Evaluation of recent land cover fragmentation in the features of ecological network and their vicinity: A case study of Galanta municipality, Slovakia

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Abstract: *In the context of ongoing climate change, the implementation of strategies for reducing greenhouse gas emissions and optimizing carbon sequestration potential must be taken into consideration even on the municipal level. One of the key inputs for such decision-making is the knowledge of the land cover, its modifications, and the spatial configuration of natural features. In this study, we analysed land cover changes, landscape fragmentation, and ecological stability in the Galanta municipality, located in the lowlands of Western Slovakia, with a special focus on the elements of the regional ecological network. Using the classified Sentinel-2 imagery from 2015, 2020, and 2025, we identified and categorized land cover changes. Consequently, land cover metrics and ecological stability coefficients were calculated. Results indicate that the overall landscape remains low-fragmented in terms of configuration but is undergoing compositional fragmentation driven primarily by urbanization, declining woody vegetation, and agriculture extensification. A 100 m buffer zone around the regional ecological network experienced intensive anthropogenic pressure, which resulted in a decrease of ecological stability. While core areas showed a persisting compactness of land cover features, gene pool centres and corridors were highly fragmented. A similar low aggregation of land cover patches was found among small, ecologically significant features. However, no significant shift occurred during the last decade. The ecological network should be refined, widened, and properly reflected in territorial plans, while specific management measures must be followed to mitigate the negative consequences of landscape fragmentation in the existing natural elements. The proposed approach is applicable beyond the case study area, and its outcomes can support ecological network assessment and protection in other municipalities as well, especially in the agricultural lowland landscape.*

Keywords: e*cological network, land cover, landscape metrics, Galanta, Slovakia*

Introduction

In terms of mitigating the negative consequences of climate change, European Union environmental policy is focused on facilitating a transition towards a green and low-carbon economy (European Commission). The analysis of environmental and geographical data can play a principal role in this process (Pfenning et al. 2023, Pino-Gallardo et al. 2025) when reflected in the decision-making of both state and local governments.

In this regard, the spatial structure of the landscape must be taken into consideration to address the carbon-storing potential of its elements. The physical state of land surface objects as they are visually perceived and identified through physiognomic and morphological attributes is reflected in land cover classifications (Comber, Fisher and Wadsworth 2005). One of the conceptual approaches to studying land cover incorporates the analysis of land cover patches' spatial configuration, something that can be quantified through a variety of land cover metrics (Leitão and Ahern 2002).

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Since the ecological value of land cover classes varies, there is a need in landscape planning to preserve, protect, or even create natural and semi-natural features, especially in the areas with a strong anthropogenic influence. This is why the concept of an ecological network (EN) was established across the European countries. The first ideas of the ecological networks were raised from the model and theory of Forman and Gordon (1986). In Central and Eastern Europe, several national EN programmes were developed in the 1980s, inspired by the polarised landscape theory of Rodoman (1974). The current concept of the EN incorporates three key components: core areas, ecological corridors, and their buffer zones. Usually, these components are delimited on different scales, from the continental (e.g., Pan-European Ecological Network; Bennett and Kalemani 2006) to the local.

In Slovakia, the Territorial System of Ecological Stability ("ÚSES") was established by the Act. No. 543/2002 (National Council of the Slovak Republic 2002). Components of the universal EN concept are preserved, while the terminology varies. Core areas are referred to as biocentres, while ecological corridors are referred to as biocorridors. Smaller features that are not necessarily connected to the rest of the EN but are still relatively ecologically stable are usually called "interaction elements" (we use the term "ecologically significant features", as in Mederly and Vrbičanová 2023). These strategic documents are being prepared on three levels: national ("GNÚSES"), regional ("RÚSES"), and territorial ("MÚSES"). Within the framework of projects supported by the European Union, the processing of pilot "MÚSES" documentations is realised for the purpose of creating a basic starting point for regulating the design of green infrastructure (Slovak Environment Agency). The methodology of its preparation was proposed by Pauditšová, Reháčková and Ružičková (2007).

Several authors have investigated the impact of land cover changes on the EN (Kubacka et al. 2025, Vidal-Llamas, Acuña-Alonso and Álvarez 2025). Although being predominantly case studies focusing on specific regions, some of their findings can be generalised, especially when addressing the degradation of the natural feature's ecological value due to specific land cover changes. Gene pool centres and core areas are often facing pressure of urbanisation, which predominantly takes the form of land cover patch fragmentation or feature shrinkage (European Environmental Agency 2022), which tends to be a more serious phenomenon than the decrease of the number of natural features (European Environmental Agency 2011). However, a bigger issue is the pressure on the corridors. Semi-wide linear natural features can be easily split by the urban development activities, resulting in the collapse of habitat connectivity, the inability of the species to migrate between the core areas, and thus their genetic degradation (Almenar et al. 2019, Yildirim et al. 2025). Disruption of corridors and the decrease of small semi-natural landscape features (e.g., hedgerows and shelterbelts) are also taking place in the agricultural land as a consequence of the activity intensification and a shift to large-block arable land (Kratschmer et al. 2024). Buffer zones in the vicinity of the EN are also of significant importance, as they protect natural elements against negative exogenous impacts (Izakovičová and Świąder 2017). Their monitoring can be beneficial in terms of on-time indication of natural elements' endangerment.

The presence of natural features in the landscape is necessary for effective carbon sequestration. Especially wetlands, forests, and pastures have a significantly higher carbon-storing potential compared to arable land or artificial surfaces (Fryer and Williams 2021, Guillaume et al. 2022). Moreover, there is evidence that a fragmentation of natural features lowers the carbon sequestration potential of the landscape (Ma et al. 2017, Hou et al. 2024).

In this study, we focus on the regional EN in Galanta Municipality. Using land cover classification from three years (2015, 2020, and 2025), we aim to evaluate land cover structural and compositional changes in each EN element group as well as in their buffer zones using land cover metrics and ecological stability assessment. The connection between these two approaches, which specifically focuses on each EN element type, has not yet been applied in Slovakia. Methodical aspects of this work are applicable also to other municipalities and pose an important contribution to the detailed knowledge of EN endangerments that should be reflected in their future refinements.

Methods

Study area

The municipality of Galanta (total area of 33.91 km^2) is an administrative part of the Trnava Self-Governing Region and incorporates three cadastral districts: Galanta, Nebojsa, and Hody. As it lies in the southern part of Slovakia, it is affected by the continental zone of middle latitudes (Polčák and Hlásny 2002). As a part of the Danube Lowlands, it is one of the regions of the Slovak Republic most affected by climate change (Nánásiová et al. 2023). The territory of the city belongs to the warm region and the warm, very dry subregion with mild winters, according to (Lapin et al. 2002). The Šárd and Derňa streams flow along the edges of the city area. Geological structures consist of Neogene grey and varied clays, silts, sands, and gravels (Biely et al. 2002). Beyond are deposited Quaternary clayey and sandy to gravelly fluvial sediments of floodplains (State Geological Institute of Dionýz Štúr). The soil cover is dominated by calcaric Haplic Chernozems and calcaric Mollic Fluvisols (Soil Science and Conservation Research Institute). Built-up areas are covered by anthrozems. Potential natural vegetation is represented by elm floodplain forests (Maglocký 2002).

