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Sustainable green corridor planning in Tekirdağ, Turkey, using the least-cost path approach

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Abstract: The rapid expansion of urban areas and the increasing impacts of climate change have intensified pressures on natural ecosystems worldwide. These challenges disrupt biodiversity, fragment habitats, and undermine ecosystem services critical for human well-being. As urbanization accelerates, innovative approaches are needed to maintain connectivity between natural and urban areas while addressing ecological, socio-economic, and recreational needs. This study focuses on Tekirdağ Province as a case study to explore the potential of sustainable green corridor planning in a region facing significant urban and agricultural pressures. Using the Least-Cost Path (LCP) method, spatial data layers including slope, stream networks, transportation routes, and land use were analyzed with GIS to design corridors connecting core natural areas with urban centers. The proposed green corridors prioritize low-gradient terrains and first- and second-order streams, utilizing agricultural lands as multifunctional transition zones to enhance recreational accessibility while preserving natural habitats and minimizing environmental degradation. This study contributes to the literature by demonstrating the effectiveness of the LCP method for local-scale green corridor planning. It demonstrates how this method effectively addresses regional challenges in areas facing the dual pressures of urbanization and agricultural activity. Detailed GIS-based analyses advance data-driven decision-making in corridor design. The proposed network offers a balanced model for conserving natural habitats while accommodating urban demands, contributing to sustainable urban development. Conducted in the Turkish context, this study provides a replicable framework for other regions. Future research should evaluate the long-term sustainability of these corridors, incorporating stakeholder input and real-time data to further optimize connectivity and multifunctionality.
Keywords: *Connectivity pathways, Green corridor, Green infrastructure, Least-cost path, Sustainable urban planning.*

1. Introduction

The rapid expansion of urban areas has increasingly widened the gap between natural ecosystems and human settlements, leading to significant biodiversity loss and exacerbating environmental challenges [1].This urbanization-driven fragmentation diminishes ecosystem services, such as air purification, carbon sequestration, and biodiversity conservation, which are critical for human health and well-being [2]. Compounding these challenges, the escalating impacts of climate change intensify the need for preserving and restoring ecosystems to enhance resilience and maintain their essential functions [3].

In this context, sustainable green corridors have emerged as vital strategies for bridging the divide between urban and natural areas, offering pathways that maintain ecosystem services while facilitating ecological and recreational connectivity. Green corridors play a multifaceted role, establishing linkages

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between forests, agricultural lands, and natural habitats, thereby preserving biodiversity and supporting ecosystem functionality [4]. These corridors also enable wildlife movement and contribute to the effective delivery of ecosystem services, all while addressing the growing demands of urban populations for recreational spaces [5].

Central to green corridor design is the concept of landscape connectivity, a critical component of conservation planning, especially in fragmented environments where ecological pathways are essential for maintaining biodiversity [6]. Landscape ecology provides the theoretical foundation for these efforts, emphasizing the interplay of patches (homogeneous ecosystem units), corridors (connective pathways), and the surrounding matrix [7, 8]. Integrating these elements ensures the continuity of ecosystems and enhances their resilience to external pressures [9].

To address these challenges, innovative methodologies such as the Least-Cost Path (LCP) analysis have gained prominence. This GIS-based approach calculates cost-efficient routes by analyzing environmental and land-use data, minimizing habitat disruption while optimizing ecological connectivity [10]. The LCP method has demonstrated its versatility across diverse planning contexts, from infrastructure development to ecological conservation, by integrating environmental, social, and economic criteria [11, 12]. Experimental studies validate its effectiveness in fragmented urban landscapes, showcasing its potential for both ecological and recreational planning [12].

This study focuses on Tekirdağ Province, Turkey, aiming to develop a sustainable green corridor plan using the Least-Cost Path method. By analyzing environmental data and land-use patterns, the study identifies low-cost transition routes that enhance connectivity between urban centers and surrounding natural habitats. Adopting a landscape ecology perspective, this research contributes to ecosystem conservation, sustainable urban planning, and local environmental management. It aligns with the European Landscape Convention's goals [13] advancing strategies for the conservation, planning, and management of landscapes. Additionally, the proposed green corridor model incorporates recreational uses, ensuring that ecological sustainability is balanced with human needs in the region.

2. Materials and Methods

2.1. Methodology

The methodology of the study is structured around a comprehensive sequence of nine distinct stages, each carefully designed to ensure a systematic approach to achieving the research objectives.

