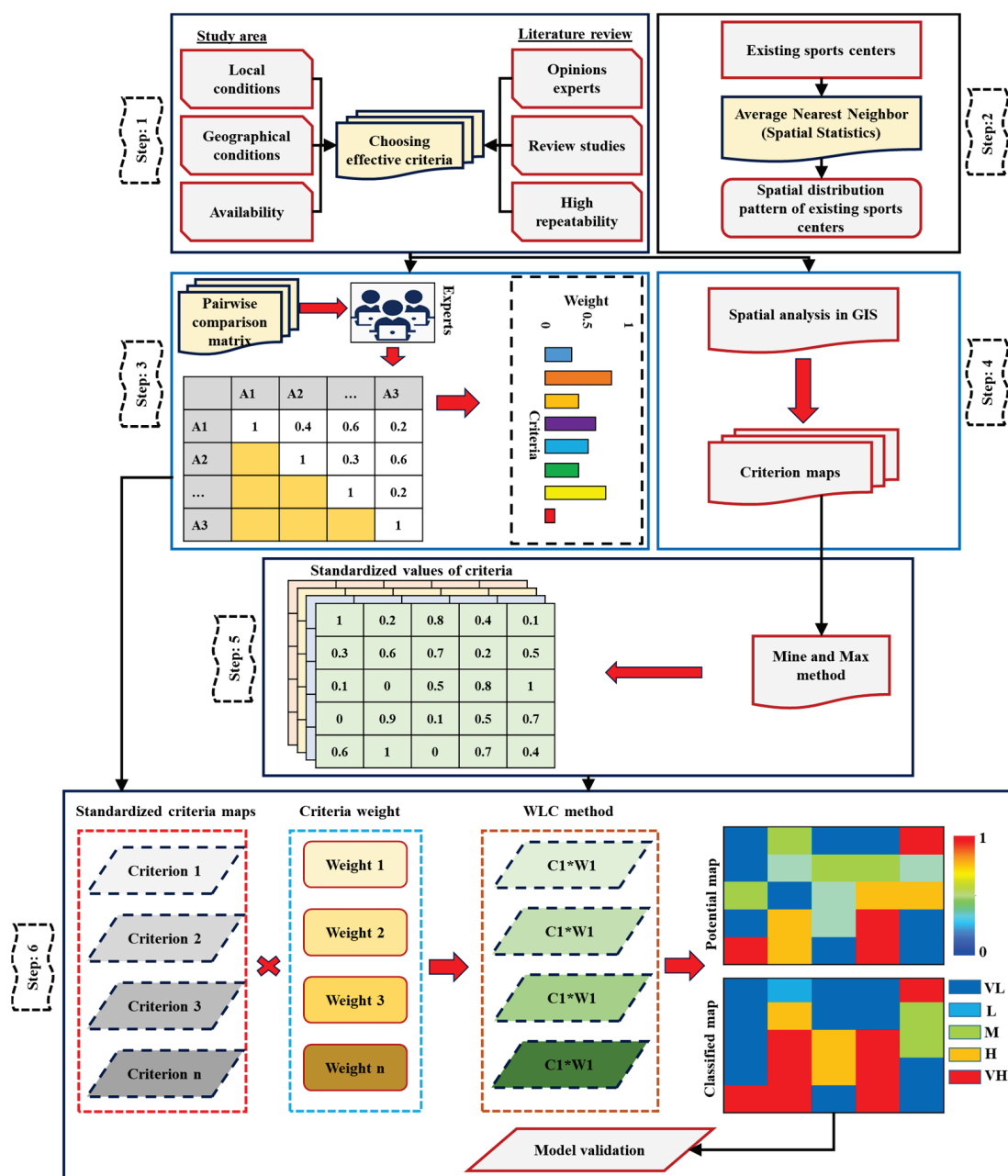


Figure 2. The main stages of the research methodology.

2.3.1. Selection of Criteria

Some scholars argue that sports facility equity should be understood as a comprehensive framework that includes both metropolitan-level stadiums and small-scale community fitness facilities [29,30]. Therefore, this study considered various scales of sports facilities to ensure equitable access across different community levels. To achieve this goal, it is essential to carefully and thoroughly examine the selection criteria for the optimal locations of sports centers. Drawing from previous research and expert opinions, including specialists from the Tehran municipality, Ministry of Sports and Youth, and academic institutions, this study identified a set of key determining factors. A total of 23 map layers were used as inputs, categorized into three main groups based on their characteristics, as compatibility criteria, environmental criteria, and infrastructural criteria. The following sections provide a detailed explanation of each criterion.

Compatibility criteria: In the process of locating sports facilities, compatibility criteria play a crucial role in ensuring accessibility, efficiency, and responsiveness to community needs. One's proximity to cultural centers promotes a healthy lifestyle and fosters a sports-oriented culture. Similarly, being near educational institutions, particularly schools and universities, encourages student participation in physical activities, contributing to their physical and mental well-being. The accessibility of sports facilities for working individuals is enhanced when located near commercial areas, where high foot traffic increases the potential engagement. Additionally, integration with recreational spaces results in a well-rounded experience, motivating greater public participation. However, maintaining an appropriate distance from industrial zones is essential to avoid exposure to air and noise pollution, which could negatively impact athletes' health. Considering existing sports centers helps achieve an equitable distribution, preventing oversaturation in certain areas while addressing shortages elsewhere. Moreover, considering the proximity to residential areas ensures greater convenience, encouraging more residents to utilize these spaces. Finally, the population density is a key factor, as higher-density areas require more sports infrastructure to meet demand, ensuring the optimal use of facilities and maximizing their impact.

Environmental criteria: These factors directly impact the safety, sustainability, and efficiency of sports facilities. The earthquake risk is a critical consideration, as constructing sports centers in high-risk earthquake zones without proper reinforcement measures can endanger athletes and citizens. Selecting locations with lower seismic risk or implementing structural reinforcement strategies is essential to minimize the potential damage. Similarly, the flood risk must be addressed, as building in flood risk areas can lead to financial losses, infrastructure damage, and operational disruptions. Therefore, sites at higher elevations and outside flood pathways are more suitable. The slope gradient is another crucial factor, as steep terrain increases the levelling costs and poses design challenges, making areas with moderate slopes preferable for reducing construction expenses and ensuring user safety. Having a close proximity to water bodies offers aesthetic and environmental benefits, such as a pleasant atmosphere and irrigation opportunities for green spaces. However, maintaining an appropriate distance is necessary to prevent issues such as excessive humidity, pest growth, and soil erosion.

Infrastructure criteria: In the site selection of sports facilities, infrastructure criteria play a crucial role in ensuring safety, accessibility, and efficiency, as well-developed infrastructure enhances the operational effectiveness and mitigates potential risks. The proximity to fire stations is a key safety factor, allowing for a swift emergency response to incidents such as fires, thereby minimizing casualties and financial losses. Similarly, having easy access to police stations enhances one's security, reduces potential crimes around sports centers, and fosters a sense of safety among users. Medical facilities and pharmacies are also vital, as athletes and visitors may require immediate medical assistance in case of injuries. Locating sports centers near hospitals, clinics, and pharmacies is particularly essential for professional and competitive sports to ensure timely medical interventions. The availability of fuel stations is another important aspect, facilitating transportation logistics and ensuring fuel supply for personal and service vehicles. Additionally, having adequate parking facilities is crucial, as many visitors commute using private vehicles, and a lack of sufficient parking spaces could lead to congestion, increased traffic, and public dissatisfaction. Access to public transportation hubs, highways, and main roads significantly influences public participation in sports activities. The proximity of metro, bus, and taxi stations to sports stadiums influences their accessibility, particularly for low-income groups, while also reducing traffic congestion caused by private vehicles. Furthermore,

locating sports facilities near major highways and main roads enhances their connectivity and increases their attractiveness for users.

In addition to the main criteria, certain constraints were considered for some of the factors. These constraints included areas that are entirely excluded from the establishment of sports facilities. Specifically, a buffer of 1500 m from airports, 200 m from earthquake risk zones, 200 m from flood risk areas, 150 m from water bodies, 150 m from fuel stations, 350 m from industrial centers, and residential areas was applied. These thresholds were determined based on a combination of the relevant literature [2,23,31], urban planning guidelines, and an expert consultation with three faculty members specializing in sports management. Similar buffer distances had been adopted in previous spatial planning studies for public facilities [8,32]. Furthermore, compliance with these distances is consistent with safety and environmental risk mitigation principles recommended in national and international urban development standards. Adhering to such constraints plays a significant role in enhancing the safety, sustainability, and efficiency of sports facilities.

