CHANGES IN LAND USE AND DIVERSITY OF AGRICULTURAL LANDSCAPE: A CASE STUDY OF THE TRIBEČ AND ŽITAVA UPLAND INTERFACE (KOLÍŇANY, ŽIRANY)

Peter Petluš[1], Viera Petlušová[1], Renáta Klimanová[1]

[1] Department of Ecology and Environmental Sciences, Faculty of Natural Sciences and Informatics, Constantine the Philosopher University in Nitra, Tr. A. Hlinku 1, 949 01 Nitra, Slovakia

Abstract

The presented study analyses the spatio-temporal dynamics of the agricultural landscape at the interface of the Tribeč Mountains and the Žitava Upland across three key periods: 1949 (pre-collectivization mosaic), 2018–2024 (large-block management), and 2025 (implementation of strip-cropping). Quantitative analysis using landscape metrics (e.g., SHDI, Edge Density, Patch Density) documents a radical transformation of the area, where initial high diversity (138 patches) declined due to collectivization into extreme homogenization (3 patches). However, the introduction of strip-cropping in 2025 demonstrated a significant increase in edge density (from 107 m/ha to 447 m/ha) and reached a historical maximum in the evenness index (0.876). The research confirms that although temporal crop diversity (TDCI = 0.625) did not numerically increase with the introduction of strips, a fundamental qualitative optimization of the landscape's spatial configuration occurred. This approach enhances ecological stability, creates mechanical barriers against water erosion, and restores the functional texture of the agricultural matrix.

Keywords: landscape diversity, landscape metrics, strip-cropping, TDCI (Temporal Diversity Crop Index), land use changes

INTRODUCTION

The intensively used agricultural landscape of the Slovak uplands represents a dynamic socio-economic system that has undergone unprecedented transformational processes over the last seven decades. The occurring changes were not merely aesthetic but, above all, functional and structural. They resulted in a reduction of landscape diversity and influenced its visual character. Current landscape diversity is a result of the interaction not only between the natural potential of the given area but also the intensity of anthropic use (Hrnčiarová, 2011). In conditions of intensive agriculture, this relationship has tilted in favor of a one-sided production function, leading to significant homogenization of the territory. The landscape is characterized by its sensitivity to land-use changes, while the unsuitable spatial configuration of patches directly determines the intensity of degradation processes, particularly water erosion.

The development of the Slovak agricultural landscape after 1948 was fundamentally influenced by political and economic changes. The pre-collectivization period was characterized by a high degree of heterogeneity, where narrow-strip parcels created a dense network of linear

https://doi.org/10.11118/978-80-7701-098-6-0025

elements and hedgerows. In terms of the quantitative assessment of landscape and diversity changes, the landscape structure exhibited high values of Edge Density (ED) and Patch Density (PD), which supported the biodiversity of agrocenoses. The process of collectivization, implemented mainly from the 1950s to the 1970s, led to a radical homogenization of the landscape. The forced amalgamation of fields and the systemic removal of balks resulted in a drastic reduction of the Total Edge (TE) length. This process of mandatory land merging transformed the intricate historical mosaic into expansive, large-scale production blocks, resulting in a severe decline in landscape diversity (Kopecká, 2011; Kuchma *et al*., 2013; Olah *et al*., 2025). As stated by Moravčíková et Ružičková (2006), this process led to a sharp decrease in the number of landscape elements and their spatial differentiation. The transformation disrupted not only ecological links but also the visual identity of the countryside (Izakovičová *et al*., 2021).

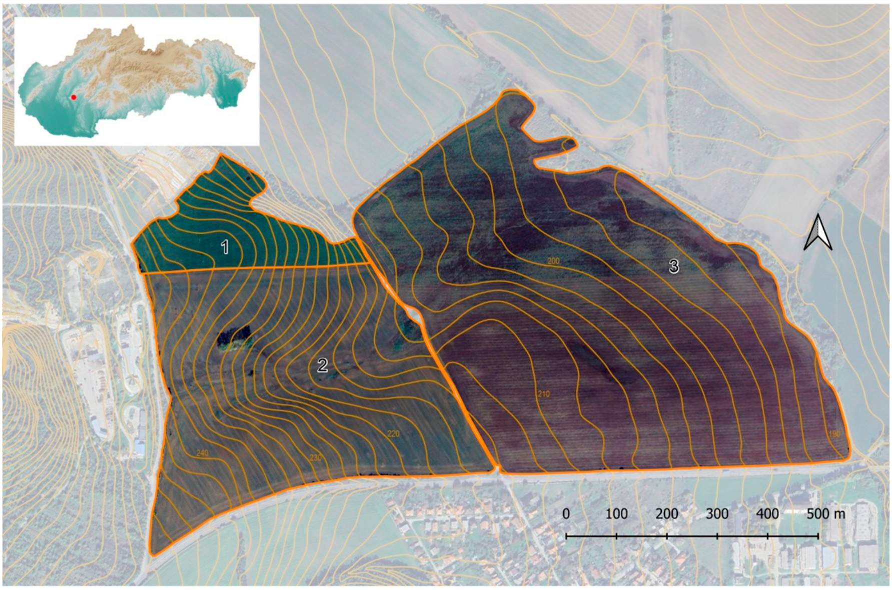
Current trends in landscape planning, driven by the EU's Common Agricultural Policy and climate change, are returning to the principles of spatial diversification. Strip-cropping and the establishment of flower strips represent a modern response to soil degradation. Mojses et Petrovič (2012) document that restoring landscape evenness through crop rotation in strips leads to increased regional diversity. Oťaheľ (2011) also highlights the increase in landscape diversity, analysing the contrast between marginalized areas and intensively used agricultural landscapes. One approach to assessing landscape diversity is the qualitative analysis of the spatial structure of the landscape, which relies on a set of metrics that allow for an objective evaluation of fragmentation, intensification, and ecological stability processes. These parameters provide key data for understanding how changes in land use affect landscape diversity, biodiversity, and the functionality of landscape ecosystems. Quantitative analysis using software tools such as FRAGSTATS or other landscape metrics has become the standard for assessing these changes (McGarigal, 2015). Key metrics include shape indices, which measure the complexity of patch shapes compared to standard geometric forms, edge density, and the size of core areas, which are critical for organisms sensitive to edge effects (McGarigal, Marks, 1995). Similarly, the Contagion Index serves as an indicator of the connectivity of landscape elements, where high values signal the dominance of large monocultural blocks and low values suggest a heterogeneous mosaic with a high degree of spatial dispersion (Li, Reynolds, 1993). Spatial heterogeneity is fundamental in agricultural landscapes because the structure of the matrix surrounding habitats determines their actual isolation (Tischendorf, Fahrig, 2000). Landscape heterogeneity has proven crucial for biodiversity assessment (Walz, 2015). Typically for an agricultural landscape, the matrix has a profound impact on landscape dynamics and should not be ignored in analyses (McGarigal, Marks, 1995).

