



THE THESES OF THE PH.D. DISSERTATION

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MAGYAR AGRÁR- ÉS
ÉLETTUDOMÁNYI EGYETEM

METHODOLOGICAL FRAMEWORK FOR THE LANDSCAPE-LEVEL APPLICATION OF ECOLOGICAL NETWORKS

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BACKGROUND OF THE RESEARCH AND OBJECTIVES

Ecological networks are widely researched, supported by a rich body of theoretical and applied literature. Their foundations were established in the 1990s and 2000s, and have since been incorporated— in various forms—into the nature conservation, spatial planning, and legal frameworks of most European countries. It can be observed, however, that research momentum on ecological networks in Europe has diminished in recent years, and the concept itself has lost some of the appeal it held in the early 2000s. Nevertheless, the challenges that originally inspired the concept at the turn of the century remain highly relevant today. Biodiversity loss, habitat degradation, and fragmentation continue to pose significant threats, which have in fact become even more pressing over the past two decades.

The primary objective of this research is to develop a novel framework methodology for the holistic renewal of ecological networks as a spatial planning instrument. A holistic interpretation of ecological networks focuses on chains of habitats, where connections are not merely physical, but also involve flows of matter and energy.. In this sense, the network functions as a dynamic, “living” system, of which human-made environments also form an integral part.

As a first step, the dissertation reviews the theoretical literature on networks and outlines the historical development of the concept. This is followed by the presentation of various methodological approaches used to define ecological networks. The aim is to compare existing planning models and tools, and to identify their practical applicability.

Subsequently, the research identifies the factors contributing to the current crisis of ecological networks, drawing on both national and international sources as well as interviews. The analysis focuses on identifying constraints that hinder the functioning and development of networks, as well as the underlying causes and driving forces behind the declining relevance of the concept.

The proposed framework methodology for supporting the planning and development of ecological networks builds upon the tools and methods identified in the research phase, while also responding to the challenges revealed. As a first component of the framework, the aim is to renew the interpretation of ecological networks in a way that aligns with current socio-economic conditions, thereby modernizing conceptual structures developed more than two decades ago. The framework employs various models and composite indices to assess the value of areas and habitat patches, as well as their potential roles within the network. It does not provide a fixed delineation of an ecological network; rather, it serves as a planning support tool to assist

professionals in defining, maintaining, and developing such networks. The framework should thus be regarded as a recommendation—an exploratory attempt to better understand and delineate ecological networks.

Through the interpretation of both partial and aggregated results, the study also aims to evaluate the applied tools and to identify the advantages and limitations of the underlying datasets. A secondary objective of the dissertation is therefore to assess the applicability of the framework and to provide feedback based on the results obtained. This iterative approach allows for the continuous refinement of the tools, including the integration of new indices or the implementation of minor adjustments, ensuring that the model accurately reflects the structure of the network. These findings do not indicate shortcomings of the method, but rather highlight opportunities for further development, thereby supporting future model corrections.

Finally, the research aims to position ecological networks within legal, conservation, and management systems, thereby contributing to the practical implementation of the proposed approach