2.3.2. SMCDA

Identifying the optimal location for a specific activity is one of the key challenges in spatial planning and management. Selecting the right site can significantly impact the success of a project, especially when factors such as the accessibility, cost, environmental conditions, and other relevant criteria are considered. One of the most effective tools used in this field is the GIS method. This technology enables the collection, analysis, and visualization of spatial data, playing a crucial role in the decision-making process.

In this context, there are two general approaches to evaluating the suitability of a location. The absolute method classifies areas strictly into two categories—suitable and unsuitable. For example, when selecting a site for a factory, if a region falls within a protected environmental zone, it is considered entirely unsuitable. In contrast, the relative method ranks locations on a continuous scale from least to most suitable. This approach offers greater flexibility, allowing decision-makers to compare different locations and select the optimal option [33]. One of the most commonly used scoring techniques in this field is the WLC method, which has been widely applied in various studies.

A suitability analysis of a location combines two key scientific fields: a spatial analysis, which examines the distribution, patterns, and spatial relationships of features; and spatial decision-making, which focuses on selecting the best options within a specific geographic context. This process is known as the integration of the GIS method with an SMCDA. The GIS-SMCDA process typically consists of four main steps [34]. First, the criteria are standardized to ensure that data with different measurement units are converted to a common scale. A commonly used technique for this is the min–max standardization method, which transforms criterion values into a predefined range (0 to 1). Next, the criteria weights are determined, as not all factors have the same level of importance. One of the widely used methods for this step is the AHP, which assigns precise weights through pairwise comparisons of criteria. Finally, decision rules are applied to prioritize the options. The most commonly used data integration method at this stage is the WLC, where the final suitability score for each option is calculated based on the weighted sum of different criteria.

2.3.3. Standardization of Criterion Values

In suitability analyses, spatial variations are implicitly incorporated into the definition of evaluation criteria. Standardization methods are employed to integrate multiple criteria, enabling decision-makers to obtain comparable units across different datasets [35]. Spatial concepts and relationships, such as the proximity and overlap, play a crucial role in defining a set of decision-making options. To enhance the accuracy in the standardization

process, the min–max standardization method is used. This approach first identifies the maximum and minimum values of each criterion and then standardizes all other values to a scale between 0 and 1. This process minimizes the impact of outliers and ensures a fairer and more precise comparison among criteria. By applying this method, a more cohesive comparison between various factors is achieved, improving the reliability of spatial analyses and decision-making processes. When standardizing positive criteria (the higher, the better) and negative criteria (the lower, the better), Equations (1) and (2) have been used, respectively.

$$\max_{ij} = \frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}} \quad (1)$$

$$\min_{ij} = \frac{x_{\max} - x_{ij}}{x_{\max} - x_{\min}} \quad (2)$$

where x_{ij} is the original data value, $x_{\min}$ is the smallest value in the dataset for the same criterion, and $x_{\max}$ is the largest value in the dataset for that criterion [36].

2.3.4. Criteria Weighting Method

The relative importance or impact of a criterion compared to other criteria is evaluated with a specific weight. Within the framework of the AHP, Saaty [37] developed the pairwise comparison method to determine the weights of criteria. This method is one of the most widely used techniques in the research literature. In this method, the pairwise comparisons are organized into a symmetric matrix $C_{n \times n}$, which is defined according to Equation (3).

$$C = \begin{bmatrix} 1 & c_{12} & \dots & c_{1n} \\ 1/c_{12} & 1 & \dots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/c_{1n} & 1/c_{2n} & \dots & 1 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \lambda_{\max} w \quad (3)$$

where $\lambda_{\max}$ is the largest eigenvalue in the pairwise comparison matrix. In the pairwise comparison matrix, each row is evaluated against the corresponding column. The elements on the main diagonal are always equal to one, and any value above the diagonal is the reciprocal of the value corresponding to the lower diagonal. To determine the importance and priority in pairwise comparisons, the Saaty and Vargas [38] scale ranging from 1 to 9 is used, which specifies the relative weights of the criteria. This scale, employed in numerous studies, including those by Şahin et al. [39] and Uyan [40], proposes a range from 1 to 9 for comparing criteria. In this scale, 1 represents equal importance between two criteria, while 9 indicates the absolute greater importance of one criterion over the other. Once the decision-makers construct the pairwise comparison matrix, the weight vector for the criteria can be calculated. These weights must satisfy the conditions established in Equations (4) and (5).

$$\sum_{k=1}^n w_k = 1 \quad \forall k = 1, 2, \dots, n \quad (4)$$

$$0 \leq w_k \leq 1 \quad (5)$$

In this method, the largest eigenvalue $\lambda_{\max}$ of the pairwise comparison matrix plays a crucial role in determining the weights of the criteria. One of the most common methods for solving Equation (3) (the above equation), which was proposed by Saaty [37], involves standardizing the elements of the matrix based on Equation (6). After standardization, the weights of the criteria are calculated using Equation (7). This process enables the

determination of the final weights, which reflect the relative importance of each criterion compared to the others.

$$c_{kp}^* = \frac{c_{kp}}{\sum_{k=1}^n c_{kp}} \quad \forall k = 1, 2, \dots, n \quad (6)$$

$$w_k = \frac{\sum_{p=1}^n c_{kp}^*}{n} \quad \forall p = 1, 2, \dots, n \quad (7)$$

When a decision-maker performs pairwise comparisons between options or criteria, the results may not always be perfectly consistent. Therefore, the consistency ratio (CR), which is determined based on Equation (8), is recommended. In this relation, the numerator represents the consistency index (CI) that is obtained from the pairwise comparison process. According to Equation (8), the CI value depends on the largest eigenvalue of the pairwise comparison matrix and the number of criteria (n). Additionally, the random index (RI), which appears in Equation (9), represents the consistency index of a randomly generated pairwise comparison matrix. According to Qureshi et al. [41], the RI values for n = 9, 10, 11, and 12 are 1.42, 1.49, 1.52, and 1.54, respectively.

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)} \quad (8)$$

$$CR = \frac{CI}{RI} \quad (9)$$

Finally, when the CR value is less than 0.1, the pairwise comparisons will be considered acceptable in terms of consistency [42]. However, if the CR value exceeds 0.1, this indicates inconsistency in the evaluations, and the pairwise comparisons may need to be reviewed and revised.

In applying the AHP methodology, an expert consultation was conducted to determine the relative weights of the selected criteria. A total of 12 experts participated in the pairwise comparison process. These experts were selected based on their professional background and academic or practical experience in urban planning, sports infrastructure development, and GIS-based spatial analyses. The panel included 3 university faculty members specializing in urban planning and spatial analyses, 3 faculty members in the field of sports management, 2 senior consultants in urban infrastructure planning, and 4 municipal decision-makers with over 10 years of experience in sports facility development and location planning. The criteria for selecting these experts included having a minimum of 5 years of experience in relevant fields, scholarly publications or project experience related to spatial planning or sports infrastructure, and availability for structured interviews and pairwise comparison tasks. To ensure the reliability of the results, the CR values were calculated for all pairwise comparison matrices, and only matrices with a CR of less than 0.1 were accepted for the analysis. The final weights were obtained by aggregating consistent individual judgments using the geometric mean method.

2.3.5. Criteria Integration Method

The WLC model, as defined in Equation (10), is one of the most commonly used methods in SMCDAs. This model operates by combining the criterion maps, where at each geographic location (x_i, y_i) , a weighted sum of the criteria is calculated. The process is carried out using weight coefficients and value functions, and the relationship is defined as follows [43]:

$$V(A_i) = \sum_{k=1}^n w_k v(a_{i,k}) \quad (10)$$

where $V(A_i)$ represents the potential value, and the subscript i indicates the option being evaluated at the location x_i, y_i . Here, w_k is the weight of the j th criterion, reflecting its importance in the decision-making model, and $v(a_{i,k})$ is the standardized value of the j th criterion at option i th [44]. In the WLC method, each cell in a GIS raster layer is treated as an option (alternative). The suitability value for each cell is calculated through the linear combination of different criteria and their corresponding weights, which is then provided as a final decision index for making the best decision. This approach allows for an aggregated view of how well each location satisfies the multiple criteria, providing an overall ranking or potential map [45].

3. Results

The analysis of the ANN, which was conducted to examine the spatial pattern of existing sports centers in Tehran (Figure 3), provided meaningful and noteworthy results. Based on the nearest neighbor ratio of 0.582584, it is evident that sports facilities are clustered in specific areas of the city. This ratio, being less than 1, indicates that the average distance to the nearest neighbors observed is shorter than the distance that would be expected in a random distribution. The Z-score value of -12.900898 is highly negative and indicates a significant deviation from randomness. This Z-score falls in the statistically significant region on the left side of the normal distribution curve, clearly confirming the clustered distribution of sports facilities.

