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Assessing the Sustainability of Landscape Structure and Prospective Land Use Change: A Territorial Function Approach in the Miskolc Agglomeration, Hungary

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Abstract

Landscapes can be evaluated through the relationship system of their territorial functions, which distinguishes conventional from sustainable land use strategies. The protection function is closely linked to ecosystem services. Unlike most retrospective studies, this study presents a prospective, plan-based territorial function assessment of the Miskolc agglomeration, a post-industrial Hungarian city-region. Using the 2022 Harmonised National High-Resolution Land Cover layer and municipal settlement plans, current and planned land use were classified into production, consumption and protection functions, the Hungarian counterpart of the Production–Living–Ecological Space (PLES) model. The dominant matrix of both states was identified with a 9.6 ha moving window from a green infrastructure perspective. The results reveal an east–west polarised structure: a homogeneous, sustainable matrix around the Bükk Mountains contrasts with a patchy, production-dominated landscape to the east and south. Currently, 52.5% of the agglomeration shows a sustainable, 31.8% a conventional and 15.7% a transitional land use strategy. The plans affect 6427.3 ha, implying a net loss of 447.8 ha of protective land and, at the matrix level, a 0.72 percentage-point (748.3 ha) shift towards conventional use, mainly around Miskolc and along radial development axes. The results suggest that landscape sustainability depends not only on areal proportions but also on the spatial configuration of the protection-dominated matrix.

Keywords: ecosystem services; green infrastructure; landscape matrix; landscape structure; landscape sustainability; land use planning; moving window; production–living–ecological space (PLES); prospective landscape assessment; territorial functions

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1. Introduction

Landscapes can be evaluated through the relationship system of their inherent territorial functions; the conceptual foundations of this idea—the relationship between natural endowments and the possibilities of human landscape shaping—were already pointed out by Vidal de la Blache [1]. The idea remains central to present-day landscape-ecological thinking [2–5]. On this basis, conventional and sustainable (balanced) land use strategies can be distinguished according to the relationship system of the territorial functions

characteristic of a landscape [6]. Understanding this relationship system is indispensable for pursuing a sustainable landscape structure, and at the same time it serves as a tool for planning optimised land use [7–9]. Conventional landscapes are characterised by a matrix—the quantitatively dominant and often homogenising "background"—formed by the totality of production function landscape elements associated with agricultural use. Sustainable land use is achieved when the matrix of a given area is formed by areas serving the preservation of ecosystem services, i.e., by natural or near-natural landscape elements of adequate extent and connectivity [6]. In regional development, a land use strategy denotes a deliberately designed framework of planning and intervention aimed at achieving a desired state; in Ángyán's [6] interpretation and in the present study, however, it conveys the specific model and logic of land use characteristic of a given landscape, i.e., the way in which the territorial functions making up the landscape are organised.

The soundness of decision-making in spatial planning can be further strengthened if the relationship system of territorial functions is examined not only as a past, static snapshot but also as a future state resulting from planning decisions. Such an assessment requires the inclusion of the regulatory environment, i.e., regional and settlement (land use) planning. This is particularly justified in Hungary, as little scientific knowledge is generally available on the local environmental protection activities of municipalities, and especially on the related sectoral activities—including spatial planning as the domestic instrument of landscape planning and protection [10,11]. In Hungary, landscape protection is enforced primarily through spatial planning, at the local level and by statutory means, without a dedicated sectoral plan. Its external legal source is the Nature Conservation Act, while its instruments—alongside institutionalised nature conservation—include regional and settlement planning, which lays down increasingly detailed rules at the local level [12]. Among municipal planning documents, the most important for landscape protection are the settlement structure plans and the zoning (regulation) plans, which depict land use and building regulations in map form [13]. Their preparation is mandatory for every local government, and they become binding norms by local decree. Although Hungarian settlement planning switched to a new document system in 2024, earlier plans still form an essential part of the regulations in force.

No relationship-system assessment based on settlement planning has yet been carried out for a Hungarian study area, while a forward-looking (prospective) approach is considered progressive internationally as well [8,14]. Most existing studies share a reliance on retrospective data analysis [8,15,16]; studies in which the regulatory environment appears alongside remote-sensing data are rare. International studies offer few consensual methods for analysing territorial functions but a wide variety of classifications and interpretations; the most recent research focuses primarily on defining territorial functions, classifying land use and land cover types, and assessing their contribution to the Sustainable Development Goals [8,17]. As Lin et al. [18] point out, the methodology for classifying territorial functions and evaluating their relationships is currently far from unified, and the range of available analytical approaches is therefore very broad.