MATERIALS AND METHODS

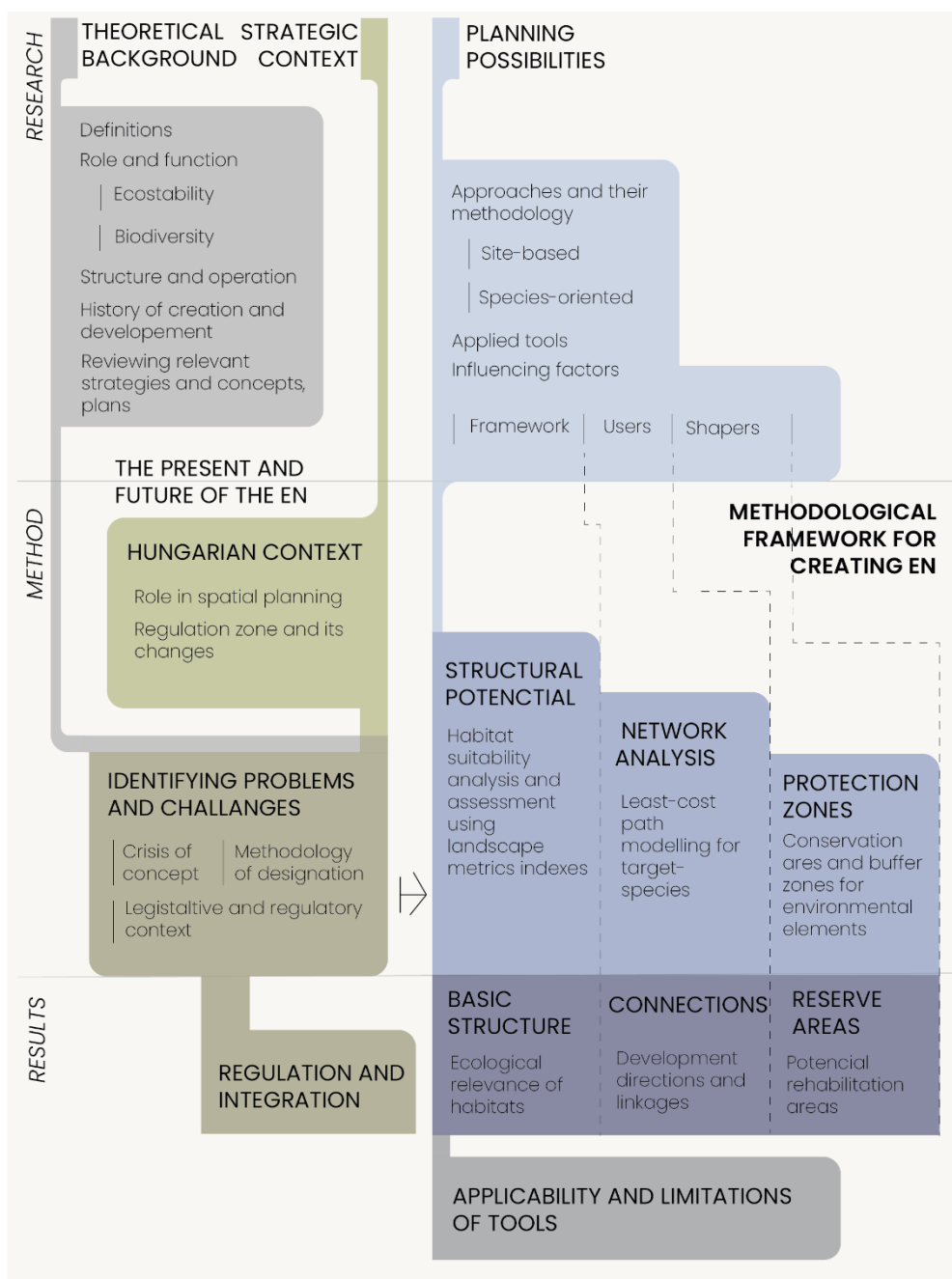
In the research phase, more than 120 academic sources related to ecological networks were reviewed. These sources predominantly focus on methodologies for network delineation, but also include theoretical works, historical overviews, and cross-country comparisons. European Union and national strategies were likewise incorporated into the analysis. To complement these findings, consultations were conducted with professionals in the field, both in the form of structured interviews and informal discussions, the insights of which were integrated into the dissertation.

Accordingly, the research was carried out along three main strands: first, the exploration of theoretical frameworks; second, the review of planning and delineation methodologies; and third, the analysis of the strategic and legal context.

In order to support the renewal of Hungary's ecological network and to develop an appropriate methodology, a detailed assessment of the national context was required. This involved examining the current state and legal regulatory framework of the National Ecological Network (hereinafter: NEN), followed by an analysis of its operational difficulties and challenges based on original assessments. Drawing on these findings, as well as on the insights gained during the research phase, the key constraints, challenges, and opportunities affecting the Hungarian NEN were identified.

In response to these findings, a tailored methodological framework for the development of ecological networks was elaborated. This framework builds

upon the approaches and diverse toolsets identified during the research, while adapting them to the databases available in the Hungarian context.