- Selecting the study area: Identifying Tekirdağ Province as the focus of the study.
- Determining the characteristics of the study area: Gathering detailed information on the area's ecological, geographical, and cultural attributes.
- Collecting data: Utilizing local reports, maps, and field observations to compile a comprehensive dataset.
- Data organization in GIS: Arranging the collected data in ArcGIS 10.8 and creating a geodatabase for analysis.
- Georeferencing and projection: Projecting data to the WGS 84-35N coordinate system for spatial accuracy.
- Data analysis: Conducting analyses using slope, hydrology, transportation, and land use data to identify key patterns and features.
- Least-Cost Path (LCP) analysis: Applying LCP analysis to determine optimal transition routes.
- Mapping core areas and green corridors: Visualizing and mapping identified core areas and connecting green corridors.
- Defining and proposing green corridors: Recommending potential green corridors for implementation based on the analyses.

2.2. Study Area

This study focuses on Tekirdağ Province, located along the Marmara Sea coast in Turkey. Tekirdağ features a Mediterranean climate, with an average annual precipitation of 600 mm, which supports the region's vegetation and biodiversity [14]. Covering an area of 6,020 km², the province is predominantly agricultural but faces increasing pressure on natural habitats due to urbanization and industrial development [15, 16]. Prominent geographical features include the Istranca Mountains in the north and Tekir Mountain in the south, both of which contribute to the ecological health of the region. Water resources such as the Ergene River provide critical habitats for waterfowl and aquatic species, underscoring the ecological significance of the area [17].

The topography of Tekirdağ ranges from 37 meters above sea level near the coast to higher elevations in the north. This gradient influences natural water flow patterns and facilitates the formation of ecological and recreational corridors [18].

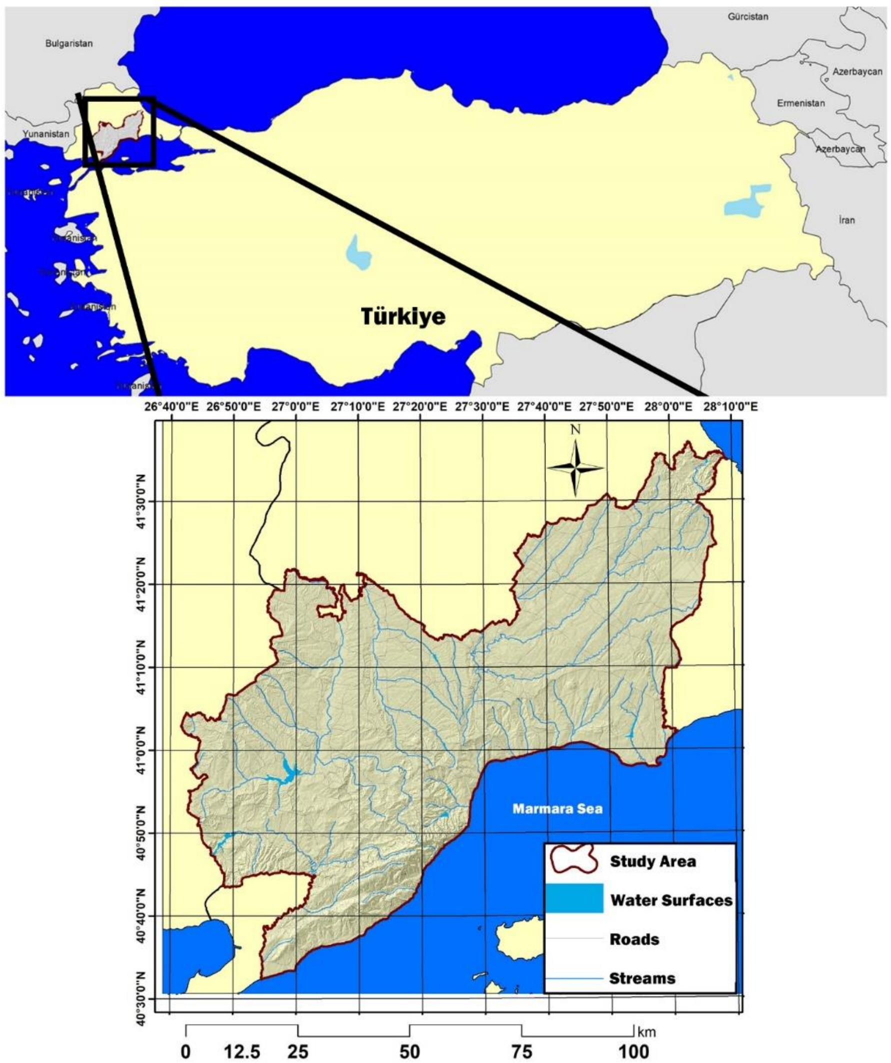

Figure 1.
Study area location.