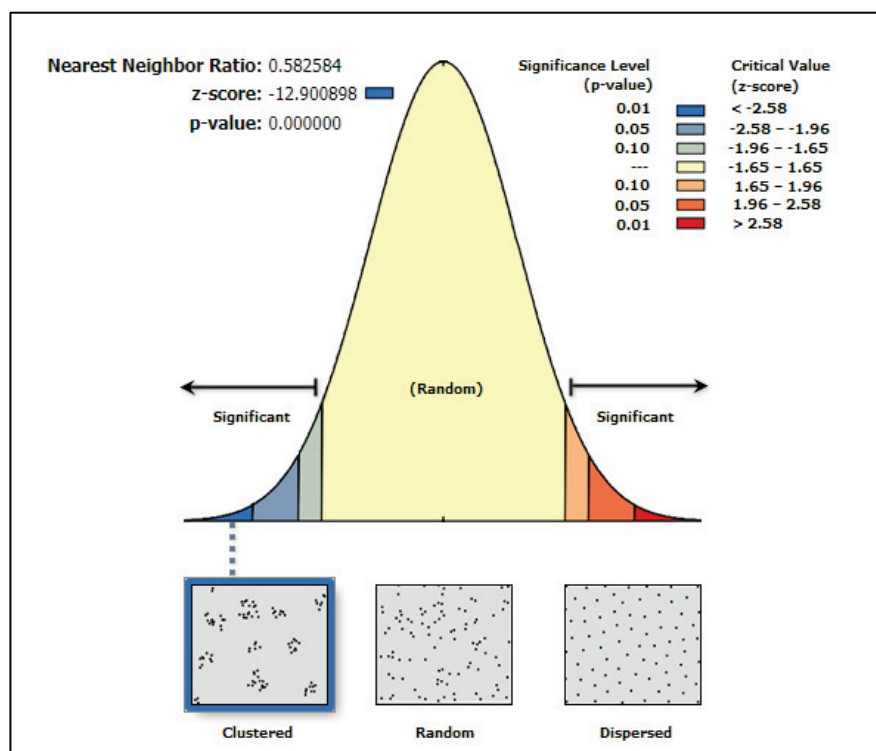


Figure 3. Spatial distribution pattern of existing sports centers in the study area.

On the other hand, the p -value of 0.000000 indicates that the probability of this pattern being random is almost zero. This value suggests that the observed pattern is statistically significant and cannot be attributed to chance. Critical values further confirm that for a 99% confidence level, the observed Z-score, which is much less than -2.58 , proves the high significance of the clustered pattern. The bell-shaped curve accompanying this analysis illustrates three types of spatial patterns—clustered, random, and dispersed. In

this analysis, the highly negative Z-score and the nearest neighbor ratio being less than 1 clearly indicate that the distribution of sports facilities in Tehran is clustered.

This clustering indicates the concentration of these locations in specific areas of the city, which could be influenced by factors such as the population density, socio-economic distribution, and access to resources. The results show that some areas of Tehran have better access to sports facilities, while others are deprived of these amenities. Therefore, this analysis highlights the spatial inequality in the distribution of sports facilities. Based on this, identifying areas lacking sports amenities and planning for the establishment of new facilities in these areas can contribute to greater spatial equity. Additionally, conducting further studies to identify the factors influencing the spatial concentration of these facilities can assist in more informed decision-making in urban development.

Table 2 shows the weights of the criteria and sub-criteria. The analysis of the criteria weights for sports facility site selection shows that the compatibility criterion, with a weight of 0.45, has the greatest impact on the selection of locations. This indicates that the alignment of a location with other urban land uses plays a key role in decision-making. Among the sub-criteria in this section, the population density (0.25) and distance from educational centers (0.18) hold greater importance. This suggests that sports facilities should be located in areas with high population density rates to maximize their utilization, and the distance from educational centers can also help increase the usage of these facilities. In addition to the compatibility criterion, the infrastructure criterion, with a weight of 0.35, highlights the importance of access to urban services and amenities. In this section, the distances from public transport stations (0.20) and medical centers (0.18) have the highest weights. These findings suggest that the ease of access to sports facilities for citizens, as well as the ability to provide emergency services, when necessary, are key factors in site selection. The environmental criterion, with a weight of 0.20, also plays an important role in the site selection process. Within this category, the earthquake risk (0.45) and flood risk (0.35) are identified as two key factors. This emphasizes the importance of minimizing natural risks when locating sports facilities, as constructing such facilities in areas prone to earthquakes or floods can pose serious risks to users. Overall, the weighting of criteria reflects a balanced approach to decision-making, considering urban compatibility, environmental risk reductions, and access to key infrastructure. The prioritization of the compatibility criterion with the urban fabric, over environmental and infrastructural criteria, indicates a focus on social needs and maximizing the use of sports facilities.

Finally, the CR in this analysis indicates the level of consistency and logical soundness in the decision-making process. The low CR values for various criteria, particularly the compatibility (0.008), environmental (0.002), and infrastructure (0.005) criteria, suggest that the judgments made were sufficiently coherent, and the selections were made based on a valid and accurate analytical method. The low CR values confirm that the pairwise comparisons made between the criteria and sub-criteria were highly reliable, and the weights assigned to each criterion were trustworthy and dependable.

The compatibility criteria map (Figure 4) for the location of sports facilities reveals that the high-potential areas (brown color) are mainly situated near cultural, educational, recreational, and commercial centers, as well as residential zones. In contrast, the low-potential areas (blue color) are mostly located on the outskirts of the city, in industrial areas, or in regions with low population density. The distribution of values in the maps indicates that central urban areas, due to their distance from commercial and educational centers, are more conducive to the establishment of sports facilities, while the outskirts and industrial areas, due to their distances from service centers and negative environmental impacts, have the lowest potential. Additionally, in the population density map, the densely populated urban areas are marked in brown, indicating that these areas, due to the high numbers of

potential users, are the most favorable for the development of sports facilities. In contrast, the sparsely populated areas, which are mostly scattered on the outskirts of the city, have the lowest scores. Moreover, the distance map from the existing sports centers shows that the areas that have so far lacked sports centers, if other favorable conditions are met, have a higher potential for the construction of new facilities.

Table 2. Weight of criteria, sub-criteria, and criterion type affecting the locations of sports facilities.

Criterion	Weight	CR	Sub-Criterion	Weight	CR	Criterion Type
Compatibility	0.45	0.003	D.F cultural centers	0.10	0.008	Minimum
			D.F educational centers	0.18		Minimum
			D.F commercial centers	0.12		Minimum
			D.F entertainment centers	0.08		Minimum
			D.F industrial areas	0.05		Maximum
			D.F existing sports centers	0.07		Maximum
			D.F residential areas	0.15		Minimum
			Population density	0.25		Maximum
Environmental	0.20		Slope	0.17	0.002	Minimum
			Flood risk	0.30		Maximum
			Earthquake risk	0.42		Maximum
			D.F water bodies	0.11		Minimum
Infrastructure	0.35		D.F fire stations	0.15	0.005	Minimum
			D.F police stations	0.10		Minimum
			D.F medical centers	0.18		Minimum
			D.F pharmacies	0.02		Minimum
			D.F fuel stations	0.05		Minimum
			D.F parking	0.06		Minimum
			D.F public transport stations	0.20		Minimum
			D.F highways	0.12		Minimum
			D.F main streets	0.08		Minimum
			D.F airports	0.04		Minimum

The environmental criteria map (Figure 5) for the locations of sports facilities reveals that the high-potential areas (brown color) are predominantly located in regions with better safety in terms of their earthquake and flood risks, suitable slopes, and favorable distances from water sources. On the other hand, the low-potential areas (blue color) are mostly scattered in high-risk and geographically unsuitable zones. In the earthquake risk map, the low-potential areas are primarily concentrated in seismically active regions, where the risks posed by earthquakes make the establishment of sports facilities inadvisable. In contrast, the safer regions, shown in brown on the map, indicate a higher potential for sports facility development. The flood risk map highlights that the low-potential areas are located in floodplains and along riverbanks, while the higher-potential areas are situated in elevated zones away from water flow paths. The slope map shows that the areas with gentle slopes, marked in brown, are ideal locations for building sports centers, as they are easier and more cost-effective to develop. Conversely, the steep and mountainous areas, shown in blue,

have lower potential due to the challenges of construction and higher costs. Furthermore, the distance from water sources map indicates that areas with an appropriate distance from water bodies, which are less prone to environmental hazards and soil erosion, offer better conditions for the development of sports facilities.