In the Galanta municipality, ecological networks on the regional level were established in 2019-2023 (Slovak Environmental Agency 2019). All its features that fall within the three cadastral districts under investigation are displayed in fig. 1 and listed in tab. 1. Moreover, "MÚSES" for the Hody cadastral district was proposed by (Kočická et al. 2018).

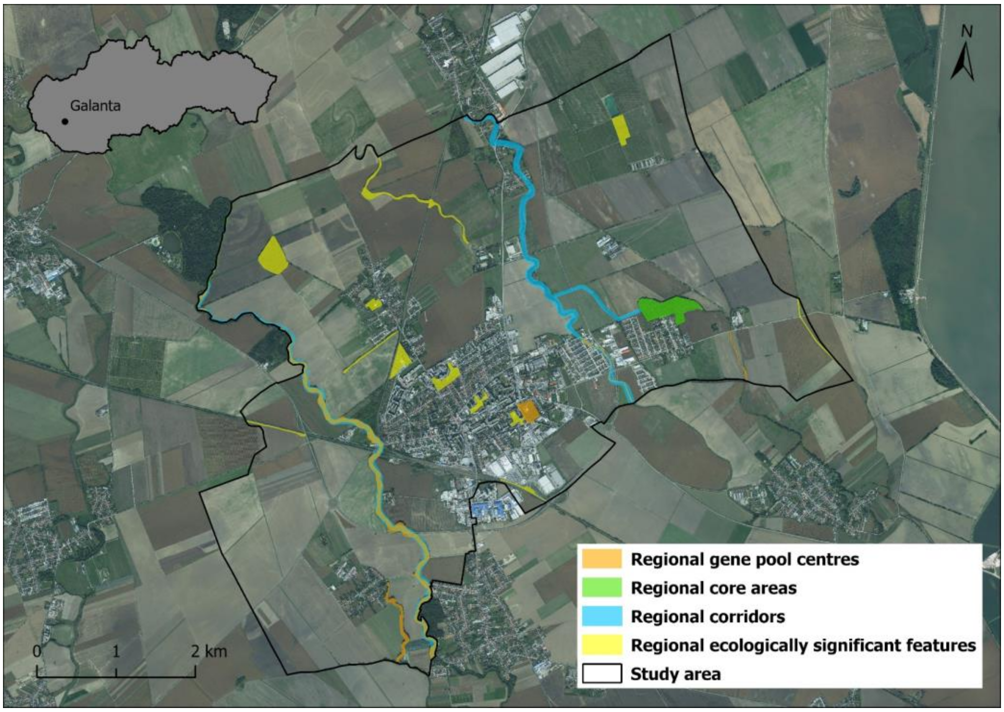

Fig. 1. *Regional ecological network of the Galanta municipality; Basemap: Ortophotomosaics of the Slovak Republic (2023), provided by the Geodesy, Cartography and Cadaster Authority of the Slovak Republic*

Tab. 1. List of the features of the regional environmental network in Galanta municipality

Type	Code	Name
Gene pool centres	GL23	Kajalský potok
	GL24	Potok Derňa I
	GL35	Park Galanta
	GL36	Potok Šárd
	GL37	Rameno Javorinka
Core areas	RBc9	Vincov les - Sládkovičova duna
	RBc10	Na Garažde
Corridors	RBk10	Derňa
	RBk12	Šárd
	RBk21	Ku Garažde
Ecologically significant features	EV 48	Lesík vow vinohradoch
	EV 52	Gorazdovský kanál
	EV 59	Izolačný porast Topoľnica - Galanta
	EV 60	Izolačný porast Galanta - Sládkovičovo
Ecologically significant features	EV 62	Medza Hody
	EV 63	Nový cintorín Galanta
	EV 64	Nemocnica Galanta
	EV 65	Sídliskový park Galanta
	EV 66	Sídliskový park Galanta
	EV 67	Park Hody
	EV 68	Lužný lesík
	EV 71	Bývalý vodný tok Gáň
	EV 158	Luh Matuškovo

Source: Slovak Environment Agency (2019)

Land cover data

The land cover classification was conducted in ArcGIS Pro using multispectral Sentinel-2 data from the years 2015, 2020, and 2025 (tab. 2). For 2015 data, only Level-1C top-of-atmosphere reflectance products were available. Using Sen2Cor , an atmospheric correction was applied to convert the imagery to surface reflectance, ensuring radiometric comparability with the Level-2A datasets. All analyses incorporated spectral Bands 2–8, 8A, 11, and 12, covering the visible, NIR, red-edge, and SWIR spectra. Since Bands 5, 6, 7, 8A, 11, and 12 were originally delivered at 20 m resolution, they were resampled to 10 m in order to achieve consistent spatial resolution across all layers. Following a series of preprocessing steps, the selected bands were then merged into multispectral composites. These composites served as inputs for the supervised classification.

***Tab. 2.** Collection of source Sentinel-2 images*

Mission	Level	Acquisition date	Max. resolution (m)
Sentinel-2	L1C	25. 11. 2015	10
Sentinel-2	L2A	9. 10. 2020	10
Sentinel-2	L2A	7. 11. 2025	10

The classification scheme comprised six land cover categories: water; grassland; shrubs and trees; arable land; vineyards; and artificial surfaces. Treating woody vegetation as a single class arises from the properties of input data, which do not provide sufficient information for a detailed structural distinction between trees and shrubs. Further refinement using alternative data sources would be inefficient since the objective of this study is landscape fragmentation and, in this case, both trees and shrubs represent natural features with similar ecological functionality. However, it should be noted that this generalisation may limit direct comparability with studies based on the CORINE Land Cover classifications. The training data were manually digitised to ensure a minimum of 20 polygons for each class, so we adequately capture spectral variability and avoid mixed pixels or transitional zones. The classification was performed using the Support Vector Machine (SVM) algorithm based on its demonstrated effectiveness in handling high-dimensional multispectral data and its robustness when training sample sizes are limited (Mountrakis et al. 2011). Comparative studies have shown that SVM performs comparably to Random Forest in land cover classification from Sentinel-2 imagery, particularly when class separability is high (Maxwell et al., 2018). Several parameter configurations were tested, with the Maximum Number of Samples Per Class parameter set to 650, as this produced the most visually consistent and thematically reliable results across all three temporal datasets.

Post-classification refinement was conducted using the LPIS – Land Parcel Information System (Agricultural Paying Agency) to improve classification accuracy, allowing correction of misclassified pixels within agricultural parcels. A rule-based approach was applied where overlapping pixels were reclassified as arable land, with the exception of the "shrubs and trees" class. This exception was maintained to preserve occurrences of woody vegetation (e.g., windbreaks or small groves) within agricultural fields. This process effectively filtered out incorrectly classified artificial surfaces on bare soil and resolved spectral confusion between some crops and grasslands. Any remaining inconsistencies were addressed through manual raster editing based on expert judgment. At last, a majority filter (eight neighbours used; replacement threshold set to majority) was applied to all the rasters to remove small, misclassified patches.