The aim of this paper is a quantitative analysis of landscape structure changes across three model periods: the pre-collectivization landscape of 1949, dominated by narrow-strip fields; the recent past with prevailing large-block arable land management (2018–2024); and the present state with implemented strip-cropping elements (2025) as an adaptation measure that increases landscape diversity with a positive impact on soil properties and the elimination of soil degradation processes. The premise for the analysis is that the decline of landscape diversity in the Slovak uplands is not a random process but a consequence of targeted socio-economic transformation, which led to changes in land use and, subsequently, a reduction in the diversity of landscape elements. The degree of landscape fragmentation and diversity, expressed through selected landscape-ecological metrics, directly correlates with the ecological stability of the area and its capacity to provide essential ecosystem services.

MATERIALS AND METHODS

Study Area

The study area is located at the interface of the Tribeč Mountains and the Žitava Upland, on the border of two cadastral territories – Kolíňany and Žirany, situated 12 km northeast of the city of Nitra. It consists of three soil units covering a total area of 75.95 ha (Fig. 1).



1: *Study area delineation*
Source: Satellite imagery of the Kolíňany area, Nitra Region. Accessed March 31, 2026, from https://www.google.com/maps; 1–3 indicate the identification of patches.

The soil units are utilized as permanent grassland (5.5 ha; Žirany), arable land (25.49 ha; Kolíňany, where in the monitoring period of 2025 spring barley Hordeum sativum L. was grown, followed by oilseed rape Brassica napus L. var. napus in 2026), and arable land under strip-cropping management (44.96 ha; Kolíňany, with alternating strips of maize Zea mays L. and spring barley Hordeum sativum L.). The soil units are separated by a grassed field road. The study area is bordered by Class I–III roads and the Bocegaj stream. The relief of the territory is gently undulating, with a slope gradient ranging from 0° to 7°. During the field research, three soil groups were identified:

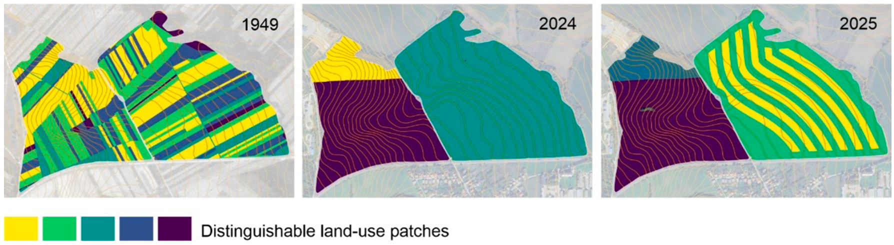
1. Initial Soils - Haplic Regosols, Anthropic Regosols, Gleyic Fluvisols;
2. Illimeric Soils – Haplic Luvisols, Stagnic Luvisol, eroded Stagnic Luvisol;
3. Mollic Soils - Haplic Gleysol (Mollic).

Loess loams, marsh loess, a stagnic (pseudogley) substrate, colluvium, and quartzite colluvium were identified within the study area. These soils developed on various substrates.

Agricultural land has been subject to long-term intensive exploitation. The narrow-strip farming characteristic of the pre-collectivization period was replaced by large-block arable land, which is currently degraded by erosion-accumulation processes and surface runoff. Erosional sediments accumulate in relief depressions and are gradually transported by surface runoff into the Bocegaj stream. During the monitoring period, the colluvial parts of the soil units remained unmanaged and were covered by common reed (Phragmites australis).