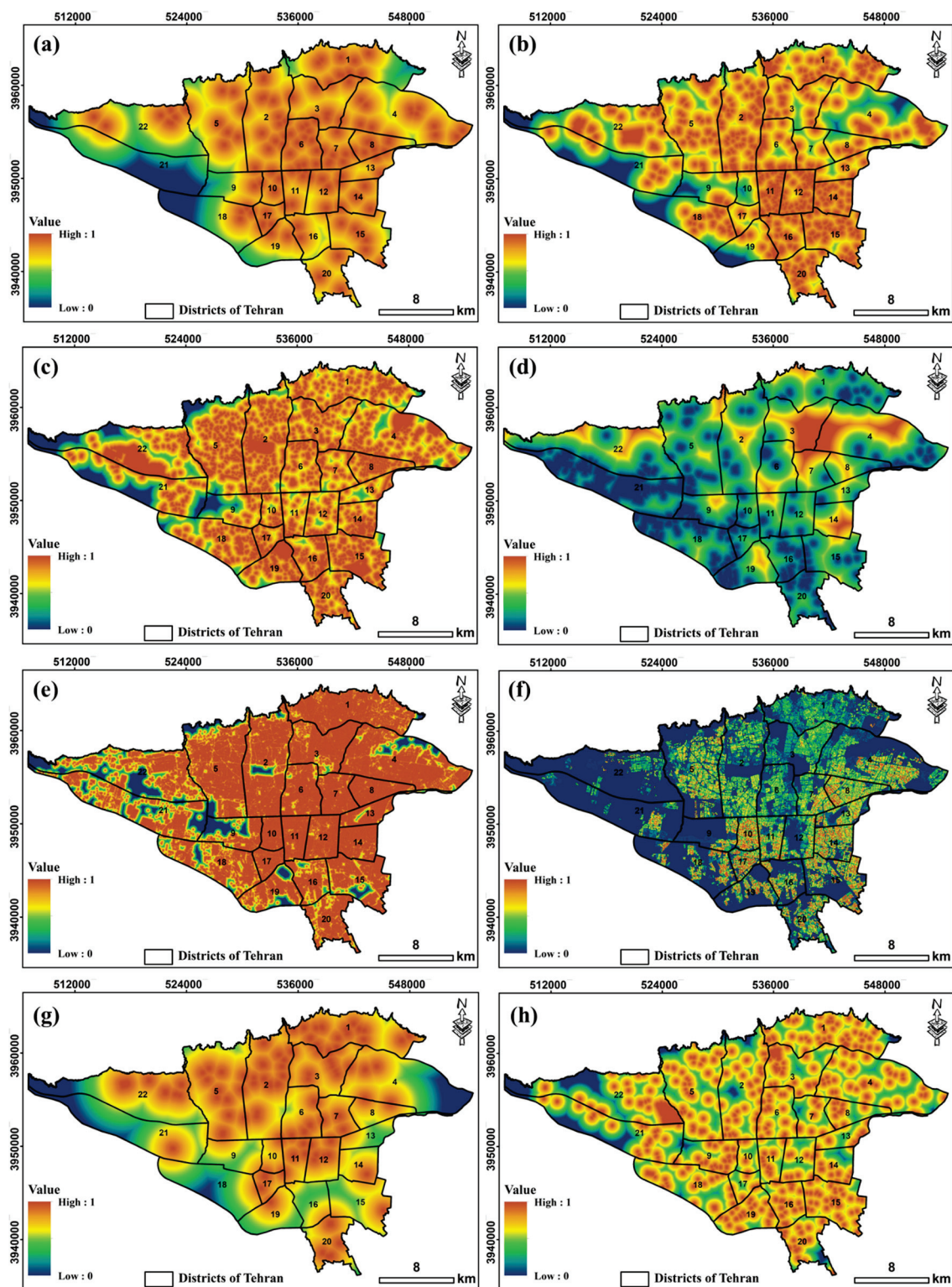


Figure 4. Map of compatibility criteria: (a) distance from cultural centers (b) distance from educational centers; (c) distance from entertainment centers; (d) distance from industrial areas; (e) distance from residential areas; (f) population density; (g) distance from commercial centers; (h) distance from existing sports centers.

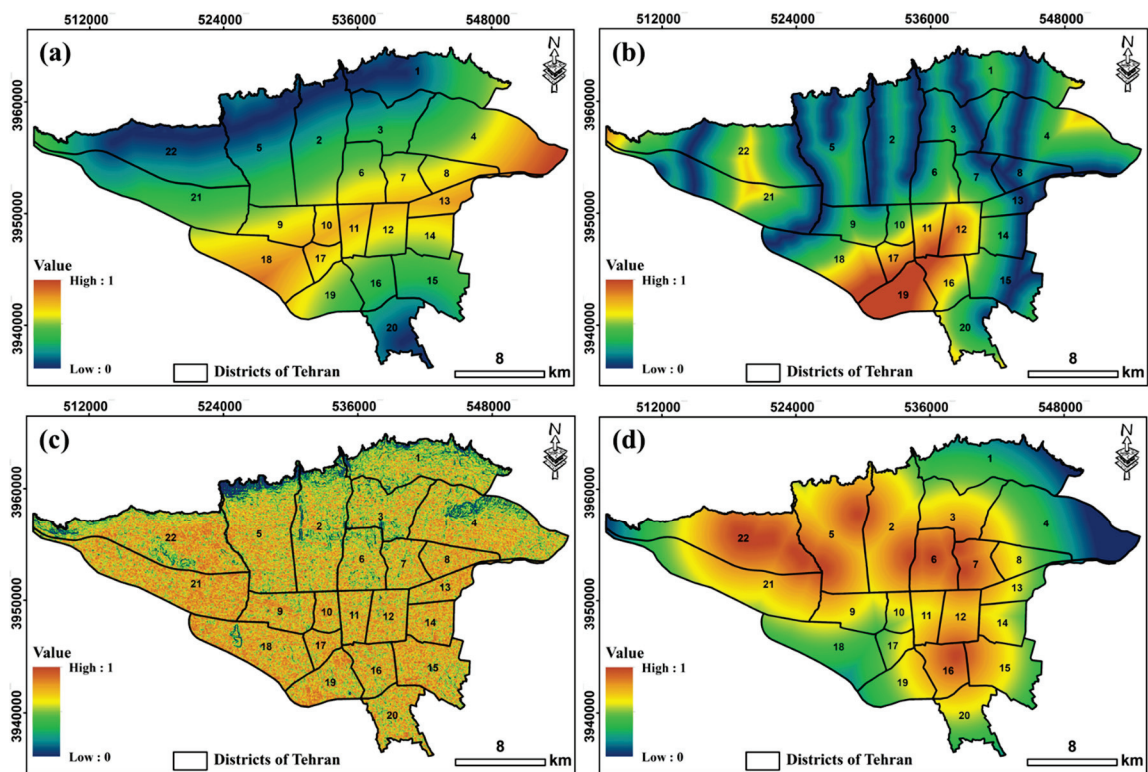


Figure 5. Map of environmental criteria: (a) earthquake risk; (b) flood risk; (c) slope; (d) distance from water bodies.

The infrastructure criteria map (Figure 6) indicates that the high-potential areas (brown color) are predominantly located near fire stations, police stations, medical centers, pharmacies, fuel stations, parking, public transport stations, highways, main streets, and airports. In contrast, the low-potential areas (blue color) are concentrated in remote zones with limited access to these essential infrastructures. The distances from fire stations and police stations enhance the safety of sports facilities, while access to medical centers and pharmacies is crucial for providing necessary medical services. Additionally, the distances from public transport stations, highways, and main streets facilitate easy access for users, while areas far from these routes have lower potential due to difficulties in movement and transportation. Access to parking and fuel stations also increases user convenience, and airports can play a significant role in the development of international sports activities. Therefore, the best locations for establishing sports facilities are those with better access to safety, healthcare, and transportation infrastructure.

The map of the spatial distribution of the constraints for sports facility construction shown in Figure 7 illustrates that a significant portion of Tehran is affected by spatial constraints, particularly in the peripheral areas in the western, southern, and eastern parts of the city, highlighted in orange. The areas with constraints cover an area of 398 square kilometers, which accounts for 65% of the total study area. This indicates that only 35% of the city is suitable for development. Regions 9, 18, 21, and 22 in the western and southwestern parts, as well as regions 15 and 19 in the south, exhibit the highest levels of limitations, which may stem from environmental factors, inadequate infrastructure, or incompatible land uses. In contrast, the central areas such as regions 6, 11, and 12 have fewer constraints and are more suitable for development. This distribution pattern suggests that urban peripheries, due to various reasons such as the density of incompatible land uses, environmental constraints, and lack of necessary infrastructure, are less appropriate for new developments. On the other hand, the central areas, due to better access to facilities and

infrastructure, have higher potential. The extent of these constraints highlights the need for careful planning and urban interventions to improve conditions in underprivileged areas and enhance suitable land uses in restricted zones.