Structure of the dissertation

The model consists of three main steps. First, habitat suitability is assessed from the perspective of the ecological network. Second, potential connections are identified using network analysis tools. Third, reserve areas are delineated, serving partly as buffer zones and primarily as areas for ecological rehabilitation.

The first step involves determining the structural potential of the ecological network, which reflects the current ecological condition of habitats through quantified, composite indicators. This step primarily employs metrics related to anthropogenic landscape structure and land cover, which are of particular relevance to ecological networks. In total, five main metrics were analyzed to characterize habitat patches.

In the second step, network analysis was carried out using the least-cost path (LCP) method. The integration of a network-based perspective complements the structural approach of the first step, enabling the identification of potential directions and opportunities for connectivity. For this analysis, three target species were selected for each study area, and their potential movement paths and corridors were modeled.

In the third step, development opportunities are explored through the identification of areas requiring protection from the perspective of different environmental components. These areas highlight potential sites for intervention, including habitat restoration or the creation of new habitats. Such “reserve areas” may serve to integrate isolated patches into the network, reduce distances between habitat patches, or increase buffer zones.

Subsequently, a proposed ecological network was delineated by synthesizing the results of the three analytical steps. This was demonstrated through a case study in the North Mecsek region, intended to illustrate how the model can be applied in spatial planning practice. At this stage, the process itself is considered just as significant as the resulting network configuration.

RESULTS AND DISCUSSION

Through GIS-based analysis of the zones of the National Ecological Network (NEN), changes over the past fifteen years were identified. The results indicate that while the overall spatial extent of the network has remained largely unchanged at the national level, its structural composition has undergone some transformation. A slight shift can be observed from buffer zones and ecological corridors toward core areas. As spatial planning regulations primarily focus on construction, changes in built-up areas were also examined. The findings show no significant differences between protected and non-protected areas within the NEN in terms of changes in the proportion of built-up land. This suggests that, despite relatively flexible regulations, the NEN has been effective in protecting habitats from development, including those not covered by other forms of protection. At the

same time, an analysis of excluded areas reveals that, in the case of new building plots or developments, areas designated for construction are often removed from the scope of the network, and therefore do not appear in zonal statistics.

The processing of the methodological results begins with the evaluation of the components of the structural potential index, including their outputs, effectiveness, advantages, and limitations. The five main indices—fragmentation, naturalness, stability, diversity, and connectivity—were calculated based on a total of ten sub-indices. Their results were presented individually for three case study areas. By aggregating these indices, the structural potential index was derived, which proved effective in reflecting the relative importance of individual habitat patches within the ecological network. This is further supported by the fact that all elements of the current NEN zoning system exhibit high structural potential values.

In the second phase, the results of the network analyses were processed and presented both by target species and in aggregated form by study area. Among the three selected target species in each case, the landscape-scale species consistently produced the most relevant results at the territorial level. At the same time, the networks of local- and regional-scale species also contributed valuable insights to the model. These analyses enabled the identification of stepping-stone habitats, local connections requiring development, and large-scale ecological linkages.

By applying protective buffer zones around environmental elements, reserve areas—i.e., potential restoration sites—were identified. The three case study areas displayed differing patterns in terms of buffer zones, reflecting their distinct environmental characteristics. Areas were also identified where rehabilitation efforts could not only expand the ecological network but also improve the condition of environmental components.

Following the presentation of results, the findings were placed into a broader context. As part of the discussion, the limitations of the input data, as well as opportunities for their improvement and expansion, were first outlined. This was followed by a critical reflection on the outputs of the applied methods. The applicability of the individual indices was evaluated, methodological decisions related to network analysis were discussed, and the performance of the applied tools was compared with findings from other studies. Finally, additional landscape metrics identified in the literature and potential directions for further development of the analysis were presented, along with the necessary model adjustments.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results, a potential ecological network was delineated for one of the case study areas, serving as a possible starting point for spatial planning

at the local scale. As an initial step, the structural potential analysis was used to identify the possible structural elements of the network. These were classified into four categories defined within the methodology: core areas, ecological corridors, buffer zones, and—following the concept of interaction zones—a secondary buffer zone was also introduced, typically encompassing lower-value, intensively managed areas. Once the fundamental structure of the network had been established with preliminary zoning categories, the results of the network analysis were incorporated to refine the functional roles of individual habitat patches. Finally, the application of protective zones enabled the identification of additional buffer areas as well as potential development zones.