At the outset of the research, cooperation with the Lechner Knowledge Centre made it possible to use the non-public Harmonised National High-Resolution Land Cover Layer (HNHRL) in a territorial function assessment. The HNHRL is a nationwide land cover dataset for Hungary, with a spatial resolution of 10 m and annual coverage. It is based on Sentinel-1 radar and Sentinel-2 optical satellite imagery, complemented by official reference data, and is generated using a semi-automated, machine-learning-based approach. Compared with the original NHRL layers, the HNHRL offers a higher level of processing and improved reliability through photo interpretation-based harmonisation and visual verification of changes between consecutive years. Its main limitation is that, beyond land cover information, it also incorporates land use and other characteristic data; furthermore,

the harmonised version is not publicly available due to the labour-intensive nature of its production. Although neither public nor non-public sources available to us contain any quantitative information regarding the accuracy of layer generation, the relevant literature describes it as a layer with a high degree of thematic accuracy [19,20].

In response to the literature gap identified above and to this data access opportunity, we carried out a prospective territorial function assessment. Given the nature of the topic—and in line with most international examples, which typically examine city-regions [8]—we selected the Miskolc agglomeration, a post-industrial region of Hungary with diverse geographical endowments that is typically exposed to its economic-development environment, and where the effects of a protracted economic and social restructuring are still observable today [21]. By using settlement plans in the analysis of the relationship system of territorial functions, we also aim to extend the body of work that considers in greater detail the anthropogenic—in our case, regulatory—background shaping these relationship systems.

Accordingly, the study addresses two main questions: (I) How can the sustainability of the Miskolc agglomeration's landscape structure be characterised on the basis of the 2022 relationship system of territorial functions? (II) What magnitude and direction of change can be expected in the relationship system of the agglomeration's territorial functions—and thereby in the sustainability of its landscape structure—based on the changes enabled by settlement plans? To answer these questions, current and planned land cover and land use information was classified into production, consumption and protection functions following the framework of Ángyán [6], the Hungarian counterpart of the internationally applied Production–Living–Ecological Space (PLES) model. The dominant matrix was identified in both time horizons using a moving window method, based on which sustainable and conventional land use strategies were delineated. As a novel approach, the green infrastructure perspective was incorporated into both the data classification and the assessment, since the sustainability of the relationship system rests on the networked connectivity of sustainably used (protection-dominated) areas capable of providing a wide range of ecosystem services.

Territorial functions, which address the relationships between the settlement, natural and agricultural environments, should be distinguished from the concept of landscape function and the closely related concept of ecosystem services. The latter two concepts are closely related [13] and focus mainly on evaluating the goods and services provided by natural systems and processes [22,23]. The difference between them is that the literature uses landscape function for the goods provided by regions and land use systems, and ecosystem services for those derived from the functioning of natural systems [13,24,25]. Green infrastructure is fundamentally defined by its capacity to provide a wide range of ecosystem services [26]. The scope of ecosystem services is, of course, broader than that of green infrastructure, as it encompasses not only the goods and services related to green infrastructure elements and systems, but those derived from the functioning of ecosystems in general. The definition of green infrastructure is not restricted to the urban environment, and several authors apply the concept in the context of agricultural landscapes, which supports the conceptual link between green infrastructure and the protection function [27–29]. Since Ángyán [30] also refers to this link with the term "ecological infrastructure", ecosystem services can, through green infrastructure, also be related to the evaluation system of territorial functions. In our work, the green infrastructure approach is implemented through the development of a land cover and land use category system adapted to territorial functions, and through the identification, as networks, of areas that are less unambiguously classifiable from a sustainability perspective. The evaluation of landscape structure also provides indirect information on the landscape conditions for preserving and enhancing ecosystem services and on their potential supply capacity.