Quantitative and Qualitative Land-Use Analysis

Landscape assessment was based on selected quantitative indicators (total area, number of patches, edge length) and qualitative parameters. The landscape structure was evaluated at the landscape-wide level using landscape metrics (McGarigal, Marks, 1995). The LecoS plugin and its Landscape Statistics tools within the QGIS environment were utilized to calculate the landscape metric indicators. The primary input material consisted of a raster layer with a 1 m pixel resolution, obtained by converting vector data types into a raster format at a 1 m resolution. The layers were analyzed based on land-use differences within each respective period (Fig. 2).



2: *Spatially distinguishable land-use patches across the 1949–2025 periods*
Source: Historical aerial photograph from 1949 (© GEODIS SLOVAKIA, s.r.o. and Historical LMS © Topographic Institute Banská Bystrica); Satellite imagery of the Kolíňany area, Nitra Region. Accessed March 31, 2026, from https://www.google.com/maps; Geodesy, Cartography and Cadastre Authority of the Slovak Republic, dataset of descriptive and graphic information from Register "E", vector cadastral map (Kolíňany, Žirany)

The following landscape structure characteristics were monitored: Total Edge (TE), Edge Density (ED), Patch Density (PD), Shannon's Diversity Index (SHDI), Simpson's Diversity Index (SIDI), and Shannon's Evenness Index (SHEI). These characteristics were analyzed across the entire study area and compared for the periods of 1949, 2018–2024, and 2025. The metrics focus on the geometric properties of patches, which, in an agricultural context, represent individual parcels (Hreško, Petrovič, 2006; Kopecká, 2011; McGarigal, Marks, 1995):

a) Total Edge (TE) - the sum of the lengths of all boundaries between different types of landscape patches. In an agricultural landscape, a high value indicates high structural complexity and the presence of ecotones (transition zones), which is beneficial for species diversity, provided it is not the result of excessive habitat fragmentation.
b) Edge Density (ED) - normalizes the total length of edges per unit area, allowing for the comparison of territories with different spatial extents. A high edge density correlates with the presence of linear green elements and smaller agricultural blocks.
c) Patch Density (PD) - indicates the number of patches per unit area and serves as a direct indicator of landscape fragmentation. Changes in land use towards intensification (land consolidation) lead to a dramatic decrease in PD. Conversely, crop diversification and the restoration of landscape elements increase patch density.
d) Shannon's Diversity Index (SHDI) - quantifies landscape diversity through two components: the number of individual patch types (compositional component) and the evenness of their spatial distribution (structural component). The index value increases when the number of different patch types rises and/or when the proportional representation of these types becomes more balanced.
e) Simpson's Diversity Index (SIDI) - expresses the probability that two randomly selected patches in the landscape will belong to different land-use types. It is less sensitive to the presence of rare patch types than Shannon's index and more accurately reflects the dominance of the primary land-use types.
f) Shannon's Evenness Index (SHEI) Buzas and Gibson's evenness version, - eliminates the influence of the number of categories and focuses exclusively on how evenly the area is distributed among these categories. It serves to express the equitability of the area distribution between individual categories within the landscape mosaic. A value of 1 for both indices indicates that all land cover types have equal spatial representation. In agricultural practice, low SHEI values signal the dominance of a single crop or land-use type (e.g., large-block arable land), which is typical for intensive production areas.

The study assumed (Forman, Godron, 1993) that the size, shape, evenness of representation, and patch density significantly influence landscape diversity. It was hypothesized that biodiversity increases due to the edge effect, correlating with increasing patch boundary length and patch density.

Landscape Diversity Analysis

The Year 1949

The landscape analysis was conducted using a historical aerial photograph from 1949 (© GEODIS SLOVAKIA, s.r.o. and Historical LMS © Topographic Institute Banská Bystrica). The objective was to create a categorized land-use layer for the year 1949. The aerial photograph was georeferenced into the S-JTSK coordinate system using ground control points (GCPs). Subsequently, manual vectorization was performed and cross-referenced with the cadastral map from Register "E".

To identify the internal structure of the historical landscape, an unsupervised classification was performed using the Attribute Based Clustering tool integrated into QGIS. To determine the diversity of landscape patches, spectral brightness (Mean) and textural variability (Standard Deviation) characteristics of the aerial photograph were extracted for each polygon via zonal statistics. These normalized values served as inputs for the K-means clustering algorithm, which assigns patches to groups based on the minimum Euclidean distance in the feature space.

To determine the optimal number of classes, the Elbow method diagnostic plot was used, monitoring the Total Within-Cluster Sum of Squares (WSS) in relation to the number of clusters (k). The plot showed a distinct "elbow" at $k = 5$, establishing the optimal number of statistically distinguishable land-use categories for 1949. The resulting five clusters were back-mapped to the polygon layer, creating a categorized historical land-use map for subsequent landscape metric analyses.

The 2018–2025 Period

The analysis for the 2018–2024 period utilized seven separate digital shapefiles (*.shp), each representing an individual growing season. Given the absolute stability of the physical landscape structure (boundaries) during this timeframe, these layers entered the general landscape metric analysis as a single consolidated state. However, for the assessment of temporal crop diversity (TDCI), all seven layers, supplemented by the crop data and were analyzed independently to capture the precise sequence of crop rotations. Forthis period was conducted using LPIS (Land Parcel Identification System) layers and digital shapefiles (*.shp) of land-use boundaries for the years 2018–2025, obtained from the National Catalogue of Open Data. The vector layers were converted into a raster format with a 1 m pixel resolution and subjected to landscape metric analysis using the LecoS plugin tools in QGIS. Diversity indices (SHDI, SIDI, SHEI) were calculated within the PAST (Paleontological Statistics) software environment using the Diversity indices module.