The accuracy assessment was based on stratified random sampling, with a total of 796 validation points distributed proportionally across all land cover classes. The number of points per class reflected their relative spatial representation in the 2025 reference dataset, which served as the basis for the sampling design. Reference labels were derived from visual interpretation of the original Sentinel-2 imagery and auxiliary data**,** while ensuring that validation samples were spatially independent from the training dataset. Class labels were assigned for each reference year (2015, 2020, and 2025) through interpretation of the corresponding imagery. Classification error matrices were generated from this dataset, presenting standard accuracy indicators (tab. 3).

Tab. 3. *Classification accuracy*

Year	**2015**		**2020**		**2025**	
Accuracy	**PA**	**UA**	**PA**	**UA**	**PA**	**UA**
water	1.00	1.00	0.82	1.00	1.00	1.00
grass	0.83	0.42	0.72	0.62	0.94	0.79
trees and shrubs	0.90	0.96	0.95	0.96	1.00	0.99
arable land	1.00	1.00	0.99	0.98	0.99	1.00
vineyards	1.00	1.00	0.89	0.95	1.00	1.00
artificial surfaces	0.95	1.00	0.97	0.97	0.98	1.00
Overall	**0.95**	**0.89**	**0.89**	**0.91**	**0.98**	**0.96**

PA = Producer's accuracy, UA = User's accuracy

Land cover change categorisation

Land cover flows between the years 2015 - 2020 and 2020 - 2025 have been categorised in order to quantify the rate of specific land cover changes (tab. 4). A conversion matrix introduced by Feranec et al. (2010) was applied in the case of five land cover flows: "urbanisation", "agriculture intensification", "agriculture extensification", "water bodies gain", and "other changes". Since we used different classification schema, these land cover classes were matched with the original ones based on their physiognomy and ecological functionality, ensuring that the character of the land cover flows remained consistent. In the case of woody vegetation, the original matrix needed to be modified, since trees and shrubs were treated as a single class. The categories of "afforestation" and "deforestation" have been replaced with "tree and shrub gain" and "tree and shrub loss". These new categories also cover some of the modifications concerning non-forest vegetation, which were originally assigned to "agriculture intensification" or "extensification".

Tab. 4. *Categorisation matrix for land cover changes*

		II.					
		W	**G**	**T**	**A**	**V**	**H**
I.	**W**	0	7	7	7	7	1
	G	6	0	4	2	2	1
	T	6	5	0	5	5	1
	A	6	3	4	0	2	1
	V	6	3	4	3	0	1
	H	6	7	7	7	7	0

Axis: I. = first time horizon, II. = second time horizon; Land cover classes: W = water, G = grass, T = trees and shrubs, A = arable land, V= vineyards, H = artificial surfaces; Categories of land cover changes: 1 = urbanisation, 2 = agriculture intensification, 3 = agriculture extensification, 4 = tree and shrub gain, 5 = tree and shrub loss, 6 = water bodies gain, 7 = other changes

Landscape metrics

To quantify key landscape characteristics, especially in terms of their horizontal structure, composition, and temporal change, several landscape metrics were calculated for a) the whole study area, b) each EN element group (gene pool areas, core areas, corridors, and ecologically significant features), and c) their 100 m buffer zones. The calculation was performed separately for each year.

Vector data of existing regional EN was obtained from the website of the Trnava self-governing region (Self-Governing Trnava Region 2025). Ecologically significant features needed to be vectorised manually, based on the map outputs of Mederly and Vrbičanová (2023) and aerial imagery from 2023 with the spatial resolution of 20 cm, provided by the Geodesy, Cartography, and Cadastre Authority of the Slovak Republic. All the spatial analyses were performed in ArcGIS PRO. Vector features of EN elements were rasterised to 10 m resolution, while snapping was applied to match the grid of classified Sentinel-2 imagery. Consequently, separate rasters were prepared for each time horizon, buffer zone, and EN element group.

Landscape metrics were calculated using the "landscapemetrics" package (He, Dezonia and Mladenoff 2000, Jaeger 2000, Hesselbarth et al. 2019) in RStudio. In tab. 5, we provide a list of 11 calculated metrics. Their selection was based mainly on the study of Kubacka et al. (2025), as well as our knowledge of study area land cover structural dynamics. Figures were computed in TABCO Statistica.

Tab. 5. *Computed landscape metrics*

Code	Name	Unit
ai	Aggregation Index	
area_mn	Average size of patches	ha
division	Landscape Division Index	
ed	Edge density	m/ha
lpi	Largest Patch Index	
mesh	Effective Mesh Size	ha
np	Number of patches	
pd	Patch density	/100 ha
pladj	Percentage of Like Adjacencies	%
shape_mn	MeanShape Index	
shdi	Shannon Diversity Index	

Ecological Stability Coefficients

To inspect temporal changes of the ecological quality, Ecological Stability Coefficients (ESC) were calculated in accordance with Löw et al. (1984) for a) the whole study area, b) the whole EN network, and c) its 100 m buffer zones. The calculation was performed separately for each year. Primarily, the degree of ecological quality was assigned to each identified LC class as follows: 5 – water and forests; 4 – trees outside the forests, shrubs, and riparian vegetation; 3 – grass; 2 – arable land and vineyards; 1 – artificial surfaces. Because all the trees and shrubs were initially a part of the single land cover class, a layer of forests (National Forestry Centre) was used as the mask to distinguish categories 5 and 4.

Consequently, the following formula was used to calculate the ESCs:

$$ESC = \frac{\frac{p_{EQ=5}}{n} \cdot 1.5 + p_{EQ=4} + \frac{p_{EQ=3}}{n} \cdot 0.5}{\frac{p_{EQ=2}}{n} \cdot 0.2 + \frac{p_{EQ=1}}{n} \cdot 0.8}$$

where $p_{EQ=k}$ is a number of pixels with assigned ecological quality k and n is a total number of pixels.

Results

Land cover changes

When considering land cover changes for the whole area of Galanta municipality, 85% of the area remained unchanged between 2015 and 2020, and 89% between 2020 and 2025. In both temporal intervals under investigation, urbanisation was the dominant process (3%), along with tree and shrub loss in the 1st interval (4%).

In terms of land cover changes, core areas represent the most stable components of the EN. More than 88% of the area remained unchanged in both intervals, with the changes connected mostly to the tree and shrub gains and losses. However, this can be simply a consequence of its low total area (only two core areas are present, while one of them protrudes marginally to the study area).

In the rest of the EN elements, up to 40% of the area has changed in each interval, with the gene pool centres (39% and 39%) and the corridors (41% and 33%) being the most modified. It must be noted that in some cases, polygons of these two element groups overlap.

The most pronounced land cover flow is the gain of grass and the loss of trees and shrubs, which was slowed down in the 2nd interval.