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The Production–Living–Ecological Space (PLES) framework originated in China, where it was developed in the 2010s as a functional basis for territorial spatial planning and land use optimisation [18,31]. It divides land into three spaces according to their primary function. Production space comprises land used to produce goods and services, mainly agricultural, industrial and mining land. Living space covers urban and rural residential land and the built-up areas serving everyday life and services. Ecological space includes land whose primary role is to protect natural systems, buffer environmental pressures and supply ecosystem services [17,18]. Ángyán's three territorial functions [6,30] correspond closely to these categories: the production function to production space, the consumption function (settlements together with their infrastructure and services) to living space, and the protection function (natural and near-natural areas with an ecological stabilising role) to ecological space. The difference is mainly one of terminology. Ángyán's agroecological approach names the functions after the human activity associated with them (producing, consuming, protecting), whereas PLES names the spaces after their role. In both frameworks, however, the ecological (protection) component is understood as the supporting background that sustains the other two [18]. The essence of the PLES model is that it examines parts of landscapes according to three function-based categories, identified mainly on the basis of the dominant land use, depending on the nature of the human activity carried out locally [31]. The classification methodology varies considerably between PLES studies [18,32]. Compared with the principle of territorial functions described by Ángyán [6], studies applying the model generally focus on landscape assessment using indicators that reflect the functioning of landscape components (production, living and ecological element types) [33]. Input data on land surface properties are remotely sensed or remote-sensing-derived data, most often land use or land cover maps [34,35]. Depending on the research aims, these layers are usually supplemented with other thematic maps or datasets, which, owing to the multifunctional perspective, often play a weighting or indexing role [31,36]. Accordingly, studies generally apply methods capable of accounting for multifunctionality and integrate numerous base datasets covering the ecological, social, cultural, economic and other dimensions of landscape components [37–39]. Between the model and the Hungarian approach to territorial functions there is a conceptual parallel rather than a methodological identity: the underlying principle of PLES research is similar to the approach applied here, but its aims and methods are not directed at a matrix-based sustainability assessment of a given landscape. Although related research supports the scientific grounding of land use planning instruments, future landscape structure is not usually assessed by directly identifying spatial changes based on the planned, statutory regulatory environment, and in the Hungarian literature even the use of the territorial function principle as an analytical perspective is uncommon.

2. Materials and Methods

2.1. Study Area

The study covers Miskolc and its agglomeration, which, according to the 2024 delineation of agglomerations, urban areas and catchment areas by the Hungarian Central Statistical Office (KSH), following Tóth [40], comprises 41 municipalities (Figure 1).

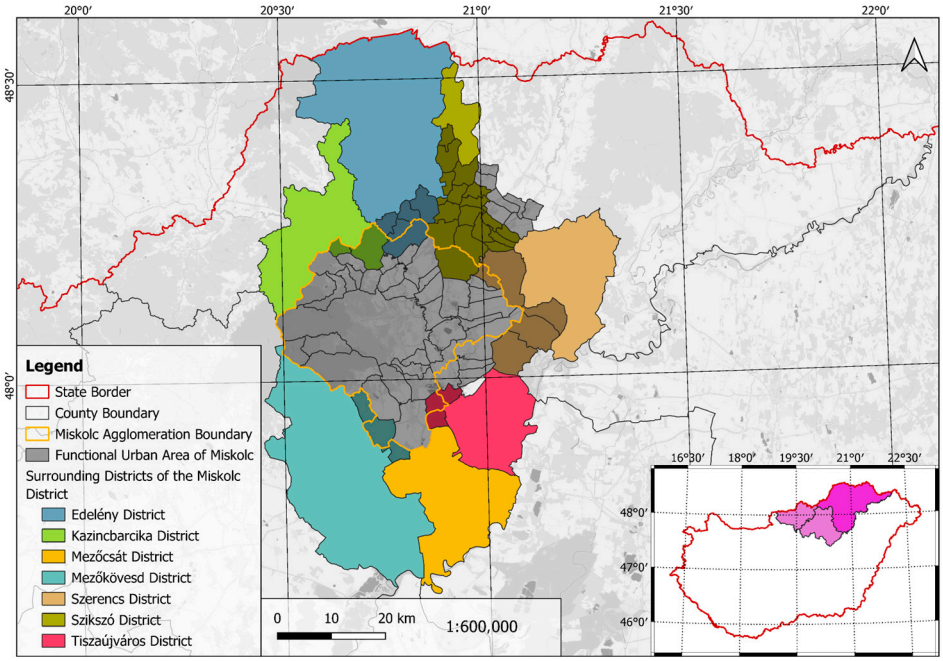
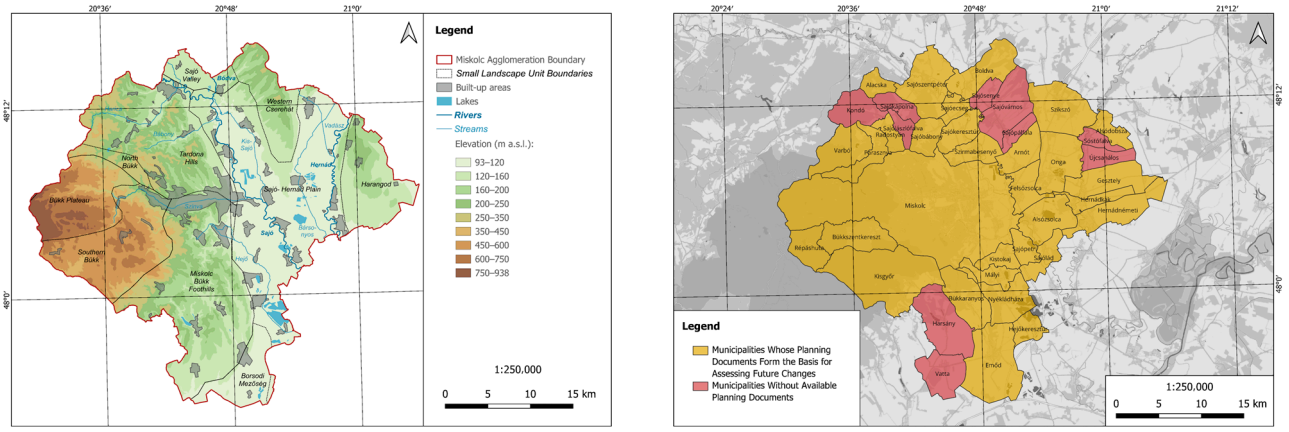