Analysis of Arable Land Use Diversity (2018–2025)

The assessment of the landscape using qualitative and quantitative metrics was supplemented by an analysis of land-use diversity for the 2018–2025 period. The objective of the arable land--use diversity analysis was to identify the internal heterogeneity of patches and to evaluate crop rotation levels over time using the Temporal Diversity Crop Index (TDCI).

The TDCI serves as a sustainability indicator for agricultural landscapes, focusing on the dynamics of crop rotation within a specific area (patch) over a defined time horizon. It reflects the adherence to crop rotation sequences and the ecological stability of the production system by quantifying the variability and sequence of crops cultivated on a given plot. A high TDCI value indicates a diverse crop rotation with regular alternating of species, while a low value signals monocultural practices. Areas where low spatial diversity (large soil blocks) overlaps with a low temporal diversity index (frequent repetition of the same crop) are identified as high-risk zones for erosion, biodiversity loss, and soil structure degradation.

The analysis utilized digital shapefiles (*.shp) of land-use boundaries from 2018–2025, obtained from the National Catalogue of Open Data. Each crop type was assigned a unique numerical code, maintained consistently throughout the 2018–2025 time series. For the purpose of raster analysis, each individual vector layer was converted into a raster format.

The index calculation was performed within QGIS using the *r.series* algorithm (a GRASS GIS module), which allowed for the processing of the eight layers as a single time series. This step resulted in a raster where each pixel value represented the absolute count of unique crops at that location. To obtain the final TDCI, the Raster Calculator was used to divide the absolute number of unique crops by the total number of monitored years ($n = 8$).

RESULTS

The quantitative analysis of agricultural landscape spatial structure is based on metrics that enable an objective assessment of fragmentation, intensification, and ecological stability processes. This is supplemented by an analysis of arable land-use diversity. These analyses express the spatio-temporal dynamics of landscape structure during the 1949–2025 period and the temporal crop diversity for the years 2018–2025.

Spatio-temporal Dynamics of Landscape Structure and Its Impact on Territorial Stability (1949–2025)

The landscape assessment was based on the analysis of selected quantitative and qualitative indicators across three distinct periods (1949, 2018–2024, and 2025). The monitored characteristics of the landscape patch structure and their respective values are presented in Tab. I.

I: *Indicators of landscape structure and diversity for agricultural areas*

Year	Total area (ha)	Total Edge (m)	Edge Density (m/ha)	Patch density (n/ha)	Shannon's Diversity Index	Simpson's Diversity Index	Evenness (eH/S)	Number of Patches
1949	75,953	83,425	1098,69	14,61	1,442	0,744	0,846	138
2018–2024	75,953	8,128	107,01	0,276	0,867	0,532	0,793	3
2025	75,953	33,888	446,99	0,47	1,254	0,693	0,876	9

The analysis of structure and diversity indicators for agricultural areas documents three fundamental stages of landscape development. Each monitored period is characterized by a distinct number of evaluated patches (*Number of Patches*).

Linear Landscape Complexity Expressed by Total Edge (TE) and Edge Density (ED)

Total Edge (TE) is the most sensitive indicator of changes in the spatial arrangement of a landscape, representing the cumulative length of boundaries between individual patches. The historical state in 1949 exhibited a maximum TE of 83.4 km, with an Edge Density (ED) of 1,098.7 m/ha. The historical landscape possessed an extraordinarily high proportion of contact zones; each hectare contained an extreme number of linear interfaces, indicating a dense network of balks and a high-diversity mosaic.

Subsequent collectivization and land consolidation after 1949 led to a critical reduction in TE. By 2018, the total edge length had plummeted to only 8.1 km. The reduced ED of 107.01 m/ha indicates a state of extreme mechanization and consolidation, representing a 90.3% loss in edge density. The landscape lost its internal linear features; through the removal of these elements, the original network collapsed, and the territory was consolidated into several massive blocks with minimal contact between different land cover types.

The state in 2025 (TE of 33.9 km) captures a significant recovery of linear elements. We observe an increase in ED to 446.99 m/ha, meaning that the edge length per hectare has increased fourfold compared to the 2018–2024 period.

Spatial Landscape Fragmentation Expressed by Number of Patches (NP) and Patch Density (PD)

These indicators evaluate the degree of territorial fragmentation into distinct spatial units. The historical state in 1949 identified up to 138 individual patches, with a density value of 14.61 patches/ha. On average, nearly 15 to 18 separate patches were located within a single hectare. The landscape functioned as a mosaic of small segments with a high frequency of alternating categories.

In contrast, the agricultural landscape in 2018 consisted of only 3 individual patches. The PD plummeted to 0.276 n/ha, representing extreme land homogenization (consolidation). The landscape was composed of vast, internally undifferentiated soil blocks. Following 2025, a slight increase in fragmentation was recorded. Although the patch density remains low, the threefold increase in the number of patches signals the beginning of a process of renewed spatial differentiation within the landscape.