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2.3. Method

This research adopts an analysis approach based on ecological, hydrological, and topographic data to establish green corridors in Tekirdağ province. The primary goal of the study is to design sustainable green corridors that support natural resources and ecosystem services in the region.

2.3.1. Data Collection

Data on topography, soil structure, vegetation, water resources, and land use were collected from local authorities, environmental reports, and published literature [14, 19]. The data were georeferenced and organized into a Geographic Information System (GIS) framework, allowing for detailed spatial analysis.

2.3.2. Identification of Core Areas

In this study, regions with sustainable functions such as the presence of coniferous, broad-leaved, and mixed forests, as well as water bodies were identified using the 2018 CORINE Land Cover data. Additionally, important natural areas data from the study by Eren and Acar [20] were considered [21]. These areas have been designated as "Core Areas as Recreational Hubs," forming the basis of the proposed green corridor network [22].

2.3.3. Least-Cost Path Analysis and Corridor Design

The Least-Cost Path (LCP) method was utilized to design green corridors connecting urban centers to core areas. This GIS-based approach calculates the minimum cumulative cost of movement across a cost surface, incorporating key factors such as habitat disturbance, land-use types, slope, and geographical features to optimize connectivity and minimize environmental disruption [10, 23]. The primary objective of the LCP analysis was to enhance biodiversity, strengthen ecosystem connectivity, and reduce ecological barriers.

Key parameters considered in the LCP analysis included:

- Streams: First- and second-order streams were prioritized as critical biodiversity corridors, forming the backbone of ecological connectivity [24].
- Slope: Low-slope areas were emphasized to reduce construction and ecological costs, ensuring the feasibility and sustainability of corridors [25].
- Transportation Networks: Local roads were integrated to facilitate community access, while buffer zones were established to minimize environmental impacts. Specifically, 100-meter-wide buffer zones were designated around major roads and highways, and 30-50-meter-wide buffers were applied to local roads, effectively reducing habitat fragmentation and mitigating environmental degradation risks [9, 26].
- Agricultural Lands: These were incorporated as multifunctional transition zones that balance ecological and recreational connectivity, while also preserving socio-economic values [27].

Natural areas were classified as low-cost zones, promoting ecological flow, while urbanized and industrial areas were categorized as high-cost zones due to their environmental resistance [28]. GIS tools, including ArcGIS and QGIS, facilitated the analysis of comprehensive datasets such as CORINE land cover, slope maps, water resources, and transportation networks [29].

To ensure accessibility, a walking distance threshold of 1,000 meters from recreational focal points, such as villages and districts, was applied [30]. Settlements closest to these focal points were prioritized, aligning with the goal of integrating human activity with ecological connectivity.

The evaluation framework for the Least-Cost Path (LCP) analysis assessed the suitability of various parameters for enhancing connectivity. Transportation routes were classified and buffered to minimize habitat fragmentation and environmental disruptions. Streams were ranked by their ecological importance, emphasizing first- and second-order streams as critical pathways. Slopes were categorized to prioritize low-gradient areas, ensuring cost-effective and environmentally sustainable pathways.

Agricultural lands were evaluated as multifunctional transition zones, serving as ecological, recreational, and socio-economic bridges. Table 1 provides a detailed summary of these criteria and their relevance in corridor design.

Table 1.
Evaluation framework for least-cost path analysis in green corridors.

Criterion	Evaluation metric	Values	Relevance
Transportation routes	Road Type	Low density roads (High), Railway (High), Main Roads (Medium) Highways (Low)	Facilitate connectivity by reducing fragmentation, with buffer zones mitigating environmental impact [9, 26].
Streams	Stream order ranking	1st and 2nd order streams (High) 3rd, 4th and 5th order streams (Low)	Provide critical biodiversity pathways, enhancing ecological flow and connectivity [24].
Slope data	Categorized gradient ranges	High (0-5%-Low), Medium (5-15%-Medium) Low (< 15-High)	Prioritize low-gradient areas for cost-effective and environmentally sustainable corridor design [25].
Agricultural land	Multifunctional transition zones	Medium	Act as ecological and recreational transition zones, integrating socio-economic and ecological objectives [27].

3. Findings

The findings of this study identified critical core areas in Tekirdağ Province to enhance ecosystem connectivity through the design of sustainable green corridors. Using 2018 CORINE Land Cover data, natural habitats such as forests, wetlands, and water bodies were classified as key zones supporting biodiversity and maintaining essential ecosystem processes. The Terkos Basin emerged as a significant core area due to its ecological richness and high biodiversity value.