Drawing on the problem analysis conducted in the research phase, recommendations were formulated for the renewal of ecological networks within existing legal and regulatory frameworks. These include considerations to be applied during the planning process, the importance of involving a wide range of experts, and proposals aimed at improving regulation, enforcement, and review mechanisms. The recommendations are structured across three spatial scales: landscape, national, and local levels. The aim of these proposals is to initiate a professional discourse, which, through critical discussion, may contribute to the establishment of a truly functional, planned, and continuously evolving ecological network.

NEW SCIENTIFIC RESULTS

Thesis 1: Various approaches, tools, and key determining factors of ecological network were compiled and evaluated. I analyzed how different methodologies are structured, what types of tools they employ, and how the identified factors are represented within planning processes.

During the literature review, more than 120 studies specifically addressing ecological networks were processed, of which 72 applied methodologies aimed at network delineation or analysis. Based on the evaluation of these methods, two principal practical interpretations of ecological networks were identified: (1) species-oriented approaches and (2) site-based approaches. Each of these was further divided into two subtypes based on the tools applied. (1) Species-oriented networks include: (1.1) habitat suitability-based modeling approaches, and (1.2) empirically derived networks based on observed movement data, corresponding to structural and functional connectivity concepts. (2) Site-based approaches focus on the evaluation of landscape patches, and are distinguished by whether they incorporate network analysis tools or not.

By categorizing the available tools, three key factors determining ecological networks were identified: (1) landscape characteristics and

environmental processes, which provide the framework; (2) biota, primarily as users of the system; and (3) human impacts, which act as influencing and disturbing forces shaping the structure of the network. While the latter two factors are typically represented through models and indices, landscape characteristics and processes generally serve as input data.

Thesis 2: Using GIS-based analyses, I identified changes in the zones of the National Ecological Network (NEN) over the past fifteen years.

At the national level, I examined the spatial extent of NEN zones between 2008 and 2024 using available spatial datasets.

2/A. I revealed shifts in zonal extent, overlaps with protected areas, and land cover changes, and identified areas lacking other forms of nature protection.

The results show that the total extent of the network changed only marginally (from 35.98% to 36.18%), while its internal structure shifted slightly from buffer zones and ecological corridors toward core areas. Between 2008 and 2024, a total of 2,144.7 km² was removed from the network, predominantly from ecological corridors and buffer zones.

Comparison with protected areas (including nationally protected areas and Natura 2000 SAC and SPA sites) showed that 39.1% of NEN zones are not covered by any additional legal protection. These areas—primarily corridors and buffers, but also including significant core areas—are the most vulnerable, as current regulations do not provide sufficient protection.

2/B. I demonstrated that zones regulated primarily through construction-related planning successfully prevented development within the network; however, this is largely due to development areas being excluded from the network beforehand.

Analysis of built-up areas (2006–2018, based on CLC data) showed no significant differences between protected and non-protected NEN zones in terms of development rates. Despite relatively flexible regulation, the network effectively protected habitats from construction. However, areas designated for development were often removed from the network, thus not appearing in zonal statistics. In these excluded areas, built-up land increased 1.6 times more than the national average (and twice as much for industrial areas), although it cannot be determined whether these areas were removed because of development or for the purpose of enabling it.

Thesis 3: I developed a novel framework methodology to support spatial planning, drawing on ecological network delineation research

from the past two decades. The model integrates available tools and is tailored to national datasets and conditions. It defines ecological networks across three levels: structural potential analysis reveals the fundamental extent and structure of the network; modeling of target species networks identifies connections and linkages; and protective zones allow for the identification of reserve areas within the ecological network.

Building on a reinterpretation of ecological networks, I established this framework by integrating the tools of 72 methodologies analyzed in the research, adapting them to the Hungarian environmental context and available databases. The aim of the framework is to support national spatial planning processes, thereby facilitating the future renewal of ecological networks.