100 m buffer zones also experienced extensification of agriculture (3%), urbanisation (5%), and tree and shrub loss (7%) in the 1st interval, which slowed down in the 2nd interval (1%, 4%, and 4% for each aforementioned land cover change category). Land cover of the entire study area in 2015, 2020, and 2025 is shown in fig. 2. Changes in proportions of land cover classes in the EN element groups are presented in fig. 3. Categorised changes are illustrated in fig. 4 and summarised in tab. 6.

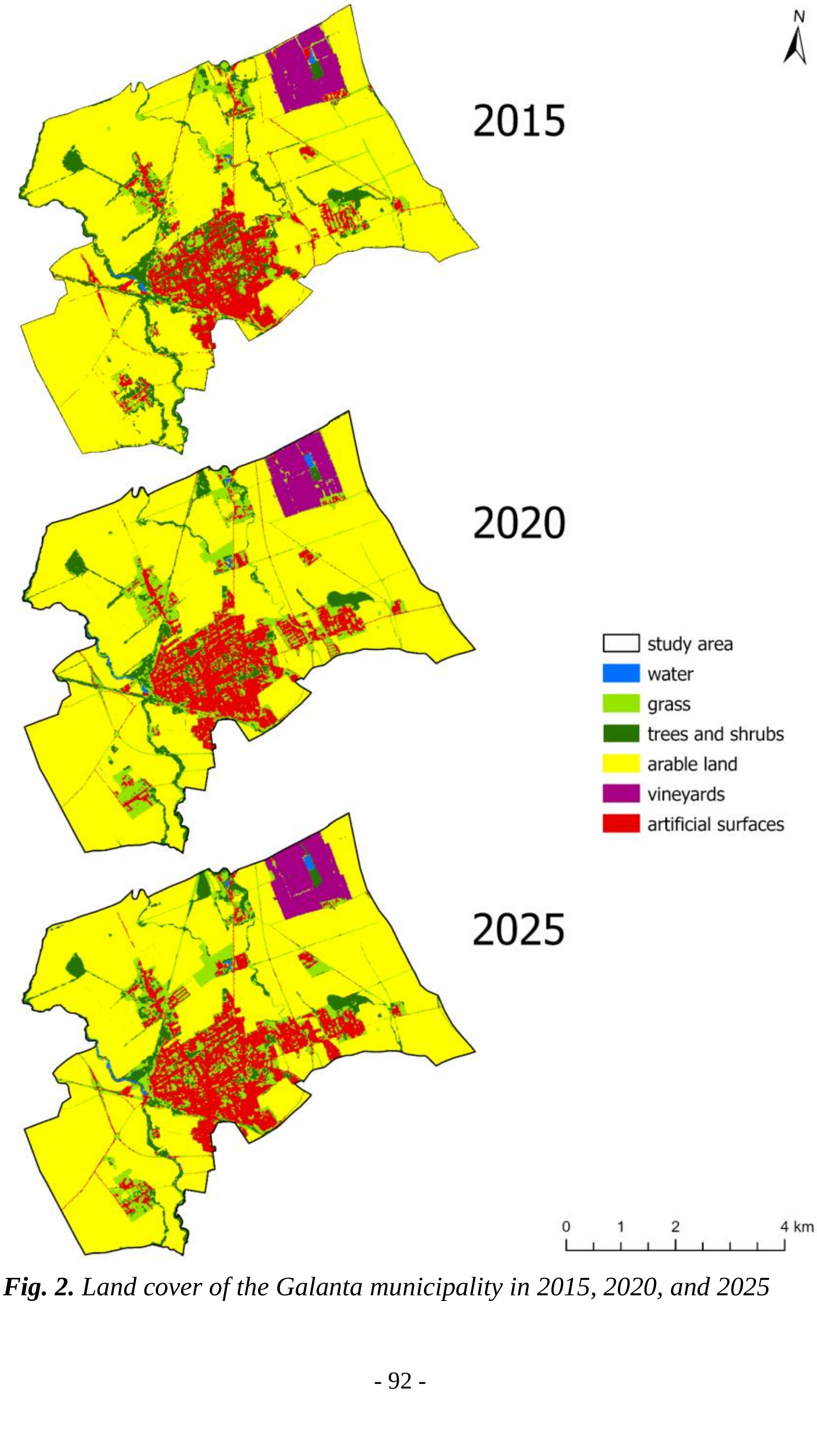

Fig. 2. *Land cover of the Galanta municipality in 2015, 2020, and 2025*

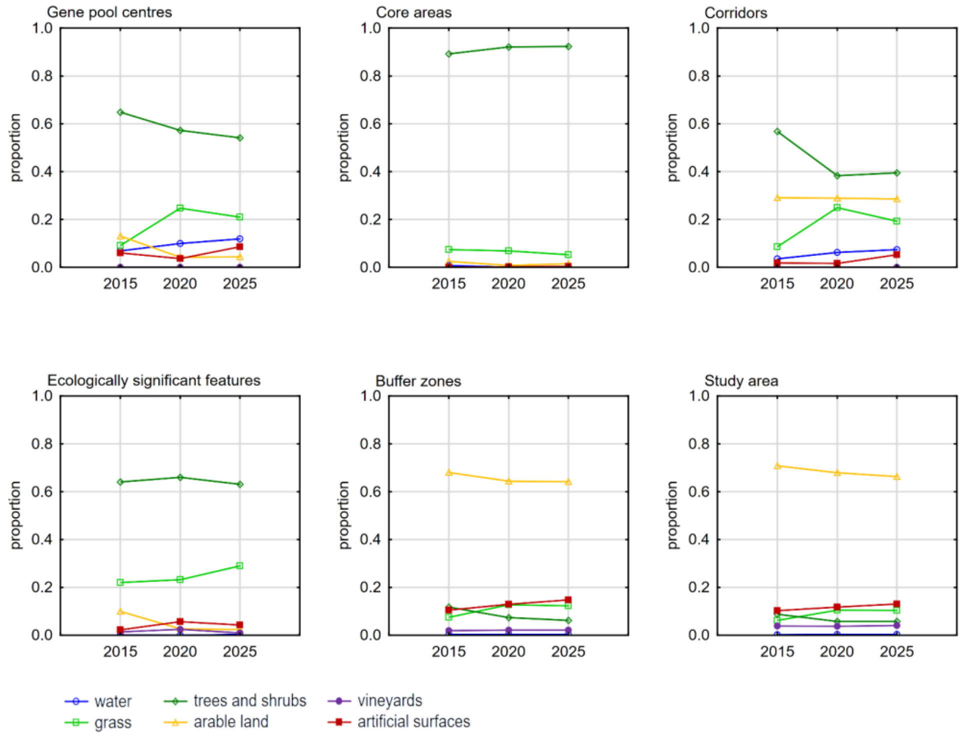

***Fig. 3.** Proportions of land cover classes in 2015, 2020, and 2025 in the entire study area, each element group of the regional ecological network, and its 100 m buffer zone*