The spatial distribution of these core areas demonstrated their strategic placement to support ecological connectivity, as illustrated in Figure 2. The analysis highlighted the importance of low-slope areas and first- and second-order streams in optimizing connectivity while minimizing environmental degradation. These findings provide a foundation for planning green corridors that integrate ecological, recreational, and socio-economic functions effectively.

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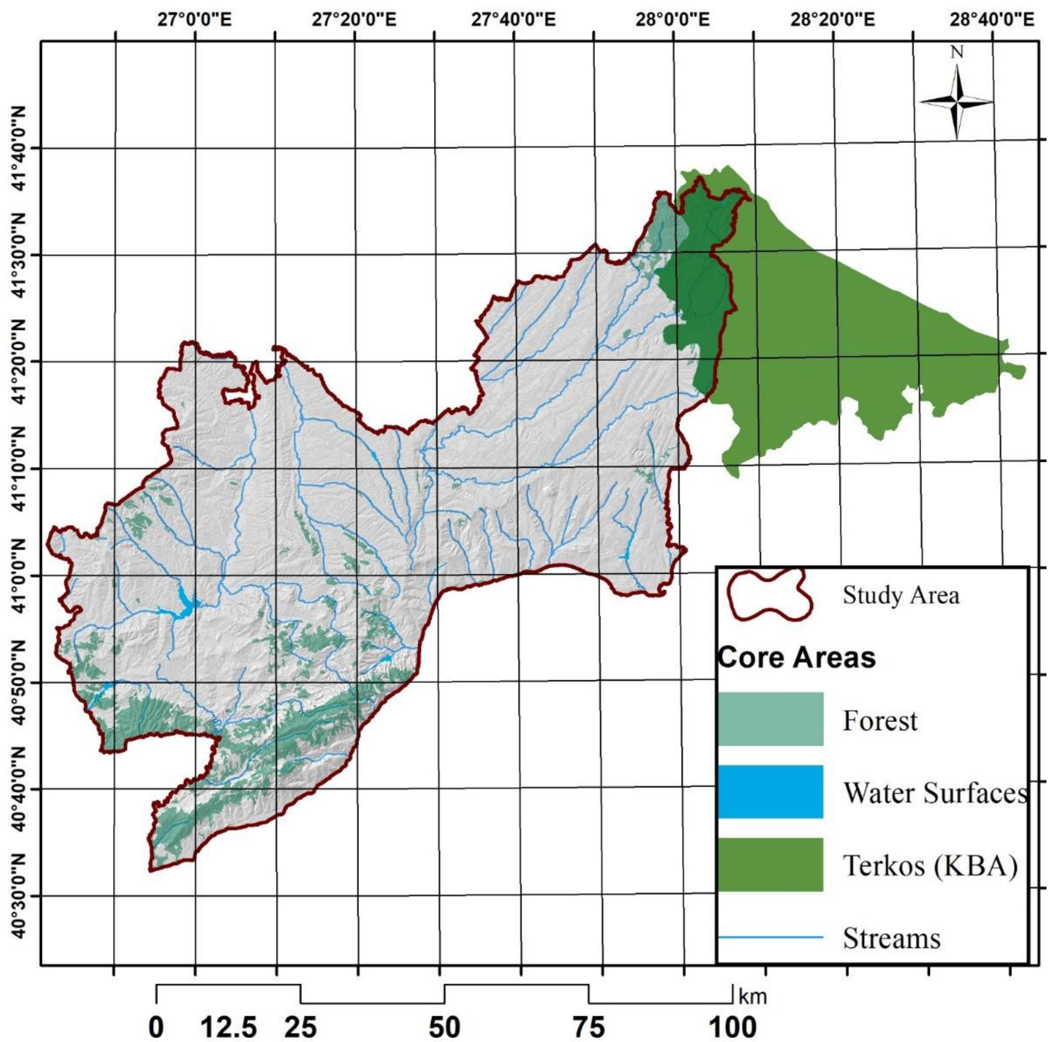

Figure 2.
Spatial distribution of identified core areas.