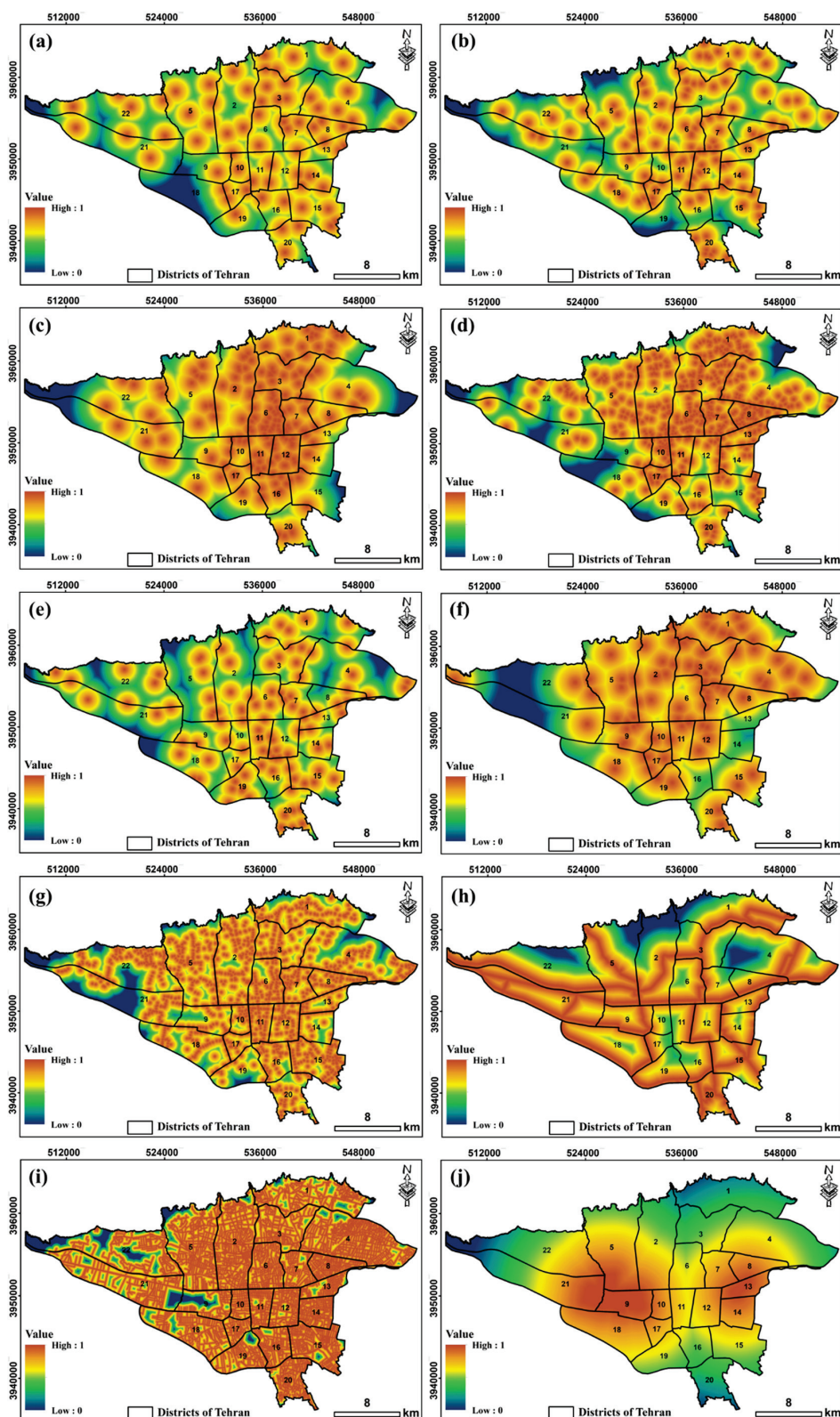


Figure 6. Map of infrastructure criteria: (a) distance from fire stations; (b) distance from police stations; (c) distance from medical centers; (d) distance from pharmacies; (e) distance from fuel stations; (f) distance from parking; (g) distance from public transport stations; (h) distance from highways; (i) distance from main streets; (j) distance from airports.

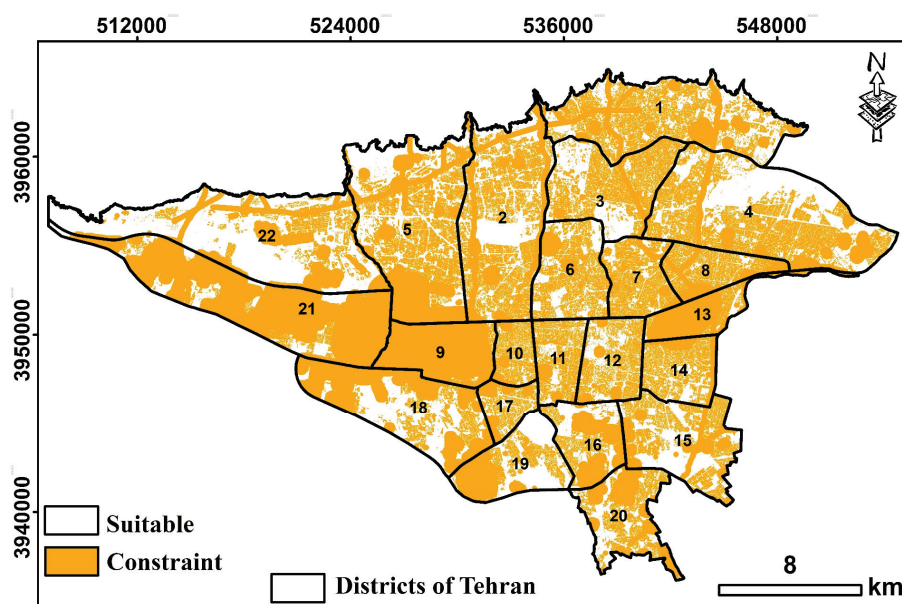


Figure 7. Map of spatial constraints for the development of sports facilities.

The standardized and classified maps for compatibility, environmental, and infrastructure criteria are presented in Figure 8. These maps are categorized into five suitability levels based on the suitability index as very low (0.0–0.2), low (0.2–0.4), moderate (0.4–0.6), high (0.6–0.8), and very high (0.8–1.0). The analysis of potential allocation maps for optimal sports facility placement in Tehran reveals a clear spatial pattern in the distribution of suitability classes across the city. In all three maps (compatibility, environmental, and infrastructure), the northern and northwestern areas of the city (especially districts 1, 2, 5, and 22) are predominantly classified in the very low to low potential classes (blue), indicating significant constraints in these regions. Conversely, the central and southern areas (such as districts 10, 11, 12, 16, and 17) are mostly classified in the high and very high potential classes (red), particularly in the infrastructure map, which highlights better access to facilities and the transportation network.

The compatibility map (Figure 8a) shows that the highest potential areas (red color) are concentrated in central and southern districts, such as districts 10, 11, 16, 17, and 19, while the northern and western districts, including 1, 2, 5, 21, and 22, have the lowest potential. This indicates that densely populated urban areas with adequate infrastructure are better suited for sports facility development. The environmental map (Figure 8b) reveals that very low and low potential classes are more widespread in the north and northwest (e.g., districts 1, 2, and 21) due to the steep slopes, high river density, and proximity to active fault lines. Conversely, southern areas such as districts 15, 16, and 19 exhibit higher potential, likely due to their gentler slopes, optimal distance from rivers and fault lines, and overall favorable environmental conditions for sports facility development. Finally, the infrastructure map (Figure 8c) indicates that the central and southeastern districts (e.g., 12, 14, 15, and 16) have the highest potential, whereas the northern (1, 2, and 5) and western (21 and 22) districts show lower potential due to weak infrastructure. This distribution suggests that sports facility development should be prioritized in the central and southern areas, considering multiple factors, while the northern districts, due to environmental constraints and limited infrastructure access, are less suitable for such developments.