Figure 1. The Miskolc agglomeration and its 41 municipalities. Source: own compilation, based on OTAB administrative boundaries and [40].

Miskolc is Hungary's fourth most populous settlement, the centre of the Northern Hungarian region and the seat of Borsod-Abaúj-Zemplén County. It lies between 48°01′ and 48°09′ N and between 20°28′ and 20°52′ E. The geomorphology of the city and its surroundings is fundamentally shaped by the meeting of two macroregions, the North Hungarian Mountains and the Great Hungarian Plain, by the foothill areas to the north and west dissected by stream valleys (Tardona Hills, Cserehát), and by the lowland character of the river terraces to the east (Sajó, Hernád). The location of the agglomeration and its municipalities is shown in Figure 2.



(**a**) (**b**)

Figure 2. Overview maps of the study area: (**a**) Topographic overview map of the Miskolc agglomeration. Source: own compilation, based on EU-DEM, Marosi & Somogyi [41] and OTAB topographic base layers. (**b**) Municipalities of the Miskolc agglomeration and the availability of the planning documents required to assess the future territorial functional state. Source: own compilation based on OTAB topographic base layers.

The agglomeration is one of Hungary's classic post-industrial regions: during post-World War II industrialisation, a well-differentiated industrial belt developed around Miskolc, whose restructuring since the change of regime still determines the region's socio-economic and, consequently, land use polarisation [21]. The selection of the study area was further justified by the fact that, compared with other urban areas in Hungary, the Miskolc agglomeration is less exposed to suburban, vacation, and recreational pressures. The Budapest agglomeration and the Lake Balaton Priority Resort Area are two priority regions in Hungary's spatial planning. In these regions, the specific development processes arising from suburbanization, vacation and recreational functions carry a degree of uncertainty that may limit the generalizability of the results when examining the impacts of future changes to land use plans. The 41 municipalities of the Miskolc agglomeration provided a more manageable study area than the Budapest agglomeration (81 municipalities, including Budapest, which has a special administrative and planning status) or the Lake Balaton region (53 municipalities in the Lake Balaton agglomeration area, totaling 180 municipalities in the Lake Balaton Priority Resort Area). Selecting a region without a special land use planning status enhances the generalizability of the methodology, since the specific regulatory environment of priority regions would necessitate further refinement of the methodology. We selected the Miskolc metropolitan area from among similar standard urban regions in Hungary because of the diversity of its physical geographical characteristics. The heterogeneity of the natural environment and the functional contrasts provide an opportunity to test the methodology under varying geographical conditions and in any region of Hungary that does not have a special status, thereby increasing the robustness of the results obtained.