Landscape Diversity and Evenness Expressed by SHDI, SIDI, and SHEI

Diversity and evenness indicators provide a deeper insight into the qualitative richness and spatial stability of the study area. The historical state in 1949 exhibited the highest degree of heterogeneity, as confirmed by an SHDI of 1.442. The high SIDI value (0.744) indicates that the landscape was not only fragmented but also compositionally diverse, with no single patch category dominantly prevailing over others. The landscape Evenness index reached 0.846, documenting a harmonious spatial distribution among individual land cover types within the historical mosaic.

Subsequent collectivization and agricultural intensification processes led to significant structural simplification and landscape homogenization. By the 2018–2024 period, a sharp decline in SHDI to 0.867 was observed, representing a loss of nearly 40% of landscape mosaicness compared to the baseline. The SIDI fell to 0.532, indicating a state of pronounced monotony where a single dominant category (large-block arable land) suppressed other landscape elements. Although the Evenness index (EI) maintained a value of 0.793, this is more a mathematical artifact of the low number of remaining segments rather than a reflection of true internal stability.

However, the current state in 2025 captures a trend of renewed diversification. The SHDI rose to 1.254, significantly approaching the historical values from the mid-20th century. The increase in SIDI to 0.693 confirms that the dominance of monocultural blocks has been weakened in favor of a more diverse representation of other categories. The most remarkable finding is the increase in Evenness to a historical maximum of 0.876. This value suggests that although there are fewer patches in the current landscape than in 1949, their mutual area ratio is distributed most optimally across the entire monitored period, creating a prerequisite for a more stable spatial configuration of the landscape.

Temporal Crop Diversity in the 2018–2025 Period

From the analysis of crop rotation dynamics, five crops were identified during the 2018–2025 period: spring barley (*Hordeum sativum* L.), maize (*Zea mays* L.), oilseed rape (*Brassica napus* L. var. napus), winter wheat (*Triticum aestivum* L.), and Styrian oil pumpkin (*Cucurbita pepo* var. *styriaca*). These crops were rotated across two soil units, while one additional soil unit was utilized as permanent grassland (Fig. 3). In the 2025 season, strip-cropping management was implemented on the soil unit, alternating between spring barley and maize (Fig. 4).

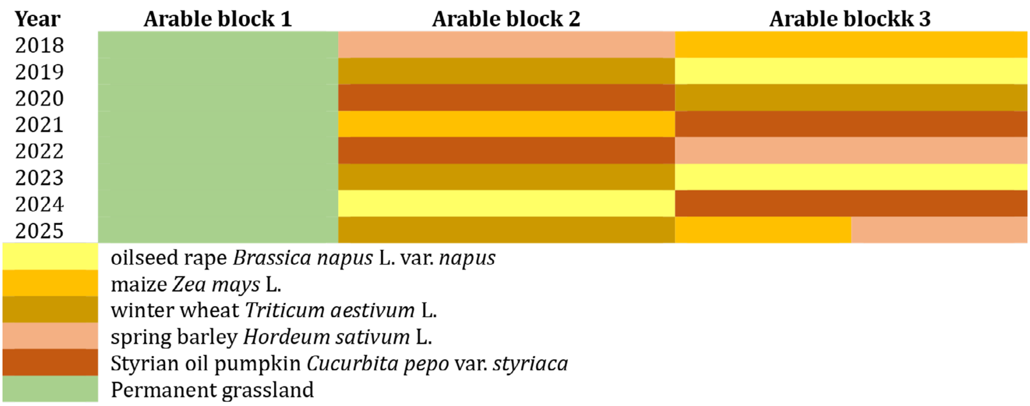
The analysis of temporal crop diversity within the study area revealed three dominant levels of crop rotation. Based on the calculated Temporal Diversity Crop Index (TDCI), three qualitatively distinct types of patches were identified.

A) Temporally Homogeneous Patch

Arable block 1 (5.5 ha, 7.2% of the territory) exhibits zero dynamic change over time (stagnant structure). This unit consists of permanent grassland. The TDCI value was 0.125. From the perspective of landscape metric assessment, this is an area with minimal internal diversity that did not change its function during the eight-year cycle. Such patches act as static elements within an otherwise dynamic agricultural landscape.

B) Suboptimal Production Scheme

On a total area of 54.276 ha (71.5% of the territory), a high degree of management schematism was recorded. The index reached a value of 0.625. During the monitored period, five crops were included in the rotation (Fig. 3). This indicates a narrow crop rotation, which, from a long-term perspective, leads to soil fatigue and landscape uniformity. This state forms a homogeneous, standard matrix of basic crop rotation commonly utilized in the agricultural landscapes of Slovakia.



3: *Temporal crop diversity in the 2018–2025 period*
Source: Digital layers of the Land Parcel Identification System (LPIS) and Land-Use Boundaries for the 2018–2025 period.

4: *Overview of arable blocks utilization in the 2025 season with implemented strip-cropping management*

C) Segments with Functional Spatial Diversification

The implementation of strip-cropping on soil unit 3 (16.182 ha; 21.3%) did not result in a numerical increase of the temporal diversity index (TDCI = 0.625); however, a fundamental qualitative transformation occurred. The crop rotation (5 crops over 8 years) achieved a high degree of asynchrony within the strip system. While in the suboptimal scheme (B), these 5 crops are cultivated uniformly in monocultural blocks, strip-cropping partitioned them into a heterogeneous spatial mosaic.