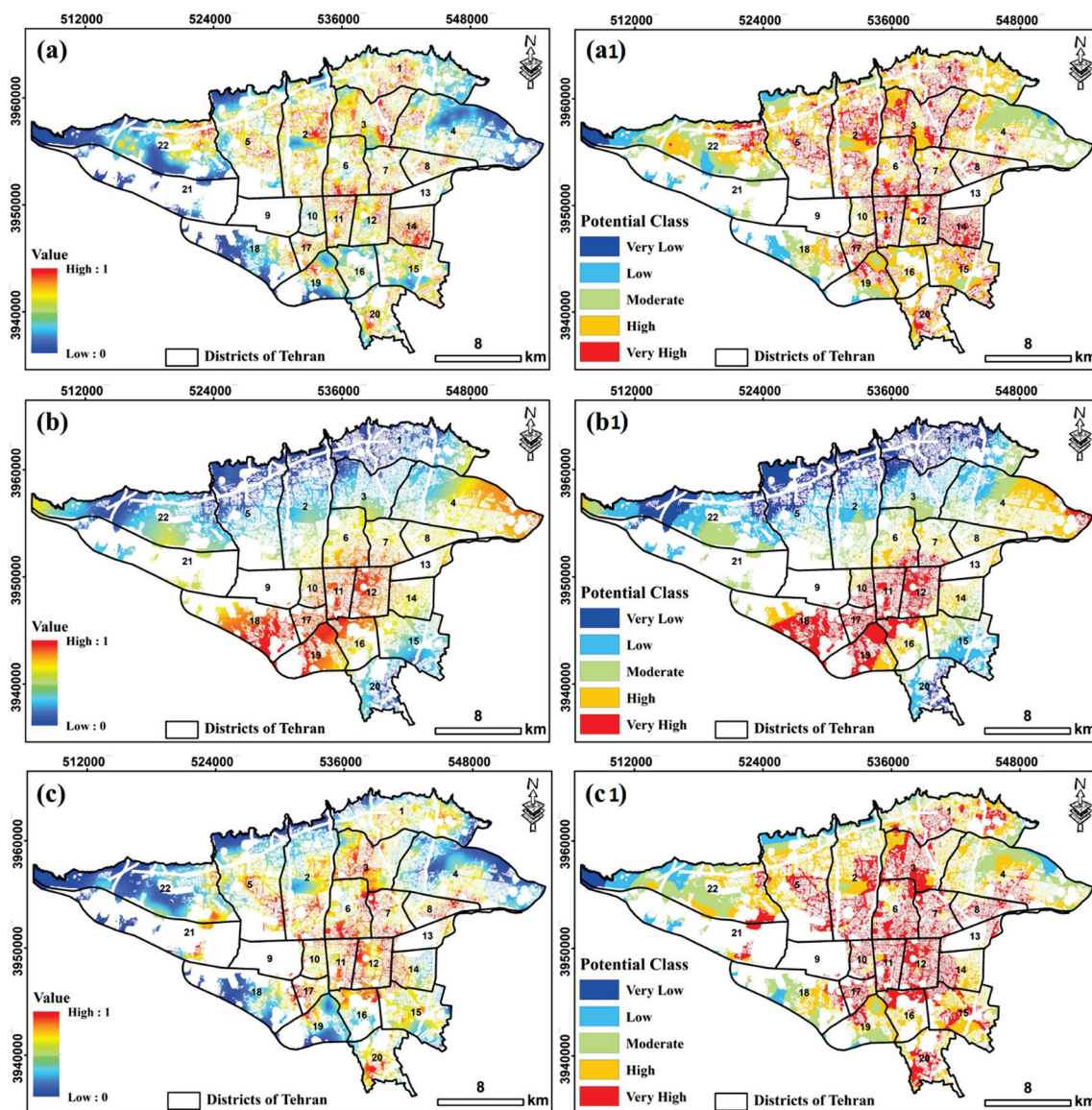


Figure 8. Integrated maps of sports facility potential: (a,a1) standardized and classified compatibility map; (b,b1) standardized and classified environmental map; (c,c1) standardized and classified infrastructure map.

The analysis of the areas of the different classes in the compatibility, environmental, and infrastructural criteria reveals a varied distribution of sports facility development potential across Tehran (Figure 9). In the compatibility criterion (Figure 9a), the largest areas belong to the high potential class (88.95 km²) and the moderate potential class (54.05 km²), indicating that a significant portion of the city has favorable conditions for establishing sports facilities. In contrast, the very low class covers a very small area (3.35 km²). In the environmental criterion (Figure 9b), the distribution is more balanced; the very low potential class (42.3 km²) and the very high potential class (35.37 km²) suggest that while some areas are highly unsuitable, others are highly suitable for development. Additionally, the moderate potential class, covering 56.73 km², holds the largest share, reflecting a relatively even spatial distribution of environmental factors in the city. In the infrastructural criterion (Figure 9c), the very high (70.13 km²) and high potential (71.86 km²) classes account for most of the area, indicating widespread access to adequate infrastructure. In contrast, the very low class has the smallest share (3.08 km²), suggesting that only a few areas suffer from severe infrastructure deficiencies for sports facility development. Overall,

the infrastructural factors present more favorable conditions for development compared to the other two criteria, while the environmental factors exhibit a more uneven distribution, and the compatibility remains at a high level of suitability.

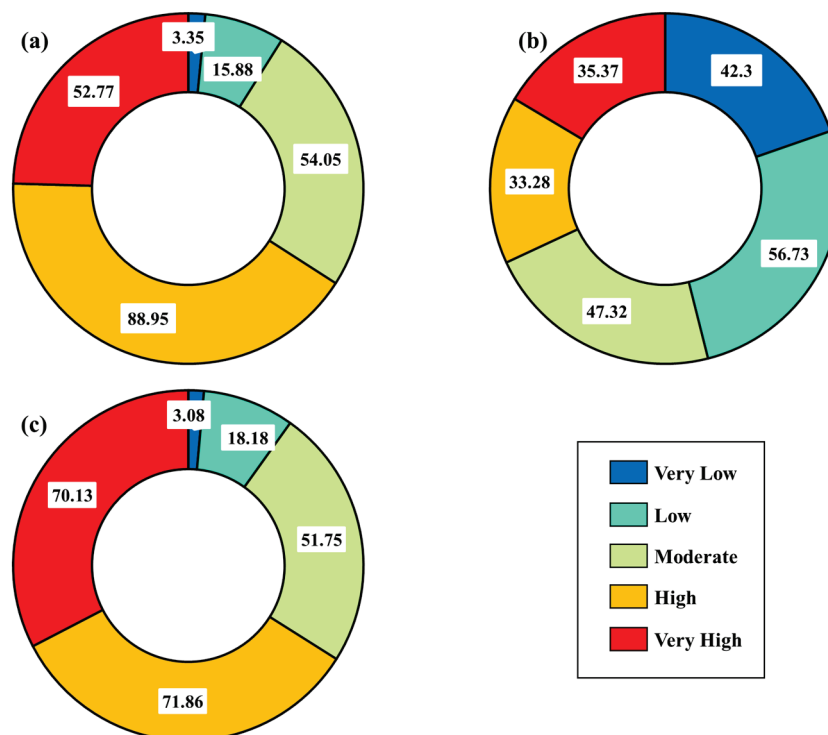


Figure 9. Areas of different classes of potential for the development of sports facilities (km²), (a) compatibility criterion, (b) environmental criterion, (c) infrastructural criterion.

The analysis of the final potential map for sports facility development in Tehran reveals a distinct spatial distribution pattern across different suitability classes. According to the normalized map (Figure 10a), the northern and western parts of the city predominantly exhibit low potential values (blue colors), while the central and southern areas show higher potential in certain sections. In the classified map (Figure 10b), the very low potential class (blue color) can be mainly observed in the northern and some western areas, indicating significant limitations for sports facility development in these regions. In contrast, the high and very high potential classes (orange and red colors) are more widely distributed in the central and parts of the southern and southeastern areas, likely due to higher population density, better infrastructure accessibility, and favorable environmental conditions. Examining Figure 10c, the moderate potential class covers the largest area, with 69.14 km², indicating that a substantial portion of the city holds moderate potential for sports facility development. Following this, the high (67.26 km²) and very high (48.58 km²) potential classes demonstrate that nearly half of the city has favorable conditions for development. Conversely, the very low (3.18 km²) and low (26.84 km²) potential classes occupy the smallest areas, suggesting that the highly unsuitable areas for sports facility development are limited. At the district level, the central and southern districts (such as districts 10, 11, 16, and 17) exhibit higher potential due to their high population density and better access to urban infrastructure. In contrast, the northern districts (such as districts 1 and 2) and certain western areas (such as district 22) display lower potential values, likely due to topographical constraints, environmental limitations, and lower population density. Overall, the spatial distribution of potential classes indicates that the central and southern areas have the highest suitability for sports facility development, whereas the northern and certain western regions face greater constraints in this regard.