To facilitate the Least-Cost Path (LCP) analysis, key spatial data layers were compiled and categorized based on their relevance to ecological and recreational corridor design (Figure 3). These layers included the transportation network map, stream order map, slope map, and land use and land cover (LULC) map. The transportation network map helped identify areas where buffer zones could minimize habitat fragmentation, while the stream order map prioritized first- and second-order streams for their critical role in supporting biodiversity and ecological flow [24]. The slope map emphasized low-gradient areas to ensure the feasibility and sustainability of the corridors, and the LULC map facilitated the classification of natural, agricultural, and urban areas, with agricultural lands serving as multifunctional transition zones. Each layer was carefully processed to highlight its contribution to corridor suitability, ensuring a balance between ecological, recreational, and socio-economic objectives.

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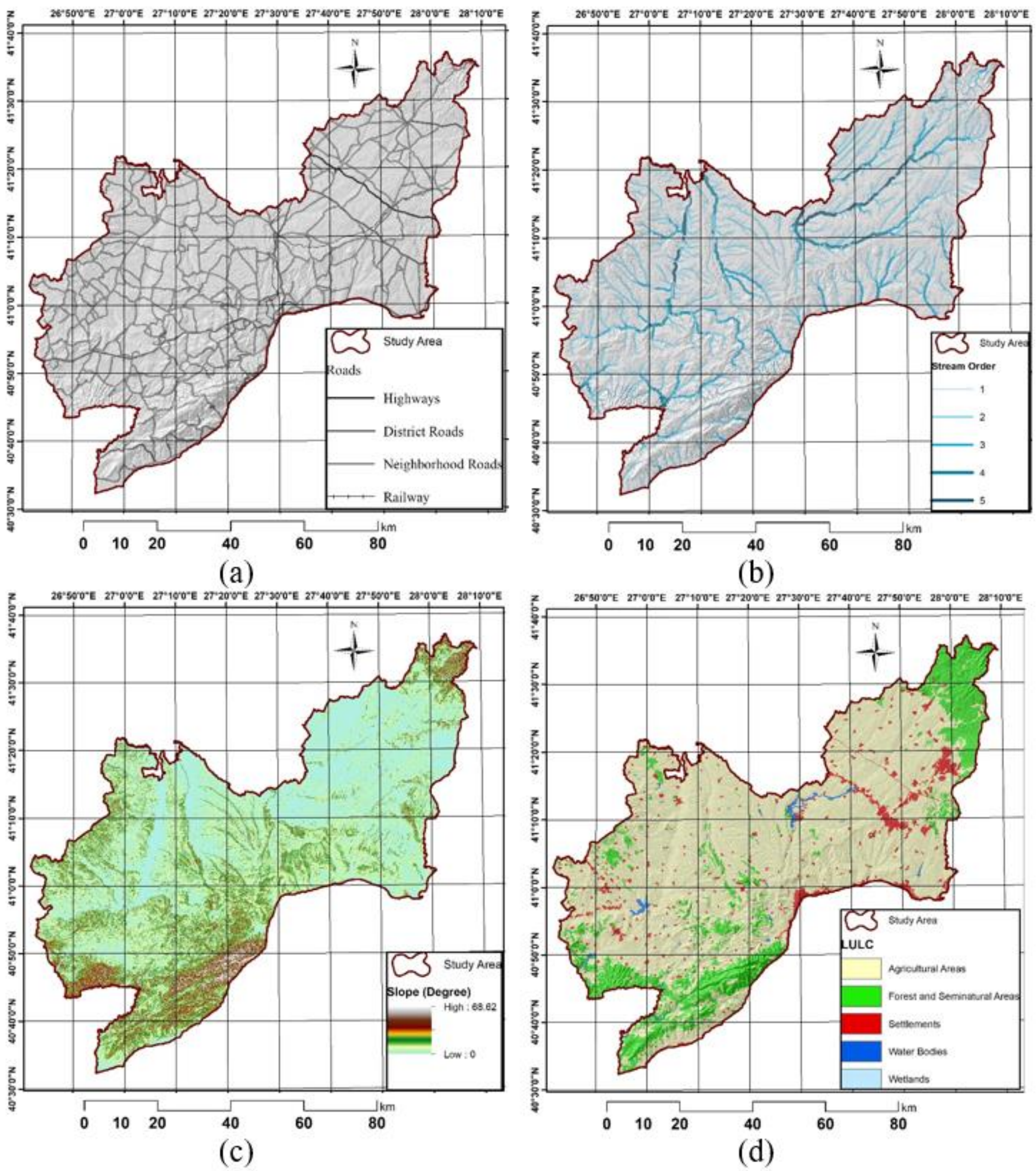

Figure 3.
Spatial data layers used in analysis (a) Transportation network map, (b) Stream order map, (c) Slope map, (d) Land use and land cover (LULC) map.