The framework defines ecological networks at three levels: (1) Through structural potential analysis, the fundamental structure of the network is determined and quantified using five key landscape metrics: diversity, naturalness, fragmentation, stability, and connectivity. These metrics enable the assessment of habitat patch value and, consequently, the structure and spatial extent of the ecological network. (2) The networks of target species representing regional, landscape, and local scales are analyzed using least-cost path modeling. This network analysis supports the identification of ecological corridors and functional connections. (3) Areas designated for the protection of environmental components function as reserve areas within the ecological network. These allow for the identification of potential restoration sites, where rehabilitation efforts can enhance not only the functionality of the network, but also contribute to the protection of surface and groundwater resources as well as soil systems.

Thesis 4: I tested the proposed model across three case study areas with distinct characteristics: a hilly region, a lowland area, and an urban agglomeration zone. The metrics applied within the framework, as well as the results of the analyses, were evaluated separately for each area, thereby revealing the strengths and limitations of the applied tools. Based on the combined results of the three analytical levels, I proposed a possible delineation of an ecological network for one of the case study areas.

The calculations defined within the framework were implemented in three landscape-scale study areas with differing environmental conditions: the topography-driven North Mecsek region, the water-influenced Middle Tisza region, and the heavily human-modified Pest Plain.

During the model testing process, I first conducted a detailed evaluation of the five aggregated structural potential indices and their eleven sub-indices across the different areas, followed by a comparative analysis to identify

relationships between them. Network analysis was then carried out using the least-cost path method, based on the habitat preferences of three target species per study area. The results were analyzed across three spatial scales, enabling the identification of connections, corridors, key habitats, and subsystems.

Finally, by delineating protective zones, I identified potential restoration areas that can contribute not only to habitat and biodiversity conservation, but also to the protection of environmental components. To complement the planning process, I carried out a sample delineation of an ecological network for the North Mecsek study area based on the framework results. This example demonstrates the practical application of the methodology and highlights the critical role of planner decision-making in the process.

Thesis 5: I identified the relationships between the tools used to assess structural potential, as well as the advantages and limitations of the applied indices and their underlying datasets through their application in the case study areas.

5/A. Cells with higher fragmentation values generally exhibited higher diversity values, primarily due to the presence of roadside vegetation.

The evaluation of results showed that cells containing elements of the road network (i.e., with measurable fragmentation) had higher diversity values than those without such elements. While no direct correlation can be established (i.e., higher fragmentation does not necessarily result in higher diversity), the presence of fragmentation tended to increase diversity values.

This can be explained by the fact that a road crossing a homogeneous patch introduces at least one additional patch type, and if edge vegetation is present, potentially two. Moreover, roads often run between different habitat types, further increasing the diversity of affected cells.

The model thus supports previous research highlighting certain positive aspects of fragmentation. It can be concluded that the presence of roads does not have exclusively negative effects from the perspective of ecological networks. In some cases, diversity and fragmentation values partially balanced each other during aggregation.

5/B. Stability indices did not clearly differentiate between natural and semi-natural habitats; instead, a positive bias was observed toward vineyards, orchards, plantations, and grasslands, which can be explained by narrower edge widths and more compact patch shapes.

Stability values were calculated based on the ratio of core area to total area, where core area was derived by subtracting edge width. Smaller patches (those not exceeding twice the defined edge width) did not yield meaningful stability values. Edge widths were estimated based on habitat characteristics.

According to the calculations, managed landscapes generally exhibited higher stability than natural habitats. Vineyards and saline grasslands showed the highest values, followed by orchards and non-native tree plantations. This is due to the fact that natural habitats tend to have wider edge zones, resulting in proportionally smaller core areas. Additionally, managed patches are typically more compact and regular in shape, yielding more favorable perimeter-area ratios. In contrast, natural habitats often have irregular forms shaped by topography and hydrology, resulting in larger perimeters. Large forest areas, which might otherwise exhibit high stability, are frequently intersected by roads, increasing internal edge density and reducing core area proportions. Thus, both methodological factors and the degree of human intervention explain the higher stability values of semi-natural patches.