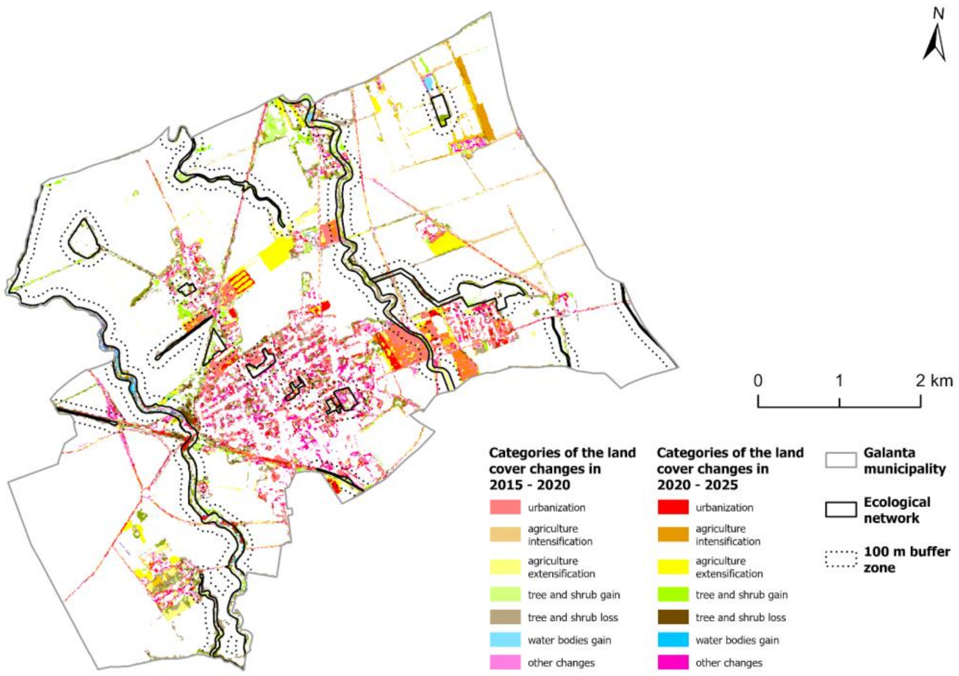

***Fig. 4.** Categorised land cover changes in 2015-2020 and 2020-2025*

Tab. 6. *Proportions (%) of categorised land cover changes in 2015-2020 and 2020-2025 calculated for the whole study area, each element group of the regional ecological network, and its 100 m buffer zone*

LC change category	Gene pool centres		Core areas		Corridors		Ecologically significant features		Buffer zones		Study area	
	2015 2020	2020 2025	2015 2020	2020 2025	2015 2020	2020 2025	2015 2020	2020 2025	2015 2020	2020 2025	2015 2020	2020 2025
no change	60.6	61.0	88.2	88.5	59.0	67.1	67.4	69.4	79.3	85.7	85.0	88.7
1	1.1	6.9	0.2	0.4	1.1	4.3	4.3	2.0	5.0	3.6	3.4	3.0
2	0.0	0.2	0.0	0.0	0.0	0.2	0.2	0.7	0.3	0.2	0.6	0.8
3	4.7	0.5	0.3	0.0	5.5	1.1	3.8	0.7	3.2	1.1	3.0	1.5
4	8.7	11.2	6.3	5.7	5.9	12.6	12.7	10.3	2.8	3.2	1.7	2.1
5	14.0	9.5	4.2	4.8	22.3	8.6	10.7	13.2	6.8	3.9	4.1	1.9
6	5.4	5.6	0.0	0.4	3.9	3.6	0.0	0.3	0.2	0.2	0.2	0.2
7	5.5	5.2	0.8	0.2	2.3	2.6	0.9	3.4	2.5	2.1	1.9	1.9

Categories of land cover changes: 1 = urbanisation, 2 = agriculture intensification, 3 = agriculture extensification, 4 = tree and shrub gain, 5 = tree and shrub loss, 6 = water bodies gain, 7 = other changes

Landscape metrics

Considering the whole study area, the spatial configuration of the landscape has not significantly changed during the observed decade while being relatively lowly fragmented. Some aggregation landscape metrics show similar values in all the time horizons ($ai \approx 93$, $pladj \approx 92\%$), indicating the stable state in terms of adjacency. Neither have changed the shapes of patches ($\bar{x}_{shape\_mn} = 1.43$, $s^2_{shape\_mn} = 0.04$, ed ≈ 149 m/ha), their size ($\bar{x}_{area\_mn} = 1.20$ ha, $s^2_{area\_mn} = 0.11$), or density ($\bar{x}_{pd} \approx 84$/100 ha, $s^2_{pd} \approx 8$). However, in terms of landscape patch composition, there is a clear movement towards higher fragmentation. It was more rapid in the 1st interval (2015 – 2020). We observed a significant shrinking of dominant patches ($lpi_{2015} \approx 47\%$, $lpi_{2025} \approx 16\%$) and a moderate increase of patch diversity ($shdi_{2015} = 1.00$, $shdi_{2025} = 1.09$).

The landscape of the 100 m buffer zones was found to be very fragmented but stable in terms of changes during the observed decade (*division* ≈ 0.98 in all the time horizons, $\bar{x}_{pd} \approx 186$/100 ha, $s^2_{pd} \approx 19$). Small patches ($\bar{x}_{area\_mn} = 0.54$ ha, $s^2_{area\_mn} = 0.05$) of regular shape ($\bar{x}_{shape\_mn} = 1.42$, $s^2_{shape\_mn} = 0.03$) and high adjacency ($pladj \approx 90$ in all the time horizons) also signify very diverse horizontal landscape structure. Small one-direction changes took place in the case of *ed* ($ed_{2015} \approx 188$ m/ha, $ed_{2025} \approx 158$ m/ha) and *shdi* ($shdi_{2015} = 1.04$, $shdi_{2020} = 1.11$).

Core areas are the least fragmented and the most stable elements of the EN. Some landscape metrics consistently indicate a high rate of the patches' aggregation in all the time horizons ($ai \approx 90$, $pladj \approx 94\%$), others show a relatively balanced state with some oscillations ($\bar{x}_{pd} \approx 84$ /100 ha, $s^2_{pd} \approx 8$, $\bar{x}_{shdi} = 0.36$, $s^2_{shdi} = 0.66$). Changes are connected especially to marginal pixels ($\bar{x}_{ed} \approx 102$ m/ha, $s^2_{ed} \approx 21$), while the cores of the elements remain stable ($lpi_{2015} \approx 80\%$, $lpi_{2025} \approx 85\%$).

In the previous chapter, we already mentioned an overlap between the areas of corridors and gene pool centres. Therefore, we identified a similar state and trend in both elements in terms of land patch fragmentation, which is the highest within the entire EN and continues to progress. This is indicated by every calculated landscape metric, whether we consider aggregation of patches (gene pool centres- $ai_{2015} \approx 73$, $ai_{2025} \approx 65$, $pladj_{2015} \approx 83\%$, $pladj_{2025} \approx 74\%$;

corridors- $ai_{2015} \approx 75$, $ai_{2025} \approx 69$, $pladj_{2015} \approx 82\%$, $pladj_{2025} \approx 75\%$), their density (gene pool centres- $pd_{2015} \approx 207$ /100 ha, $pd_{2025} \approx 314$ / 100 ha; corridors- $pd_{2015} \approx 295$ /100 ha, $pd_{2025} \approx 539$ /100 ha), or mean area (gene pool centres- $area\_mn_{2015} = 0.20$ ha, $area\_mn_{2025} = 0.11$ ha; corridors- $area\_mn_{2015} = 0.34$ ha, $area\_mn_{2025} = 0.11$ ha). Comparing the rate of fragmentation in corridors and gene pool centres, several metrics suggest that corridors experience a more dynamic rise of heterogeneity, e. g., in terms of patch composition (gene pool centres- $\Delta\ shdi_{(2015\text{-}2025)} = 0.14$; corridors- $\Delta\ shdi_{(2015\text{-}2025)} = 0.31$).