The weighted overlay map (Figure 4a) integrated key factors such as slope, land use, and proximity to streams to identify areas with the highest potential for ecological connectivity. This map formed the basis for the LCP analysis by highlighting regions where green corridors would provide the greatest ecological and recreational benefits. The cost distance raster (Figure 4b) visualized the cumulative cost of movement originating from core areas, enabling the identification of optimal pathways that minimize environmental disruption. Additionally, the cost backlink raster (Figure 4c) offered critical directional data for LCP calculations, ensuring that the proposed corridors adhered to paths of least resistance while accounting for influential factors such as land use patterns and terrain characteristics.

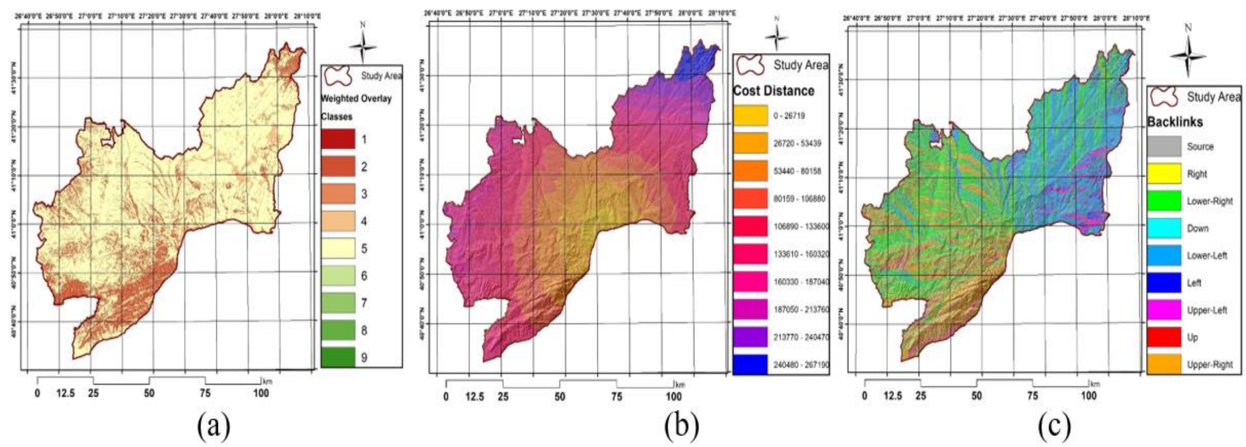

Figure 4.
Key outputs of the least-cost path (LPC) analysis (a) Weighted Overlay Map, (b) Cost Distance Raster, (c) Cost Backlink Raster.

These analyses culminated in the design of sustainable green corridors connecting the Süleymanpaşa city center to identified core areas. Agricultural lands were integrated as multifunctional transition zones, balancing ecological connectivity with recreational functions. This approach provided dual benefits: enhancing ecosystem conservation while offering socio-economic value to local communities.

The proposed green corridors were optimized to align with low-gradient terrain (3%-15% slopes) and natural streamlines, with first-order streams serving as the backbone of the network and second-order streams enhancing ecological connectivity. Transportation infrastructure was integrated thoughtfully, prioritizing local roads and railways to ensure accessibility while minimizing environmental impacts. Major roads were incorporated with appropriately sized buffer zones to mitigate habitat fragmentation and ecological disruption.

The connectivity map (Figure 5) demonstrates how these key elements—transportation networks, streams, slopes, and agricultural lands—were cohesively integrated to form a sustainable green corridor network. The resulting design not only supports biodiversity conservation but also provides opportunities for human-nature interactions, fostering recreational activities that align with ecological sustainability principles. This network highlights the potential of green corridors to establish a balanced relationship between urban development and natural ecosystems, addressing the dual challenges of urbanization and climate change.