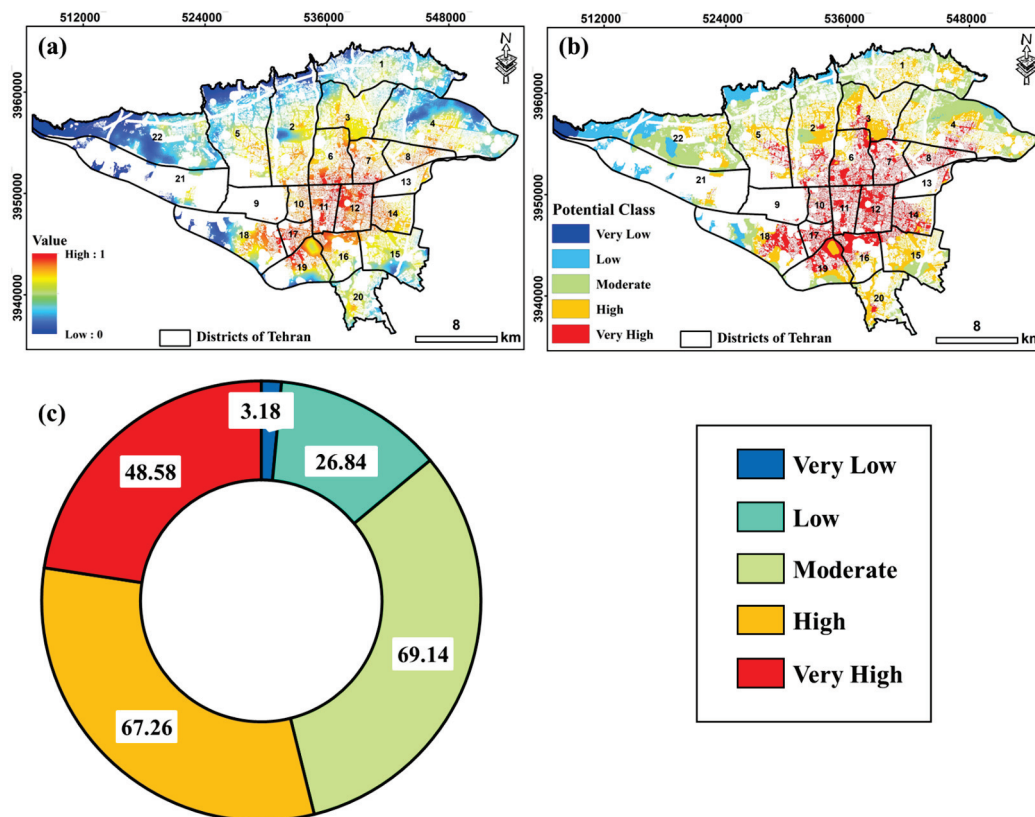


Figure 10. Potential map of sports facility development using the integration of the maps of compatibility, environmental, and infrastructure criteria, (a) standardized map, (b) classified map, (c) areas of different classes of potential (km²).

In the final stage, a validation process was incorporated into the research to assess the accuracy of the spatial modeling results (Figure 11). This validation included a visual inspection of satellite images, field visits, and a comparison with the proposed model's results. Based on the provided map, the spatial analysis of the selected locations for optimal sports facility allocation indicates that the areas with very high potential (marked in red) are primarily concentrated in the central and densely populated urban regions of Tehran. These areas offer favorable conditions for sports facility development in terms of population density; accessibility to the road network; and proximity to key land uses such as educational centers, public spaces, and residential zones. Additionally, the satellite imagery analysis confirms that the selected locations provide adequate space for the construction of sports complexes in terms of size and physical characteristics. Many of these sites are situated in underutilized land or open urban spaces, allowing for efficient land use. Furthermore, their proximity to major transportation routes facilitates easy access for citizens, which can contribute to greater public participation in sports activities.

In addition to the visual and spatial validation, a quantitative evaluation of the model was conducted using two performance indicators—the proportion of existing sports facilities located in each suitability class and the corresponding prediction rate [46] (Table 3). This approach provided a more objective measure of the model's effectiveness in identifying optimal locations. The results of this assessment demonstrate a strong correlation between the model's predictions and the actual distribution of sports facilities. Notably, 45% of the existing facilities were located in the very high suitability class, which also recorded the highest prediction rate of 1.99. This indicates a strong spatial match and confirms that the model successfully prioritizes the most appropriate areas for development. The high

suitability class further supports this trend, containing 37% of the existing facilities and achieving a prediction rate of 1.17.

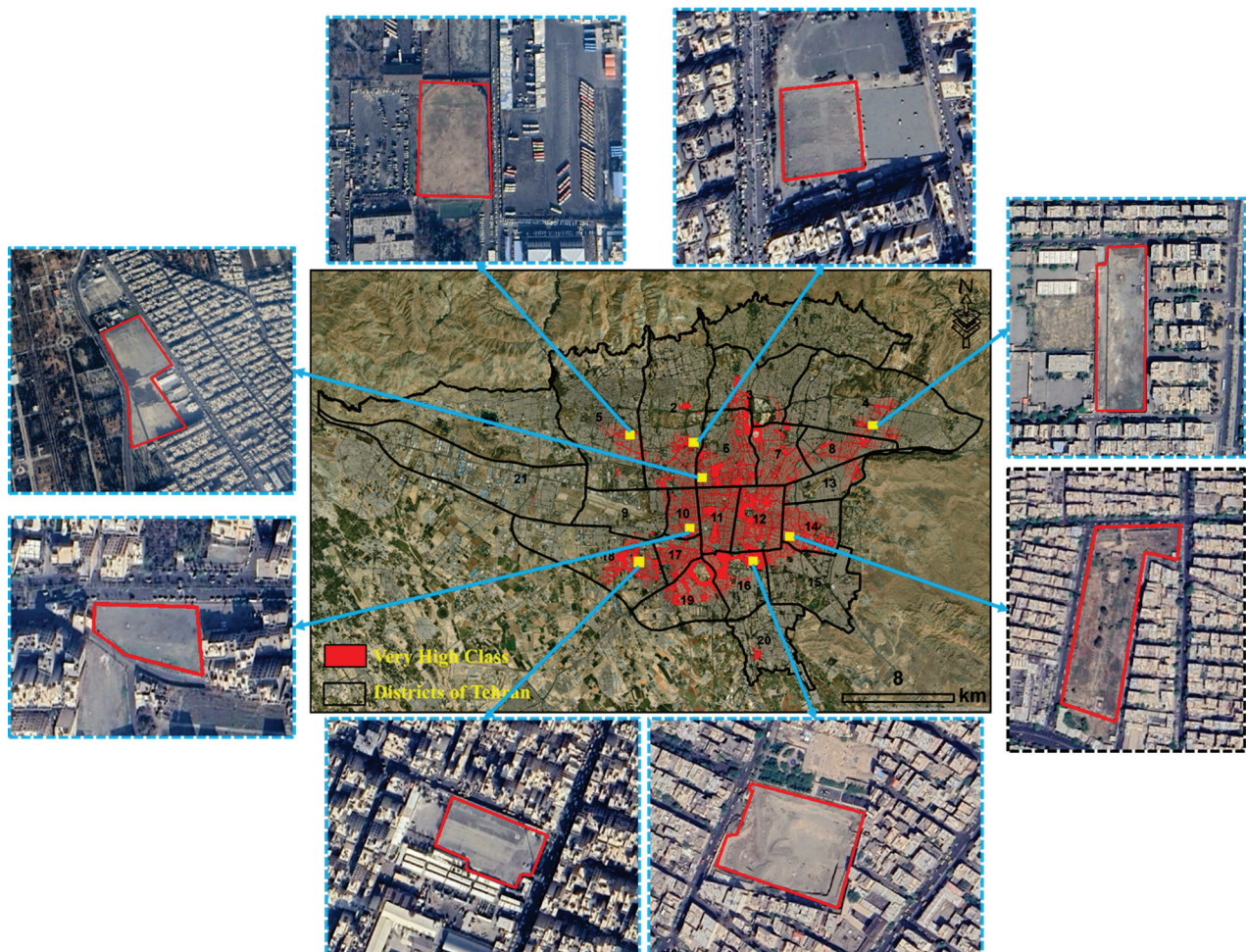


Figure 11. Validation of spatial modeling results for the very high potential class using Google Earth satellite image and field visits.

Table 3. Distribution of existing sports facilities and prediction rate across spatial potential classes.

Potential Class	Proportion of Existing Sports Facilities (%)	Prediction Rate
Very Low	0.00	0.00
Low	0.01	0.12
Moderate	0.17	0.52
High	0.37	1.17
Very High	0.45	1.99

Together, these two classes account for over 80% of the current sports facility locations, validating the model's ability to identify and prioritize highly viable zones. Equally significant is the model's capacity to accurately exclude less suitable areas. The low and very low classes include only 1% and 0% of the existing facilities, respectively, with prediction rates near zero. This demonstrates the model's reliability not only in identifying optimal areas but also in effectively minimizing false positives in unsuitable zones. Overall, the high concentration of existing facilities in top-ranking suitability classes, combined

with the strong prediction rates, confirms the robustness of the spatial model. It reflects a well-calibrated and evidence-based methodology that can be confidently used to support future decision-making for sports facility site planning and urban development.