Ecologically significant features also show a relatively high level of landscape fragmentation; however, this state is quite stable and hasn't changed significantly during the last decade. There were some small movements towards a more heterogeneous landscape, especially in the 1st observed period ($pd_{2015} \approx 534$ /100 ha, $pd_{2020} \approx 620$ / 100 ha, $ai_{2015} \approx 76$, $ai_{2020} \approx 72$). Other characteristics indicated a fragmented but stable state in terms of patch aggregation ($mesh \approx 3$, $pladj \approx 84$), while some metrics were oscillating without an obvious one-direction movement ($\bar{x}_{ed} \approx 266$, $s^2_{ed} \approx 32$, $\bar{x}_{shdi} = 1.08$, $s^2_{shdi} = 0.16$).

All the calculated values of landscape metrics for the whole study area, each element group of the regional EN, and its 100 m buffer zone are listed in tab. 7.

Ecological Stability Coefficients

The value of the ESC for the entire area of Galanta municipality decreased over the last decade (fig. 5), with the most dynamic change between 2015 and 2020 ($\Delta ESC_{(2015\text{-}2020)} = 0.04$). The current value ($ESC_{2025} = 0.49$) indicates a landscape that is significantly disturbed by anthropogenic factors (Löw et al. 1984).

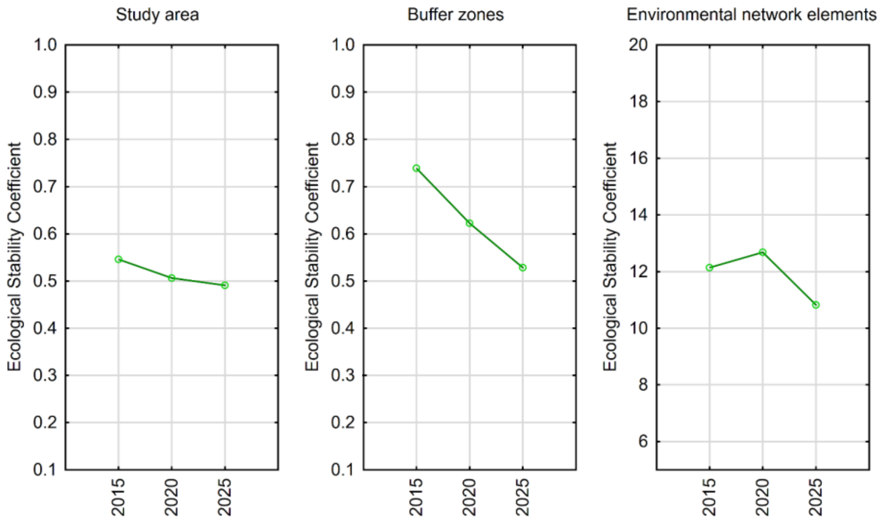

Fig. 5. *Ecological stability coefficient according to Löw et al. (1984) in 2015, 2020, and 2025, calculated for the whole study area, environmental network and its 100 m buffer zone*

A similar state of landscape ecological stability was found in the case of 100 m buffer zones of the EN ($ESC_{2025} = 0.53$), although their decrease was more pronounced over the entire last decade ($\Delta ESC_{(2015\text{-}2020)} = 0.12$, $\Delta ESC_{(2020\text{-}2025)} = 0.09$).

Ecological stability of the EN elements remains high ($ESC_{2025} = 10.82$), indicating landscape close to its natural state (Löw et al. 1984). While there is a significant decrease of ESC value, especially between 2020 and 2025 ($\Delta ESC_{(2020\text{-}2025)} = 1.86$), this is likely emphasised by the relatively small area of the EN, in which even the small land cover changes have a high impact on the resulting values.

Tab. 7. *Landscape metrics calculated for the whole study area, each element group of the regional ecological network, and its 100 m buffer zone*

Landscape metric	Year	Gene pool centres	Core areas	Corridors	Eco. signif. features	Buffer zones	Study area
ai	2015	72.51	89.09	75.39	75.85	84.74	92.42
	2020	67.93	91.10	70.64	72.46	85.77	92.64
	2025	64.62	89.97	69.21	73.92	86.28	92.62
area_mn	2015	0.20	0.48	0.34	0.19	0.48	1.11
	2020	0.16	0.51	0.24	0.16	0.59	1.33
	2025	0.11	0.32	0.19	0.16	0.55	1.17
division	2015	0.94	0.36	0.96	0.93	0.97	0.74
	2020	0.95	0.31	0.98	0.93	0.98	0.90
	2025	0.97	0.27	0.98	0.93	0.98	0.92
ed	2015	289.06	122.40	321.64	233.14	187.96	151.38
	2020	377.18	80.29	416.63	297.50	167.68	147.23
	2025	442.08	102.19	445.24	267.73	157.65	147.66
lpi	2015	16.03	79.79	9.00	21.85	8.15	47.25
	2020	15.13	83.04	9.14	22.04	5.25	19.41
	2025	8.45	85.40	5.53	21.54	5.31	15.53
mesh	2015	2.67	11.46	3.45	3.29	13.71	868.72
	2020	2.10	12.36	2.20	3.27	9.32	342.18
	2025	1.44	13.02	1.69	3.32	9.57	257.19
np	2015	229.00	37.00	264.00	244.00	1080.00	3059.00
	2020	300.00	35.00	369.00	283.00	889.00	2558.00
	2025	405.00	56.00	482.00	280.00	953.00	2893.00
pd	2015	492.16	207.75	295.04	534.15	206.38	90.20
	2020	644.75	196.52	412.38	619.53	169.88	75.43
	2025	870.41	314.43	538.67	612.96	182.11	85.31
pladj	2015	82.94	93.24	82.09	86.34	89.94	92.41
	2020	77.75	95.51	76.81	82.58	91.02	92.62
	2025	73.93	94.33	75.22	84.32	91.56	92.59
shape_mn	2015	1.41	1.34	1.56	1.38	1.41	1.40
	2020	1.38	1.30	1.54	1.41	1.45	1.47
	2025	1.33	1.19	1.45	1.33	1.39	1.41
shdi	2015	1.12	0.43	1.08	1.01	1.04	1.00
	2020	1.15	0.31	1.31	0.96	1.11	1.06
	2025	1.26	0.34	1.39	1.26	1.10	1.09

Discussion

Land cover changes in the Galanta municipality

The ongoing fragmentation of the relatively lowly fragmented entire study area in terms of patch composition is mainly a consequence of urbanization and tree and shrub losses. Decrease in ESC implies that the landscape inclines to an even more anthropogenic ally modified state. Urbanization is a consequence of landscape planning decision-making, which often meets the interests of local investors rather than sustainable development. Mederly and Vrbičanová (2023) point out that in the Galanta municipality, urbanization took place mostly on high-quality arable land. While utilizing the land use point of view, similar trends can be observed also in other municipalities of Slovakia (Šveda and Vigašová 2010), as well as in neighbouring countries (Spilková and Šefrna 2010, Csomós, Szalai and Farkas 2024). Another important issue is a decrease in total tree and shrub area. The presence of woody vegetation in the agricultural land not only enhances ecosystem services and biodiversity (Rubio-Delgado et al. 2024) but also increases the carbon sequestration potential of the area (Drexler and Don 2024).