In the context of landscape metrics, measurable changes occurred on this area that the TDCI index is unable to capture. Edge Density (ED) increased to 447 m/ha, evidencing the creation of a dense network of linear interfaces. These boundaries between strips in different phenological stages function as biotic and mechanical barriers (Fig. 5). They disrupt the continuity of surface runoff and subsequent soil loss a phenomenon that is absent in conventional areas (B) despite an identical crop rotation scheme. The landscape has thus lost its character as a uniform "production block" and acquired the features of functional diversification. The year 2025 confirms that the benefit of strip-cropping does not lie in the expansion of crop species composition (as the crop pool remained unchanged) but in the optimization of the spatial configuration. This arrangement maximizes the ecological stability and erosion-control potential of the territory while maintaining the current production scheme.

DISCUSSION

The implementation of strip-cropping within the study area in 2025 represents a fundamental turning point in the quality of landscape structure. This relatively simple management intervention has indicated a potential reversal of the decades-long degradation of spatial heterogeneity. This is consistent with the findings of Hanušin, Štefunková (2015), who state that an increase in landscape diversity is contingent upon a shift in spatial arrangement, which in turn is driven by the intensity of anthropogenic influence on the landscape. The most significant manifestation of this change is the radical transformation of the territory's linear complexity. While during the 2018–2024 period, the Total Edge (TE) reached a critically low level of 8.1 km, in 2025 it rose to 33.9 km. This fourfold increase in Edge Density (ED) fundamentally altered the nature of the landscape surface in terms of geomorphological processes. A homogeneous landscape acts as a smooth recipient of precipitation, facilitating uncontrolled surface runoff. In contrast, strip-cropping introduces a shift toward higher surface roughness, where each patch interface functions as a natural mechanical filter and barrier. This landscape transformation process had a direct impact on diversity indices (Hrnčiarová, 2011; Izakovičová *et al.*, 2022). By partitioning large-block fields into a system of nine functional patches, the Shannon Diversity Index was successfully increased from 0.867 to 1.254. An even more remarkable result is the achievement of the historically highest level of Evenness (SHEI = 0.876), which surpassed even the parameters of the original mosaic landscape from 1949. Characterizing landscape heterogeneity, often through the quantification of landscape diversity, remains a critical focus of landscape ecology (Crow *et al.*, 1999; Dale *et al.*, 2000; Haines-Young, Chopping, 1996). Greater spatial heterogeneity can significantly influence the dispersal of flora and fauna by increasing the number of land cover types encountered during movement (de Roos, Sabelis, 1995; Gustafson, Gardner, 1996). Strip-cropping has introduced a geometric order and uniform crop distribution to the territory, thereby eliminating the dominance of large-scale monocultures typical of a degraded agrarian matrix. Landscape diversity can be enhanced through several pathways, including temporal, spatial, or genetic diversification (Ditzler *et al.*, 2021). Increasing crop diversity is equally vital for the diversification of the agricultural system, its stability, and crop quality (Morel, Léger, 2016). From the perspective of spatio-temporal dynamics (TDCI), the implementation of strips has enabled the emergence of a so-called asynchronous heterogeneous landscape. Structural landscape heterogeneity is decisive for both agroecosystem stability (Forman, Godron, 1993) and profitability, as demonstrated in studies investigating the relationships between crop productivity and landscape diversity (Abson *et al.*, 2013; Carvalheiro *et al.*, 2011). Although the overall crop pool within the rotation remains limited to five species, their arrangement into strips within category 3 (TDCI = 0.625) creates critical temporal interfaces in 2025. However, there is still a persistent lack of methods, tools, and indicators that incorporate in-field spatial assessment as a core component of cropping system planning. For instance, in a recently proposed indicator framework for assessing diversified cropping systems (Iocola *et al*., 2020), only one indicator—the crop diversity index—addressed spatial aspects at the field or farm level, and even then, only in a spatially implicit manner. This approach accounts for the number of different crops per measured area but neglects their specific allocation and interactions (Juventia *et al*., 2022). Consequently, the landscape mosaic is no longer perceived as a static production block, but as a dynamic environment with a higher frequency of vegetation cover phase rotations. Landscape metrics, however, serve as a powerful tool for the spatial planning of agricultural structures and the selection of optimal landscape arrangement and land-use models by quantifying the composition, configuration, and density of landscape structure elements (Kuchma *et al*., 2013). The straightforward transition to strip-cropping in 2025 demonstrably improved the landscape by restoring its functional texture, increasing its complexity, and creating barriers that laid the foundation for more sustainable stability across the entire study area. Strip-cropping can be considered an appropriate method for the spatial organization of cropping areas and one of the core pillars of regenerative agriculture and soil erosion control. In the context of an intensively utilized agricultural landscape, it fulfills this function by alternating narrow strips of crops with distinct biological and agrotechnical properties (Fig. 5).

5: *Linear interface between crops in a strip-cropping system, highlighting the soil-protective function of barley stubble following harvest*

In light of the presented results of the Temporal Diversity Crop Index (TDCI), it is evident that the agricultural landscape within the contact zone of the Tribeč Mountains and the Žitavská pahorkatina Upland exhibits significant structural and functional heterogeneity. This state is determined not only by the natural transition from a mountain range to an upland landform but primarily by the intensity and mode of anthropogenic land use. The identified three levels of temporal diversity reflect a broader trend in contemporary Slovak agriculture.