5/C. The NÖSZTÉP database proved suitable for most calculations and, despite its raster format, can be effectively used as input data for the indices defined in the framework. However, its resolution is overly detailed for landscape-scale analyses, and its main limitation emerges in urban environments, where it does not distinguish between different types of green spaces.

Contrary to initial assumptions, NÖSZTÉP was suitable for calculating all ten sub-indices of the structural potential analysis, producing results that accurately reflect real-world conditions. No significant disadvantages arose specifically from its raster nature during result interpretation. However, the calculations required methodological adjustments to accommodate the raster structure.

A critical aspect was ensuring that the analytical grid aligned precisely with NÖSZTÉP pixels, so that each pixel belonged to only one grid cell, thereby avoiding distortions. This was particularly important for diversity-related sub-indices, where patch number and patch type were measured.

The primary limitation of the database stems not from its raster format, but from its land cover classification system. Although urban green areas are categorized (e.g., wooded vs. non-wooded), they are not differentiated by function or actual size. As a result, private gardens, residential green spaces, institutional gardens, and public parks are grouped into the same category.

While these green spaces may be ecologically similar in some respects, the analysis demonstrated that, in urban environments, it is essential to distinguish contiguous green areas that function as habitat patches. Based solely on NÖSZTÉP, it is not possible to determine whether adjacent pixels represent a continuous green space or fragmented, disconnected garden plots separated by fences.

Therefore, it is recommended to complement NÖSZTÉP with an additional dataset that distinguishes functionally relevant green spaces within built

environments. Despite its applicability, it is advisable to develop a vector-based land cover database prior to ecological network planning, tailored in scale, detail, and classification to the specific planning area.

Thesis 6: Based on the results of the structural potential analysis conducted across the case study areas, I concluded that the applied metrics—despite their methodological differences—can be meaningfully aggregated when assigned appropriate signs. The indices and sub-indices complement one another, each capturing a distinct aspect relevant to ecological networks. This is supported by the finding that all zones of the National Ecological Network (NEN) were identified as highly valuable following the static analysis.

Of the five indices associated with structural potential, diversity, naturalness, stability, and connectivity contributed positively, while fragmentation was incorporated with a negative sign, following the normalization of sub-indices. No weighting was applied among the metrics.

The methodology was designed to produce the most objective results possible; accordingly, the sub-indices were structured to balance each other and compensate for potential shortcomings. For example, in the case of diversity, the combined use of patch number and patch-type number was intended to correct for the overrepresentation of highly fragmented patches. Connectivity sub-indices quantified the roles of patches within the system from multiple perspectives. In the case of fragmentation, different traffic intensities of road types were also taken into account to ensure that the final values more accurately reflect actual fragmentation effects.

The indices also balance each other conceptually. Each metric emphasizes a different aspect relevant to ecological networks: some highlight ecological value or negative impacts, while others reflect patch geometry, size, spatial position, and configuration.

The aggregation of indices and the analysis of the resulting maps confirm that these metrics can indeed be combined despite their differences. No area was identified as valuable without having a justifiable role within the ecological network from at least one perspective. This is further supported by the strong correspondence between the results and the spatial extent of the NEN: all zonal elements ranked at least in the mid-range, but more typically among the highest-value areas. No NEN element received a low value, although additional high-potential habitats were identified outside the current network boundaries.

Given that the designation of NEN zones was originally based on ecological value without the use of network analysis, the strong alignment between the results and the existing network further validates the effectiveness of the proposed methodology.

Theiss 7: The case study investigations confirmed the essential role of network analysis in ecological network planning. Network analysis allows the identification of connections and key habitats, serving as the primary tool for delineating ecological corridors. The evaluation of results demonstrated that using target species at three different scales contributed unique and complementary perspectives to network design.

The networks of target species were analyzed using the least-cost path method at three spatial scales per study area, based on the habitat requirements of three or four representative species. In all cases, the landscape-scale target species model proved most suitable for the scale of the study areas, while both larger and smaller scales also provided valuable information for mapping the network. Local-scale target species offered detailed information on key patches, stepping stones, and tightly connected subnetworks, which enhanced the understanding of the landscape network. Regional-scale analysis positioned the landscape-scale areas within the broader system, identifying connections that function as important routes both within and beyond the study area.