The promotion of semi-natural landscape elements across Slovak agricultural landscapes has been supported through the Common Agricultural Policy (CAP) greening measures. These are intended to enhance biodiversity, increase habitat heterogeneity, and strengthen ecological functions within intensively cultivated landscapes (Pe’er et al. 2016). Their influence on the observed trends appears to be limited. Implementation of CAP measures may have contributed to the slight increase in fragmentation observed across the entire study area. However, this influence is expected to occur primarily within the agricultural landscape matrix, as existing natural and semi-natural elements forming part of the EN are not usually the direct targets of these measures.

Functional fragmentation of the buffer zones

Monitoring of 100 m buffer zones around the features of the EN is essential for the assessment of external pressures. In contrast to other cases (Kubacka et al. 2025, Lopes, Veettil and Saldanha 2021), our buffer zones are just a concept considered in the study, with no real incorporation into the landscape planning documentation nor any correspondence to the actual landscape physiognomy. Similarly to the whole study area, the ecological stability of the buffer zones is low, and during the last decade, it has been continuously decreasing. Dominant land cover changes comprise urbanization, fluctuations in the tree and shrub cover, and between 2020 and 2025 also extensification of agriculture (modification of arable land to grass). Abandonment of arable land tends to be a lost potential also in the sense of the high fertility of local soils, which can yield a significant amount of biomass (including crops).

Generally, this gives us a valuable insight into what the uncontrolled urbanization (leading land cover change type) in the vicinity of the lowland-situated small city looks like: areas surrounding the EN elements are undergoing a strong functional fragmentation (decline of *mesh*, increase of *division*), which dwells in the introduction of anthropogenic barriers and the connectivity loss. Meanwhile, the landscape structure does not change significantly (as indicated e.g., by *area_mn*, and *np*). Urbanization and the agriculture extensification are here simultaneous, hence the causality of this phenomenon needs to be further investigated. Although our analysis was based only on conceptual buffer zones, their assessment and long-term monitoring appear to be crucial. The observed functional instability in these zones may affect the core areas of ecological networks if appropriate mitigation measures are not implemented in time by local authorities.

Questionable stability of the core areas

Except for the margin of RBc10 – Na Garažde, there is only one core area in the Galanta municipality. RBc9 Vincov les was proven to be a stable landscape feature with high ecological quality and a low level of fragmentation. A similar description is provided by Mederly and Vrbičanová (2023), while they mention an indirect negative impact of agriculture. In ÚSES documentation (Slovak Environment Agency 2019), Vincov les is characterized as a hardwood riparian forest, while there is also a sand dune with phytogeographically significant plant species, protected by a natural reserve.

Principally, core areas seem like perfectly stable features based solely on the landscape metrics interpretation. However, in this case, a systematic point of view, incorporating also their number, size, density and connectivity should be utilized. There is a single core area of approximately 45 ha with a disrupted connectivity to other features (as described in the following subchapter). This may imply that although larger natural areas in the strongly anthropogenically altered landscape do get a sufficient formal protection, their ecological significance is often limited by the poor connectivity and very low number. This is an inevitable consequence of historical land cover changes. While creating new large semi-natural elements in the agricultural landscape is unfeasible, the connectivity, and the presence of small ecologically significant features is important.

Landscape connectivity loss as a result of corridors disintegration

According to our findings, gene pool centres and corridors are the most fragmented features of the EN. The aggregation of patches has decreased during the last decade. The most important land cover changes were the fluctuations in the woody vegetation cover and urbanization. Both corridors and gene pool centres are predominantly (GL 23, GL 24, GL 36, RBk10, RBk12) delimited on the regulated waterways Derňa and Šárd with some meanders and fragmented semi-natural vegetation growing along them. RÚSES documentation (Slovak Environment Agency 2019) mentions several endangerments of these features, e. g., spreading of invasive plant species, illegal depositing of waste, ruderalisation of plant species communities, pollution of ground and underground waters, urbanization, and the vicinity of intensive agriculture.

Similar negative factors have been described in other municipalities as well (Siman and Velísková 2020, Vaseková et al. 2022). According to Petrášová-Šibíková, Bacigál and Jarolímek (2017), disruption of floodplain forest borders can lead to increased contact with the surrounding environment, greater edge effect, and easier penetration of non-native plant species. Concerning ecological significance, the worst condition is assigned to the practically non-functional RBk21, which is a channel of insufficient proportions influenced by invasive species, agriculture, and urbanization. The only gene pool centre located in the city itself is GL 35, a historical city park with an established protected area, which, however, needs revitalization.

These results clearly demonstrate that linear natural features are more prone to fragmentation compared to the larger and more compact ones (core areas). Even without major land cover transitions, the landscape is undergoing a gradual disintegration. From the ecological point of view, such disruption reduces habitat connectivity (decrease of *ai* and *pladj*) and amplifies the aforementioned edge effect (increase of *ed*). Functional collapse of corridors in the agricultural landscape, especially when overlapped by gene pool centres, should be mitigated by their widening and by clearing of invasive plant species along with planting of native woody vegetation to reduce edge density.

Significance of "stepping stones"

Ecologically significant features are delimited within ecosystems with relatively higher ecological quality compared to the neighbouring landscape, especially when experiencing a high rate of anthropic influence. They do not meet spatial criteria to be considered core areas or corridors but still have a significant function in terms of ecological connectivity, preserving the genetic diversity of species, and enhancing ecological stability of the area. Although they do not belong to the general framework of the EN, they are usually considered when proposing designing "MÚSES" (Slovak Environment Agency 2019). In Galanta municipality, these features cover small forests (EV 48), city parks (EV 64, 65, 66, 67), cemeteries (EV 63), existing or former small water bodies (EV 52, EV 68, EV 71, EV 158), or vegetation belts (EV 59, EV 60, EV 62). According to Hrivnák et al. (2025), who investigated species diversity in the different urban ecosystems in Slovakia, the highest species richness was found in the cemeteries and the lowest in the town centres. Calculated landscape metrics show that they are highly fragmented but have been relatively stable in the last decade. The most significant land cover changes were oscillations in woody vegetation cover, urbanization, and extensification of agriculture.