The dominance of the suboptimal production scheme confirms a persistent orientation toward a narrow assortment of market crops a high degree of intensification that prioritizes economic efficiency over ecological sustainability. From a landscape ecology perspective, such managed areas create large-scale blocks within the landscape matrix, contributing to the visual and functional uniformity of the Žitavská pahorkatina Upland. The long-term application of this scheme inevitably increases the risk of soil degradation, particularly in the context of soil fatigue and the landscape's reduced capacity to withstand climatic extremes.

In contrast to these dynamic yet schematic areas, permanent grasslands fulfil a critical stabilizing function. Within an intensively utilized agricultural landscape, they are essential for preserving biodiversity and soil protective functions, especially on the sloping terrains at the foothills of the Tribeč Mountains. Based on the results, the implementation of strip-cropping is considered the most significant finding. The increased mosaicism and the emergence of distinct spatial boundaries between individual crop rotation phases directly correlate with enhanced landscape complexity. This process of fragmenting large production blocks into smaller, functionally distinct segments represents a desirable step toward strengthening the ecological stability of the territory. Based on the findings within the study area, it is recommended to implement measures aimed at increasing agricultural landscape diversity, focusing on crop diversification, spatial restructuring, and regenerative approaches. Regarding crop rotation diversification and the mitigation of soil fatigue, it is advisable to incorporate, for example, legumes or oilseeds into the rotation and to implement cover crops (catch crops). Spatial optimization should be enhanced through the planting of linear green elements or flowering strips for pollinators. Furthermore, grassed waterways or filter strips should be established to connect permanent grasslands with the newly formed strip-cropping segments, thereby creating a continuous ecological network within the study area.

CONCLUSION

The presented study documents the structural and functional transformation of the agricultural landscape at the interface of the Tribeč Mountains and the Žitavská pahorkatina Upland, confirming that the current level of diversity is a direct reflection of the chosen management approach. The analysis of three temporal horizons identified key trends ranging from historical heterogeneity through extreme homogenization to contemporary efforts toward spatial diversification. Quantitative analysis using landscape metrics demonstrated that both historical land use and traditional narrow-strip farming were characterized by high diversity, which significantly decreased during the period of collectivization and increased again through the implementation of strip-cropping. The application of strip-cropping initiated a process of landscape restoration. The analysis of temporal dynamics during the 2018–2025 period highlighted the limitations of current crop rotations, which may lead to soil fatigue. The results confirm that the introduction of strip-cropping in 2025 represents a fundamental turning point, restoring the landscape's functional texture and increasing its complexity. To further enhance the stability of the agricultural landscape within the study area, it is advisable to diversify crop rotations by incorporating legumes and cover crops to eliminate monoculture effects, expand spatial restructuring through flowering strips and linear green elements, and build ecological connectivity by linking permanent grasslands with new strip-cropping segments. Strip-cropping thus emerges as a core pillar of regenerative agriculture, capable of effectively transforming degraded production blocks into a functionally diversified and more resilient agricultural landscape.

Acknowledgements

This research was supported by the project APVV-23-0530 Strip-Crop Rotation in Combination with Agroforestry - An Innovative Land Management System under Climatic Change Conditions and project KEGA 024UKF-4/2025 Main soil threat processes in agricultural landscapes.

REFERENCES

ABSON, D. J., FRASER, E. D., BENTON, T. G. 2013. Landscape diversity and the resilience of agricultural returns: a portfolio analysis of land-use patterns and economic returns from lowland agriculture. *Agriculture & Food Security*. 2(1), 2.

CARVALHEIRO, L. G., VELDTMAN, R., SHENKUTE, A. G., TESFAY, G. B., PIRK, C. W. W., DONALDSON, J. S., NICOLSON, S. W. 2011. Natural and within-farmland biodiversity enhances crop productivity. *Ecology Letters*. 14(3):, 251–259.

CROW, T. R., HOST, G. E., MLADENOFF, D. J. 1999. Ownership and ecosystem as sources of spatial heterogeneity in a forested landscape, Wisconsin, USA. *Landscape Ecology*. 14(5), 449–463.

DALE, V. H., BROWN, S., HAEUBER, R. A., HOBBS, N. T., HUNTLY, N., NAIMAN, R. J., RIEBSAME, W. E., TURNER, M. G., VALONE, T. J. 2000. Ecological Principles and Guidelines for Managing the Use of Land. *Ecological Applications*. 10(3), 639–670.

DE ROOS, A. M., SABELIS, M. W. 1995. Why does space matter? In a spatial world it is hard to see the forest before the trees. *Oikos*. 74, 347–348. https://hdl.handle.net/11245/1.111257

DITZLER, L., APELDOORN, D. F. VAN, SCHULTE, R. P. O., TITTONELL, P., ROSSING, W. A. H. 2021. Redefining the field to mobilize three-dimensional diversity and ecosystem services on the arable farm. *European Journal of Agronomy*. 122, 126197.

FORMAN, R. T. T., GODRON, M. 1993. *Krajinná ekologie*. 1. vydání. Praha. Academia. p. 583

GUSTAFSON, E. J., GARDNER, R. H. 1996. The Effect of Landscape Heterogeneity on the Probability of Patch Colonization. *Ecology*. 77(1), 94–107.