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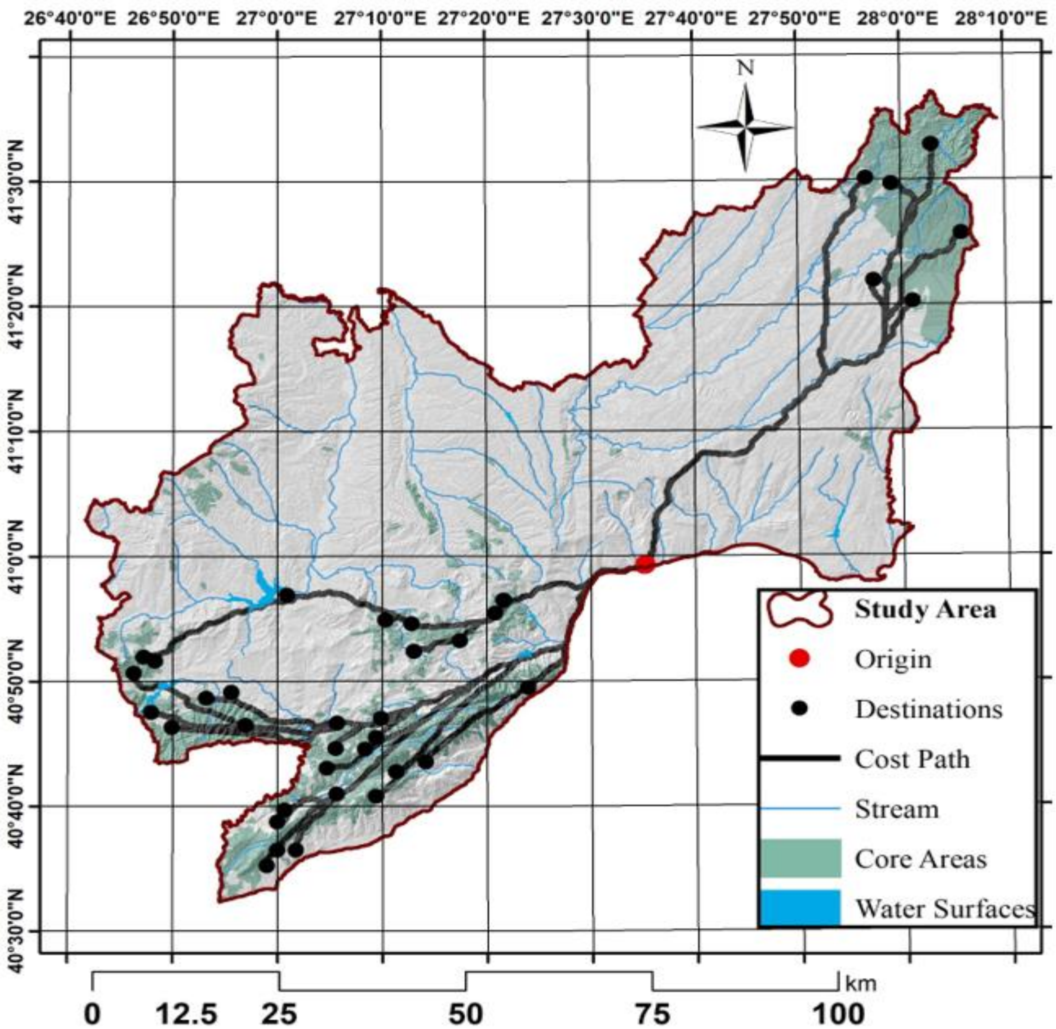

Figure 5.
The proposed green corridor network map.

4. Conclusion and Discussion

This study addresses the dual challenges of urbanization and biodiversity conservation by establishing a strategic framework for designing sustainable green corridors. Using the Least-Cost Path (LCP) method, the research highlights the potential of green corridors to enhance ecological connectivity while minimizing environmental disruption. In Tekirdağ Province, the proposed corridors utilized low-gradient terrains and prioritized first- and second-order streams, effectively reducing habitat fragmentation. Buffer zones around major roads were incorporated to mitigate ecological degradation, while agricultural lands were successfully integrated as multifunctional transition zones, balancing ecological and recreational needs.

The findings demonstrate the effectiveness of the LCP method in optimizing environmental and economic costs, making it a valuable tool for ecological network design. These results align with prior research, such as Adriaensen, et al. [28] and Tang, et al. [10] which underscore the method's efficiency in designing cost-effective and ecologically sensitive pathways [10, 28]. Prioritizing first- and second-order streams further emphasizes their role in maintaining biodiversity and ecosystem processes, as highlighted by Strahler [24] and Forman [7]. Furthermore, the integration of agricultural lands as ecological transition zones provided dual benefits for biodiversity conservation and recreational accessibility. This approach, consistent with findings by Jongman [31] and Turner [32] highlights the potential of agricultural landscapes to act as ecological bridges between natural and urban environments [31, 32].

Beyond ecological benefits, the proposed green corridors offer substantial socio-economic advantages. Integrating buffer zones along major roads and incorporating local roads with minimal environmental impact enhances accessibility while preserving ecological integrity. These features foster human-nature interactions, improve recreational opportunities, and enhance quality of life, as highlighted by studies such as Tyrväinen and Väänänen [33] and Teng, et al. [5]. This multifunctional approach ensures that the corridors meet both ecological and societal needs, contributing significantly to sustainable urban development in Tekirdağ Province.