In general, small ecologically significant natural or semi-natural features can be perceived as "stepping stones" in terms of habitat connectivity (Saura, Bodin and Fortin 2013). These isolated patches naturally show a high rate of landscape fragmentation (as indicated, e.g., by *division* and *area_mn*) as well as high edge density (*ed*). However, when interpreting their ecological functionality, temporal stability of the aggregation metrics as well as stability of their spatial configuration tends to be more important than the actual state of fragmentation.

Comparison with Central European studies

The results from the Galanta municipality illustrate fragmentation dynamics that are characteristic for small towns in intensively managed Central European lowland agricultural landscapes. In other Slovak regions, the overall landscape matrix remained relatively stable in terms of aggregation metrics, while a pronounced increase in heterogeneity and patch subdivision occurred at the level of EN elements, particularly corridors (Pazúrová et al. 2018).

Our findings correspond to observations from Wielkopolska region in Poland, where primarily ecological corridors of farmland areas face a high risk of fragmentation (Kubacka et al. 2025). In South Moravia long-term land-use change has led to the gradual transformation of once continuous semi-natural features into fragmented mosaics embedded within agricultural matrices (Skokanová and Eremiášová 2012).

The Galanta case study supports the notion that fragmentation in lowland towns is driven less by the loss of core habitats and more by the structural degradation of connective elements, which play a critical role in maintaining landscape-scale ecological functionality. This confirms earlier findings from Central European lowlands, where corridors represent the weakest elements of formally designated ecological networks (Kovács et al. 2020).

Such changes directly reduce functional connectivity and intensify edge effects, undermining species movement across ecological networks. Opdam et al. (2006) emphasise that ecological networks depend not only on the presence of core areas but primarily on the functional continuity of corridors.

Ecological network in landscape planning

Forest stands, non-forest woody vegetation, small-block arable land, and natural watercourses were identified as positive phenomena in the project of "MÚSES" in the cadastral territory of Hody (Kočická et al. 2018). Proposals of their study included the re-evaluation of nature and landscape conservation.

Mederly and Vrbičanová (2023) report a direct impact of future city development on 15.7% of the "RÚSES" elements area. Also, they emphasize the need for renaturation and management measures in the case of RBk10 and RBk21.

The territorial plan of the city of Galanta (Galanta City 2011) proposes the creation of new green areas of industrial and warehouse areas as well as areas of isolating green areas separating the areas from residential and recreational zones. The document includes a map of the proposed "ÚSES" elements (some of them are not included in the investigated "RÚSES"), while most of these natural or semi-natural features are already part of the landscape structure.

Primarily, we propose consistent re-evaluation and subsequent implementation of proposed local "MÚSES" elements (Galanta City 2011) in the territorial plan, so it doesn't collide with other interests. Revitalization of existing corridors or creation of new vegetation belts in agricultural land has a potential to improve the ecological connectivity of the natural features (Marcantonio et al. 2024, Tiang et al. 2021). Active management of the existing elements, especially corridors and gene pool centres, should include prevention of border disruption in the case of forests, clearing of invasive species of plants (Modiba et al. 2017), and removal of illegal waste disposal.

Limitations

Input layers of the EN did not reflect the proposal of "MÚSES" by Kočická et al. (2018) for the Hody cadastral district. Their EN elements were designed on a larger scale, using different methods and only in one part of our study area. The regional level was maintained in all the analyses, since we believe that such a dichotomy caused by the different scales and spatial density of investigated features would introduce bias to our results.

Maintaining a 5-year period length required usage of Sentinel-2 imagery from 2015. Only two records were available for this year. We opted for the imagery from the late autumn, and a similar acquisition date was selected also in the case of 2020 and 2025. By using imagery from the end of the year, we ensured that land cover changes from the almost entire year 2020 would be correctly assigned to the 1st investigated interval and that possible changes in late 2025 would also be recorded. On the other hand, this might cause some recorded fluctuations in the tree and shrub cover as a result of differences in phenological phases of broadleaved species. This is why some minor fluctuations in the woody vegetation cover (especially in the core areas and ecologically significant features) should be taken with caution.

While the 10-m resolution of the Sentinel-2 imagery is sufficient in the detection of major land cover changes, its accurate identification is challenging in the case of narrow or linear elements. These may represent ecologically stable features (e.g. windbreaks, waterways) that enhance the connectivity of the EN elements but also linear artificial objects as roads that cause the disintegration of natural features. Therefore, the impact of this spatial constraint on the interpretation of presented change statistics is difficult to evaluate. It must be noted that the usage of more detailed aerial imagery would be challenging as there are no freely available data for 2015.

After the imagery classification, a relatively low UA for grass was found in several cases, particularly in 2015, indicating confusion with forest and agricultural classes. Although post-classification masking using the LPIS layer improved thematic consistency within agricultural parcels, it does not fully eliminate classification errors, especially outside LPIS-defined areas or in transitional zones. However, as grassland represents only a small proportion of the study area, its influence on landscape-level metrics is expected to be limited, although not entirely negligible.

A six-level scale of ecological stability introduced by Löw et al. (1984) was applied in the calculation of the ESC. Although Pauditšová and Reháčková (2007) refer to some more detailed scales, our classification design did not allow us to distinguish between their individual categories which are based on characteristics that cannot be obtained from the satellite imagery (e.g., intensity of agricultural activity, species composition of the forest stands). Therefore, the performed computation of the ESCs is simplified as the result of applied classification. This method of ESC calculation was originally designed for larger and more diverse areas (e.g., entire municipalities) with the various impacts of anthropogenic land cover modifications. Because the ESC is calculated as a weighted combination of the proportions of land-cover categories assigned different ecological significance, its value is strongly influenced by the relative representation of individual categories within the assessed area. Consequently, areas with substantially different land-cover compositions may exhibit markedly different ESC values even when the ecological condition of particular categories remains unchanged. Our application of the index to smaller areas was intended primarily to provide a simplified quantitative expression of changes in the representation of categories with different ecological significance. Therefore, the results should be interpreted mainly as indicators of temporal trends rather than as absolute values directly comparable among areas with substantially different compositions.

Conclusion

Galanta municipality is characterized by a prevalence of arable land and a low overall level of landscape fragmentation, although land cover patches showed a gradual decrease of their aggregation during the last decade, mainly due to urbanization, agriculture extensification, and loss of woody vegetation cover. Unlike the entire study area, land cover within the established features of the regional EN was proven to be close to the natural state, although it experiences significant fragmentation in the sense of both patches' configuration and composition. The land cover patches of corridors and gene pool centres were less aggregated, while the single core area was most compact. Dynamic fragmentation and the decrease of ecological stability were also observed in the 100 m buffer zone of the EN.

The regional EN of the Galanta municipality needs to be properly implemented into territorial plans, as well as refined and widened at the local level. In addition, targeted management measures for the existing EN elements should be adopted to promote ecological quality within such anthropogenically modified landscape.

Our analytical procedures can also be applicable to ecological networks of other municipalities, especially in the agricultural lowlands, and findings have the potential to provide beneficial insights for enhancement of their protection. Moreover, the proposed methodological workflow is replicable and can be incorporated into the assessment of the ecological networks on the regional or municipal level.

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