It was observed that careful selection of target species and their combinations is critical, as missing or disproportionately represented habitat preferences can bias the perception of the network and result in certain habitats being entirely excluded from the modeling process.

The results of the network analysis clearly delineated habitat connections, pathways, and corridors, providing significant guidance for the identification of ecological corridors. The practical application of the method, demonstrated through the first case study area, confirmed that network analysis is indispensable in ecological network planning, as it provides the primary insight needed to determine ecological corridors and inform future development opportunities.

Thesis 8: Incorporating protective zones for environmental elements is rarely addressed in ecological network research, yet identifying these areas allows for the designation of restoration zones, making this a novel component of planning methodologies.

Based on the research results, it can be concluded that in most ecological network planning models, environmental elements serve primarily as input data. Protective areas are most often considered in relation to surface waters, particularly rivers, due to their ecological significance. Examples integrating groundwater protection or soil conservation are much less common. Therefore, including environmental elements—especially groundwater, soil erosion, and flood-prone areas—as explicit factors in the model represents an innovative aspect of the framework I developed.

The results showed that the areas most sensitive in terms of environmental elements are also ecologically valuable, often already forming part of the network. Some additional areas are not recoverable (e.g., built-up areas), but others can potentially be rehabilitated. Restoration of these areas would not only expand the ecological network but also improve the condition of environmental elements. Thus, the method demonstrates that by examining protective zones, the reserve areas and potential development opportunities of the ecological network can be effectively identified.

MOST IMPORTANT RELATED PUBLICATIONS

Journal articles

Virág, Kutnyánszky and Szilvácsku, Zsolt Miklós (2022) “*Landscape planning dilemmas and challenges in designation and management of the ecological network alongside the Tisza River in Hungary.*,” Proceedings of the Fábos Conference on Landscape and Greenway Planning: Vol. 7: Iss. 1, Article 19. DOI: <https://doi.org/10.7275/c359-5776>

Virág, Kutnyánszky and Szilvácsku, Zsolt Miklós (2023) „Dilemmas in the use and layout of ecological network in Hungary, in: 4D DOI: <https://doi.org/10.36249/4d.67.3728>

Virág, Kutnyánszky and Szilvácsku, Zsolt Miklós (2023): The relationship between landscape management, land use and the ecological network in Nagykőrű, Journal of Environmental Geogrphay DOI: <https://doi.org/10.14232/jengeo-2023-44682>

Virág, Kutnyánszky, Ammar Auda, Szilvácsku, Zsolt Miklós (2024): The relationship between the ecological network and the water system in the Carpathian basin - Finding a way for sustainable land use, in Journal of Environmental Geography DOI: <https://doi.org/10.14232/jengeo-2024-45788>

Kutnyánszky Virág, Szilvácsku Miklós Zsolt (2024): Eszközök és lehetőségek az ökológiai hálózat lehatárolására, in: 4D, DOI: <https://doi.org/10.36249/4d.74>

Conference papers (full paper)

Kutnyánszky Virág, Máté Klaudia, Dr. Szilvácsku Miklós Zsolt (2021): Ökológiai hálózat madárvédelmi fejlesztése Szekszárd térségében (Georgikon Konferencia, 2021)

Kutnyánszky Virág, Dr. Szilvácsku Miklós Zsolt (2024): Ökológiai hálózatok táji szintű alkalmazásának módszertani megalapozása (Tavaszi Szel Konferencia, 2024) link: http://dosz.hu/ur/1/tszk2024_tanulmanykotet_I

Kutnyánszky Virág, Dr. Szilvácsku Miklós Zsolt (2024): Indikátorfajok kiválasztásának szempontjai ökológiai hálózat tervezéséhez (Tájökológiai Konferencia, 2024) ISBN 978-963-623-117-0

Book excerpts

Filepné Kovács Krisztina, Kutnyánszky Virág: Ökológiai hálózatok – Alapfogalmak, in: Filepné Kovács Krisztina és Szilvácsku Zsolt (szerk.) (2024): Ökológiai hálózat és szakpolitikák, ISBN 978-963-623-090-6