In order to assess the sustainability of the landscape structure on the basis of green infrastructure, it is important to briefly review the nature conservation characteristics of the selected area, with particular regard to the elements established to promote ecological connectivity. In Hungarian nature conservation, this objective is served by Natura 2000 sites designated in accordance with the European Union's Birds and Habitats Directives, within related categories that do not constitute nature conservation protection established by specific legislation or '*ex lege*'. The area contains both Special Protection Areas (SPAs) and Special Areas of Conservation (SACs). The six SACs cover the Bükk Plateau and certain surrounding valleys and foothills, as well as the immediate surroundings of the rivers Sajó, Hernád and Bódva, with the aim of protecting open and closed low-mountain forests and wetland habitats. There are two SPAs that overlap significantly with these, covering the Bükk Mountains and their peripheral areas, as well as the Hernád Valley.

In addition to the Natura 2000 sites, the National Ecological Network also serves the purpose of ecological connectivity within other nature conservation categories; it covers more than a third of the agglomeration. The core areas of the network extend almost exclusively across the Bükk Mountains massif, covering nearly its entire extent. Fragments of the core areas cover the surrounding foothills, whilst small areas can be found in the north-eastern regions. The network's ecological corridors are highly fragmented and occur in the hilly areas around the Sajó and Hernád rivers. There are a small number of buffer zones, located at the junctions of the two sub-categories and where their fragments meet. Among the nature conservation designations, it is worth highlighting the areas under special protection at national level. The most important of these, a natural area of national significance protected by specific legislation, is the core area of the Bükk National Park in the central massif of the mountain range. In this category, the agglomeration has only one other area in the form of a Nature Conservation Area, at Alsódobsza.

As a first step in the study, we aligned the HNHRL land cover categories with the territorial functions of production, consumption and protection—we reclassified the layer. To delineate areas where changes are anticipated, we collected the planning

documents of 41 municipalities via a freedom-of-information request, and georeferenced the plan maps for 31 of these municipalities. Based on the set of criteria defined in the plan maps, we delineated the areas anticipated to undergo land use change. We then matched the individual land use types in these areas to the territorial functions, and used this to correct the three-function base layer. As the sustainability of the landscape structure is determined by the relationship between protective and non-protective functions, we combined the production and consumption functions in the current and future layers of territorial functions and carried out matrix identification using the moving window method. To define land use strategies, we classified the results layer in two ways and also interpreted the data according to their statistical indicators. Geospatial processing and synthesis were carried out in QGIS 3.40.11 "Bratislava".

2.2. Land Cover Data and Reclassification into Territorial Functions

The current (baseline) state was represented by the 2022 version of the HNHRL, a 10 m resolution product generated by semi-automated processing of Sentinel-1 and Sentinel-2 satellite imagery and maintained by the Lechner Knowledge Centre [19,20]. The non-public layer was obtained through cooperation with the Lechner Knowledge Centre, clipped to the agglomeration. Since the HNHRL extends 50–100 m beyond the administrative boundary of the agglomeration along most of its length, edge effects in the moving-window analysis were reduced. To obtain accurate areal data, the final result layers were masked to the extent of the agglomeration. The overall research procedure is summarised in Figure 3.

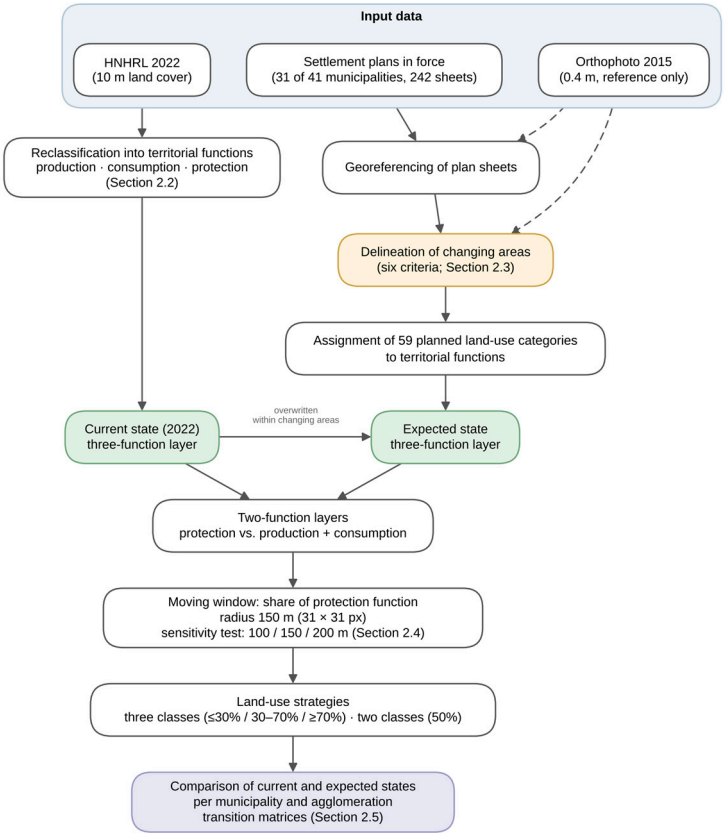


Figure 3. Methodological flowchart of the study. Source: own compilation.