4. Discussion

The integration of different maps and models for evaluating the optimal allocation of sports facilities in a specific region can help optimize the decision-making process and identify the most suitable locations for the establishment of these facilities. Properly locating sports facilities by considering multiple criteria such as compatibility with urban land uses, environmental conditions, and access to infrastructure allows for the maximum utilization of these spaces and enhances the effectiveness of urban investments. This process is particularly important in areas that require the integration of various social, economic, and environmental factors. One of the main challenges in this regard is the fair and efficient distribution of sports facilities in accordance with the demographic and spatial needs of the city. For instance, areas with high population density require more sports infrastructure, while areas prone to environmental hazards such as flooding or earthquakes need to be carefully selected for facility development. Among the compatibility criteria, the population density and residential areas are of greater importance and weight. These factors play a crucial role in determining the optimal locations for sports facilities, as densely populated areas tend to have a higher demand for such amenities. Among the environmental criteria, the earthquake risk has been identified as a key factor, ensuring that sports facilities are located in areas less prone to earthquakes. Regarding the infrastructural criteria, accessibility to public transportation has shown significant importance, as easy access to these facilities encourages greater public participation. Furthermore, the compatibility criteria have been found to be more influential than environmental and infrastructural criteria in the decision-making process for site selection. This suggests that ensuring harmony with existing urban land use and demographic patterns is more critical than environmental constraints or infrastructural considerations when determining the optimal allocation of sports facilities. The findings of this study align with and expand upon previous research in the field. For instance, studies such as those by Higgs et al. [47] and Namazi et al. [8] similarly emphasized the importance of compatibility and population density in determining optimal locations for urban facilities. Other studies have employed multi-criteria approaches and GIS-based models to assess spatial equity and accessibility, yet many have not integrated a set of infrastructural, environmental, and compatibility criteria as comprehensive as that used in this research. Moreover, unlike some prior studies that primarily focused on technical optimization, this study also highlights social considerations such as spatial justice and equity in underserved areas. This broader approach contributes to a more holistic understanding of sports facility planning in urban settings.

The AHP method, as one of the most widely used techniques in multi-criteria decision-making, has gained significant importance among researchers and specialists. This method enables the precise weighting of criteria and prioritization of options through pairwise comparisons. Due to its hierarchical structure, the AHP allows decision-makers to evaluate different criteria at various levels and determine their relative weights. Unlike some decision-making methods that require complex mathematical processing, the AHP provides a clear and logical framework, enabling the simultaneous analysis of both qualitative and quantitative criteria [48]. One of the key advantages of this method is the validation of results through the calculation of the CR, which allows for checking the accuracy and coherence of the judgments made [49]. A low CR value indicates high consistency in pairwise comparisons and the reliability of the results. Furthermore, the AHP method performs optimally in complex decision-making processes that require combining spatial

and non-spatial data, especially when integrated with the GIS method, and provides the ability to select the most optimal option based on the calculated weights for the criteria.

GIS methods are widely used in evaluation and optimal allocation projects. These systems are particularly effective when there is a need to analyze spatial and geographic data. One of the main advantages of the GIS method is its ability to integrate various data and criteria, including social, environmental, infrastructural, and economic factors, into a unified system [50]. This data integration, especially in complex projects involving multi-criteria assessments of suitable locations for sports facilities, can help clarify the results and improve decision-making. Alongside the GIS method, SMCDA methods are also recognized as important tools for sports facility location planning. These models have the ability to analyze and evaluate different criteria within a geographic framework and can assist in identifying optimal locations for developing sports facilities. Especially in areas with specific geographical features and environmental or infrastructural challenges, SMCDA methods can, using spatial and geographic data, determine the best locations for constructing these facilities.

One of the key goals of this study beyond the technical optimization of facility locations was to contribute to social equity and spatial justice. While the model applies spatial and infrastructural criteria, a special emphasis was placed on identifying underserved and disadvantaged communities by including indicators such as high population density levels and a lack of existing sports infrastructure. This allowed the model to prioritize areas, particularly in the southern districts of Tehran, which are socioeconomically less advantaged. By directing new facility development toward these regions, the proposed approach actively promotes more equitable access to sports services and helps reduce urban disparities. Therefore, the GIS-SMCDA integration used in this study is not only a technical tool but also a means of operationalizing social justice in urban planning.

The varying levels of suitability identified across Tehran's urban landscape can be explained by spatial inequalities in demographic distribution, infrastructure access, and environmental safety. For example, the central and southern districts with higher population densities and limited existing sports infrastructure were deemed more suitable due to both demand-based criteria and equity considerations. In contrast, environmentally sensitive zones such as floodplains or areas near fault lines scored lower, regardless of demand. These differences reveal a causal interaction among the criteria; for instance, the combination of a high population density and poor infrastructure magnifies the need and increases the priority for facility development. Moreover, urban planning issues such as unbalanced land use patterns, historical investment gaps, and irregular service distributions have contributed to the current spatial disparities. Recognizing and addressing these underlying causes is essential for sustainable and equitable sports facility planning.

This research faces challenges and limitations that should be addressed in future studies. One of the biggest challenges is the accuracy and reliability of spatial data used in GIS evaluations for locating sports facilities. Data such as land use maps, transportation networks, and satellite images may be affected by factors such as seasonal changes or technological limitations, which could reduce the accuracy of the analyses. Additionally, expert opinions were used for weighting criteria in this study, which could lead to inconsistencies and errors in prioritizing the factors. These subjective evaluations might influence the results of the potential analysis for sports facility development. It should also be noted that the WLC method assumes linear and additive relationships among criteria, which may oversimplify real-world spatial dynamics. In reality, complex and non-linear interactions may exist between variables (e.g., population density and service accessibility). Future studies are recommended to explore alternative decision models, such as fuzzy logic or machine learning-based approaches, to better capture these complexities.

In addition, it is essential that special attention be given to the economic and social dimensions of sports facility development in future research. Analyses such as cost-benefit simulations and assessments of citizen engagement with sports facilities and the social and cultural impacts of these centers can play a significant role in accurately evaluating the potential of different areas for developing such spaces. Furthermore, integrating various models, including economic, social, and environmental analyses, is recommended to provide a comprehensive framework for the allocation of sports facilities, ensuring that all influencing factors are considered simultaneously. Additionally, conducting sensitivity analyses and examining uncertainties in the location selection process can help reduce errors arising from inaccurate data or expert judgments, thereby enhancing the decision-making accuracy. Finally, advanced simulations and spatial optimization models can contribute significantly to a more precise evaluation of suitable areas for establishing sports facilities and creating a balanced and efficient network of such amenities at the urban and regional levels.

5. Conclusions

This study, by presenting a novel managerial approach, comprehensively evaluated potential locations for the optimal siting and allocation of sports facilities in Tehran, considering environmental conditions, infrastructure, and compatibility. The findings of this research demonstrated that the use of GIS-based multi-criteria decision-making methods can play a significant role in the optimal location selection of sports facilities. The analysis of various criteria revealed that compatibility with the urban environment has the greatest impact on the decision-making process, followed by infrastructural and environmental criteria. The findings indicate that the central and southern areas of the city, particularly districts 10, 11, 16, and 17, have the highest potential for the development of sports facilities due to their high population density, proximity to educational centers, and favorable access to transportation infrastructure. In contrast, the northern and western areas face less favorable conditions due to their steep slopes, environmental risks, and weaknesses in public transportation infrastructure. The clustered distribution of sports facilities across the city indicates an uneven dispersion, leaving some areas deprived of adequate access to these amenities, emphasizing the necessity of a fair redistribution. Moreover, the use of the AHP method, due to its capability in structuring the decision-making process and accurately weighting criteria, is considered an effective approach for the location selection of sports facilities. In this study, the application of this method enabled the simultaneous analysis of multiple criteria based on spatial data. Given the importance of equitable access to sports services and the impact on citizens' quality of life, the findings of this study can assist urban planners in promoting sustainable development and optimizing the allocation of sports facilities. This study has several limitations, including potential inaccuracies in spatial data, a reliance on expert judgment for criteria weighting, and the assumptions inherent in the WLC method. These factors may affect the precision of the location analysis. It is recommended that future studies incorporate more precise data, advanced machine learning models, and enhanced sensitivity analyses to improve the accuracy and feasibility of the resulting recommendations, thereby strengthening evidence-based and data-driven urban planning.

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