HAINES-YOUNG, R., CHOPPING, M. 1996. Quantifying landscape structure: a review of landscape indices and their application to forested landscapes. *Progress in Physical Geography: Earth and Environment*. 20(4), 418–445.

HANUŠIN, J., ŠTEFUNKOVÁ, D. 2015. Zmeny diverzity vinohradníckej krajiny v zázemí Svätého Jura v období 1896–2011. *Geografický časopis/Geographical Journal*. 67(3), 243–259.

HREŠKO, J., PETROVIČ, F., VRÁBELOVÁ, M. 2006. Metódy priestorového hodnotenia zmien druhotnej krajinnej štruktúry v oblasti chránených území. *Acta Environmentalica Universitatis Comenianae (Bratislava)*. 14(1), 15–20.

HRNČIAROVÁ, T. 2011. Hodnotenie diverzity krajiny vybranými účelovými vlastnosťami. *Životné prostredie*. 45(4), 206–211.

IOCOLA, I., ANGEVIN, F., BOCKSTALLER, C., CATARINO, R., CURRAN, M., MESSÉAN, A., SCHADER, C., STILMANT, D., STAPPEN, F. V., VANHOVE, P., AHNEMANN, H., BERTHOMIER, J., COLOMBO, L., GUCCIONE, G. D., MÉROT, E., PALUMBO, M., VIRZÌ, N., CANALI, S. 2020. An Actor-Oriented Multi-Criteria Assessment Framework to Support a Transition towards Sustainable Agricultural Systems Based on Crop Diversification. *Sustainability*. 12(13), 5434. https://doi.org/10.3390/su12135434

IZAKOVIČOVÁ, Z., PETROVIČ, F., PAUDITŠOVÁ, E. 2021. The Impacts of Urbanisation on Landscape and Environment: The Case of Slovakia. *Sustainability*. 14(1), 60.

IZAKOVIČOVÁ, Z., ŠPULEROVÁ, J., RANIAK, A. 2022. The Development of the Slovak Agricultural Landscape in a Changing World. *Frontiers in Sustainable Food Systems*. 6, 862451. https://www.frontiersin.org/article/10.3389/fsufs.2022.862451

JUVENTIA, S. D., SELIN NORÉN, I. L. M., VAN APELDOORN, D. F., DITZLER, L., ROSSING, W. A. H. 2022. Spatio-temporal design of strip cropping systems. *Agricultural Systems*. 201, 103455.

KOPECKÁ, M. 2011. Indikátory hodnotenia diverzity krajiny. Životné prostredie.45(4), 198–202.

KUCHMA, T., TARARIKO, O., SYROTENKO, O. 2013. Landscape Diversity Indexes Application for Agricultural Land Use Optimization. *Procedia Technology*. 8, 566–569.

LI, H., REYNOLDS, J. F. 1993. A new contagion index to quantify spatial patterns of landscapes. *Landscape Ecology*. 8(3), 155–162.

McGARIGAL, K. 2015. *Fragstats Help*. University of Massachusetts, Amherst. https://www.researchgate.net/profile/Samuel-Cushman-2/publication/259011515_FRAGSTATS_Spatial_pattern_analysis_program_for_categorical_maps/links/564217ea08aebaaea1f8b8dd/FRAGSTATS-Spatial-pattern-analysis-program-for-categorical-maps.pdf

McGARIGAL, K., MARKS, B. J. 1995. *FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure*. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. p. 132.

MOJSES, M., PETROVIČ, F. 2012. Vplyv zmien využitia zeme na diverzitu krajiny. *Životné prostredie.* 46(1), 23–27.

MORAVČÍKOVÁ, Z., RUŽIČKOVÁ, J. 2006. Hodnotenie diverzity krajiny z pohľadu historického vývoja v katastrálnom území Dúbravka (Bratislava). *Acta Environmentalica Universitatis Comenianae (Bratislava).* 14(1), 85–96.

MOREL, K., LÉGER, F. 2016. A conceptual framework for alternative farmers' strategic choices: the case of French organic market gardening microfarms. *Agroecology and Sustainable Food Systems*. 40(5), 466–492.

OLAH, B., GALLAY, I., SLÁMOVÁ, M., LEPEŠKA, T., GALLAYOVÁ, Z., PAULÍKOVÁ, V. 2025. From Historical Maps to LiDAR Data-Enhancing Landscape Ecological Research of Cultural Landscape Using Modern Remote Sensing Data Illustrated with Examples from Slovak Traditional Heritage Landscapes. *Land*. 14(7), 1370.

OŤAHEĽ, J. 2011. Diverzita krajiny: miera diferenciácie prírodných podmienok a využívania krajiny. *Životné prostredie*. 45(4), 176–181.

TISCHENDORF, L., FAHRIG, L. 2000. On the usage and measurement of landscape connectivity. *Oikos.* 90(1), 7–19.

WALZ, U. 2015. Indicators to monitor the structural diversity of landscapes. *Ecological Modelling.* 295, 88–106.

Contact informations

Peter Petluš: ppetlus@ukf.sk, https://orcid.org/0000-0002-5034-5539
Viera Petlušová: https://orcid.org/0000-0001-6976-5712