The 14 HNHRL categories occurring in the study area were assigned to production, consumption and protection functions following the principle of Ángyán [6], as the

Hungarian counterpart of the internationally applied Production–Living–Ecological Space (PLES) model (Table 1).

The protection function brings together the land cover types whose primary role is to sustain natural and near-natural ecosystems and the ecosystem services they provide, in line with Ángyán's concept of ecological infrastructure [30] and with the definition of green infrastructure [26]. Forests, shrublands, permanent herbaceous vegetation, wet grasslands, wetlands and water bodies belong to this function, together with perennial cultures and green areas in artificial environments that maintain a permanent, biologically active cover. The production and consumption functions, by contrast, comprise land managed primarily for agricultural output or for settlements, infrastructure and services. The extent and spatial arrangement of the protection function can therefore be read as an indicator of the landscape-structural conditions for ecosystem services, although the services themselves were not quantified in this study.

Table 1. Reclassification of HNHRL land cover categories by territorial function, based on Ángyán [6].

HNHRL Code	Land Cover Category	Territorial Function
21	Annual arable crops	Production
111	Buildings	Consumption
12	Bare and paved surfaces	Consumption
13	Paved road and railway network	Consumption
26	Permanent herbaceous vegetation	Protection
27	Orchards	Protection
28	Vineyards	Protection
29	Heterogeneous green areas in artificial environments	Protection
30	Shrub-covered areas	Protection
31	Broadleaved forests	Protection
33	Coniferous forests	Protection
36	Wet grasslands	Protection
41	Wetlands	Protection
51	Water bodies	Protection

HNHRL = Harmonised National High-Resolution Land Cover Layer.

Where land cover could not be clearly matched to land use functions, we categorised it based on the land cover's role within biotope networks and green infrastructure. The 'Permanent herbaceous vegetation (26)', 'Orchards (27)' and 'Vineyards (28)' were therefore classified in the protection category due to their permanent vegetation cover—which is comparable to that of landscape features with a protective function—and their relatively stable land cover and land use characteristics over the long term.

2.3. Land Use Planning Documents and Delineation of Changing Areas

To project the future (expected) territorial function state, the settlement planning documents in force—primarily the local building regulations and zoning plans, or, in their absence, the settlement structure plan or settlement development concept—were requested from all 41 municipalities under the freedom-of-information procedure (Act CXII of 2011), with a validity date of 28 January 2025. Usable and sufficiently up-to-date planning documents were available for 31 municipalities (Figure 2); for the remaining municipalities, the current territorial function state was left unchanged in the future layer.

The 242 plan sheets documenting plan amendments were converted into high-resolution, georeferenced images, using the Lechner Knowledge Centre's 2015 orthophoto (0.4

m/px) as reference. On this basis, areas affected by expected land use change ("changing areas") were delineated. It was necessary to use the orthophoto, in addition to georeferencing, because the planning documents contained sections regulating land use—listed as 'status' but not actually implemented—in addition to the parts designated as 'plans'. To identify these, it was necessary to incorporate an orthophoto reference that is more detailed than the HNHRL and shows actual land use as an image; for this, we used high-resolution public data from the year closest to 2022 (2015). We visually validated the delineated areas due to the temporal discrepancy between the orthophoto and the HNHRL included in the analysis, and removed any features that had been developed in the meantime. The orthophoto was used only as a reference for these tasks; it did not form the basis of any analysis. We distinguished between the categories of 'changes permitted and indicated by the plan' and 'deviations regulated by status' solely for the sake of methodological clarity; from the perspective of the study, the two different regulatory origins of the individual delineated areas had no practical significance.