Despite its strengths, this study has certain limitations. Key environmental factors, such as soil permeability, surface runoff, and erosion, were not included in the analysis, which restricts the scope of ecological assessments. Incorporating these factors in future research, as suggested by Turner [32] and Fryirs and Brierley [25] could provide a more comprehensive evaluation of corridor sustainability [25, 32]. Additionally, the absence of socio-economic data, such as population density and recreational preferences, limits the ability to assess the broader societal impacts of the corridors. Including such data in future studies would enhance public engagement and ensure the long-term maintenance of green infrastructure projects, as noted by Benedict and McMahon [9].

Implementing the proposed green corridor network presents challenges, including technical feasibility, financial constraints, and the necessity for multi-stakeholder collaboration. Establishing effective governance frameworks, as emphasized by Jongman [31] will be critical to overcoming these challenges. Prioritization frameworks, such as those highlighted by Teng, et al. [5] could aid in resource allocation and maximize both ecological and socio-economic benefits. Field validation of LCP predictions, as suggested by Balbi, et al. [12] would also strengthen stakeholder confidence and facilitate successful implementation [5, 12, 31].

This study contributes to the growing body of literature on green infrastructure by addressing global challenges such as urbanization, habitat fragmentation, and climate change. By connecting urban centers with natural habitats, the proposed green corridors in Tekirdağ enhance biodiversity conservation and ecosystem resilience. These findings align with McDonald, et al. [34] and Ahern [35] who emphasize the role of green infrastructure in enhancing urban sustainability. Expanding this adaptable framework to other regions would allow for scalable applications of the LCP method, addressing diverse ecological and socio-economic contexts [34, 35].

Future research should explore advanced analytical techniques, such as kernel density analysis, to provide insights into corridor use intensity and connectivity prioritization. Additionally, integrating Multi-Criteria Evaluation (MCE), as suggested by Bagli, et al. [11] would enable planners to balance ecological, social, and economic objectives in green infrastructure projects. Scaling this approach to regional and national levels could significantly advance sustainable urban planning efforts globally Bagli, et al. [11].

By optimizing design approaches and strategically integrating diverse land uses, the proposed green corridor model serves as a replicable guide for other regions facing similar challenges. This framework supports the integration of ecological sustainability into urban planning, fostering the development of more resilient, livable, and environmentally adaptive cities on a global scale.

5. Recommendations

To enhance the effectiveness and ensure the long-term sustainability of the proposed green corridors, several key strategies are suggested:

First, field validation is essential to verify the accuracy of spatial analyses and assess the practicality of the proposed corridors in real-world conditions. On-site studies will ensure that the designed corridors align with both ecological objectives and local implementation realities, bridging the gap between theoretical models and practical application [12, 25].

Engaging stakeholders is another critical step in the planning and implementation process. Involving local communities, policymakers, and environmental organizations will help balance ecological and societal needs, ensuring that the corridors address diverse priorities. Stakeholder engagement not only fosters community support but also facilitates a more comprehensive understanding of local conditions and challenges [9, 31].

Incorporating real-time environmental and socio-economic data into the design process is crucial for ensuring the adaptability of green corridors. Dynamic data on land use, climate fluctuations, and biodiversity trends will allow for more responsive and effective management. This integration will enable corridor designs to remain relevant and functional in the face of changing environmental conditions [10, 11].

Establishing a long-term monitoring and maintenance framework is also vital. Regular assessment of the ecological and recreational performance of the corridors will help identify challenges and provide opportunities for timely adjustments. This framework will ensure the continued functionality and impact of the corridors, safeguarding their ecological and socio-economic contributions [23, 31].

Expanding multifunctional zones, such as agricultural lands and other transitional areas, is recommended to enhance ecological connectivity and socio-economic benefits. These zones can serve dual purposes, providing habitat continuity for wildlife while offering recreational and economic opportunities for local communities. Strategically increasing these zones will further strengthen the multifunctionality of the green corridors [27, 31].

Finally, the Tekirdağ green corridor model should be used as a replicable framework for other regions facing similar urban and agricultural pressures. By tailoring the model to the specific conditions of different areas, it can serve as a valuable blueprint for sustainable urban planning and biodiversity conservation on a broader scale [34, 35].

Implementing these recommendations will improve the functionality, resilience, and adaptability of green corridor networks. Such initiatives will contribute significantly to sustainable urban development, ecological conservation, and improved quality of life for communities, addressing both local and global challenges in urban planning [3, 9].

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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