The planned land uses can be clearly distinguished visually in the planning documents. However, there are sections which clearly show a planned status but, in terms of their formal appearance, were graphic elements regulated as existing conditions. In order to identify the changes in land use permitted by the planning documents, we have delineated on the plan sheets the parts of the planned land use units and zones that have not yet been realised, as well as those parts that are not planned but are regulated differently from the actual land use. Hungarian settlement plans regulate land use through zones and land use units, but they do not systematically distinguish between existing and planned states. A planned change may appear as a new zone, as the extension of an adjacent zone, or even as a land use regulated "as existing" that differs from the actual land cover. A criterion based solely on the "planned" notation of the plans would therefore miss a considerable part of the land use changes they enable. The delineation criteria were derived inductively from the planning documents. We reviewed all 242 plan sheets and collected two types of areas: those designated for change in the plans, and those already assigned to a different land use category but still under their original land use. All collected cases could be grouped into six recurring types, which were then formalised as delineation criteria. Criteria (a) and (d) capture explicitly planned changes, (b) and (c) capture discrepancies between the regulation and the actual land use, and (e) and (f) capture changes in development intensity or land use that are enabled without a change in zoning category. Together, they cover every situation encountered in the plans in which a land use different from the current one is permitted. An area was delineated as a changing area if it met at least one of the following criteria:

- (a) Unrealised planned zone: the area was a plot of land within the area designated for development, but with a land use that differed from the specified land use units shown on the reference map; or, in the absence of a closed unit, it was a plot of land bordering the proposed regulatory boundary;
- (b) Deviation regulated "as existing": the area was regulated as it actually existed, but—in order to avoid having to examine every individual plot of land—land use in the area was characterised by a situation that differed entirely from this regulation at the level of zones and units;
- (c) Inactive mining designation: the area was designated as a mining site, not as a land use category but under a different designation, although no active mining operations were taking place there;
- (d) Unmapped extension of an adjacent zone: an extension of the neighbouring, existing zone/unit is planned at the expense of the area, and this extension is not shown on the reference map;

- (e) Potential subdivision: the area was a part of a plot subject to a potential subdivision that had not yet been subdivided, thereby suggesting a potential increase in land use density and a change in development intensity;
- (f) Indicated change consistent with current regulation: in the area, the plan indicates a foreseeable change in land use, although the regulatory provisions are consistent with the current land use (e.g., the possibility of installing a wind farm).

Geometric errors (multi-part features, self-intersections, overlaps, sliver polygons) were corrected, and the 63 amendment sheets presented as separate plan sheets were also considered in the delineation. The delineated polygons were aligned with the extent and raster grid of the HNHRL. The 59 land use categories occurring in the collected plans were matched to the three territorial functions using the same logic as the classification of the current state (e.g., extensively used agricultural land of meadow or pasture character was assigned to the protection function, whereas commercial land subject to restrictions that do not alter land use—such as archaeological sites—remained in the consumption function) (Supplementary Table S1). To reduce researcher subjectivity in the classification, the land cover typical of each category in plan parts regulated "as existing" (i.e., not delineated as changing areas) was used as a reference, supporting the unambiguous assignment of territorial functions to land use categories.

2.4. Matrix Identification: Moving Window Analysis

Following the patch–corridor–matrix model, the dominant, background-forming landscape element (the matrix) was identified using the moving window method widely applied in landscape-pattern analysis [42,43], whose parameters always depend strongly on the aims of the study. A square kernel of 31 × 31 pixels centred on each pixel (≈9.6 ha at 10 m resolution; ≈150 m window radius; Figure 4) was selected on the basis of the range of window sizes found suitable in the literature for matrix and landscape-pattern analyses at comparable scales, and of the available base data (layer resolution, size of the study region) [44–49], balancing the preservation of local heterogeneity against representative results at the agglomeration scale. To this end, in order to determine the compromise parameters based on data from the literature, we first tested three different options, in which we examined the generalising effect of the moving window size on landscape structure identification and the level of detail of the output layer, based on area proportion and boundary length. The geoinformatics convolution method we use—that is, the principle behind the moving window—can be described by the following observation-based mathematical model:

$$r = nb, \tag{1}$$

$$a = (2n + 1)b \tag{2}$$

$$d = (2n + 1)b \tag{3}$$

Therefore:

$$a_{min} = d_{min} = 3b \tag{4}$$

where:

$$n \in \mathbb{N}, n \geq 1 \tag{5}$$

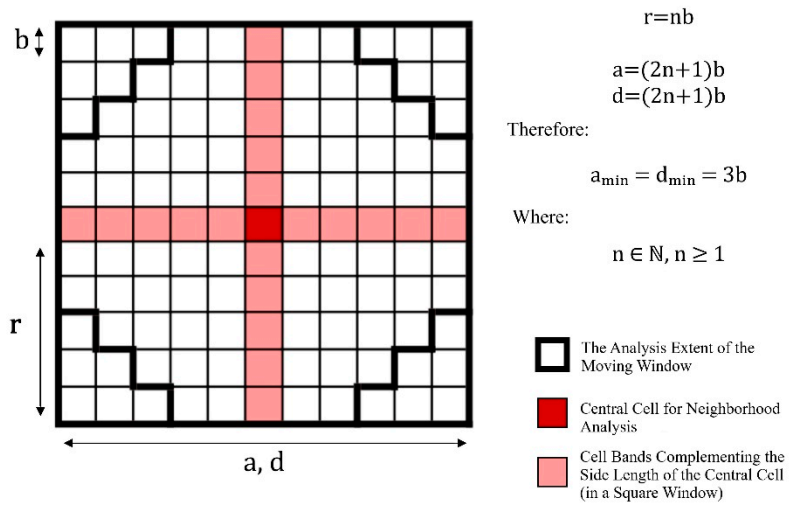
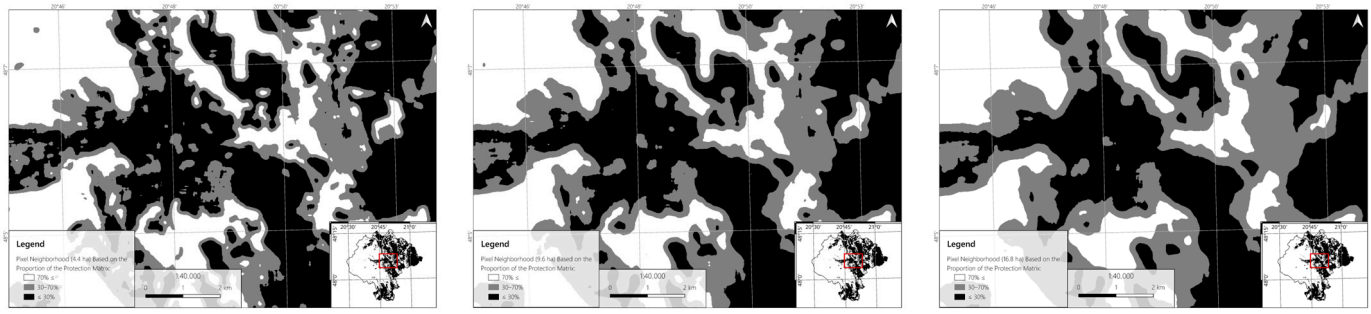


Figure 4. Operating principle and formulas of the moving window method. a—side length (square window); b—raster resolution/step size; d—diameter (circular window); r—window radius (circular window); n—positive integer defining the window size. Source: own compilation.

In addition to the 150-metre window radius, we tested window radii of 100 metres (window size: 21 × 21, area ≈ 4.4 ha) and 200 metres (window size: 41 × 41, area ≈ 16.8 ha) to determine the possible size of the moving window (Figure 5). Within the windows, the share of protection function (sustainable) land cover was calculated for each pixel from the two-function layer, yielding a continuous result layer in the range [0, 1]. The analysis units were then assigned to three land use strategy categories: sustainable (protection share ≥70%), transitional (30–70%) and conventional (≤30%).



(**a**) (**b**) (**c**)

Figure 5. A sensitivity analysis of the stability of matrix categorisation using three different sizes of moving windows on a randomly selected part of the agglomeration (**a**) Window radius: 100 metres (**b**) Window radius: 150 metres (**c**) Window radius: 200 metres. Source: own compilation based on HNHRL 2022.

As the radius of the moving window was increased by 50 metres, the landscape structure became increasingly generalised and less fragmented, whilst the transitional category expanded. As the window size increased, the complexity of the spatial structure was significantly simplified; there was a 37.3% decrease between moving windows with radii of 100 and 200 metres (Table 2). In view of the structure shown in Figure 5 and its demonstrable sensitivity, we found a window radius of 150 metres—which was also predictable based on the literature—to be appropriate among the values examined, as the size of the selected moving window must be sufficiently large to allow for genuine matrix identification whilst avoiding excessive detail. Furthermore, in order to reveal local spatial structural patterns and identify changes in these, we considered it advisable to avoid the

homogenising effect of an excessively large window. A window radius of 200 metres already resulted in a more pronounced smoothing out of local structural differences. The sensitivity analysis was performed on the raster outputs of the moving window for the entire study area (Table 2); Figure 5 illustrates the same comparison for a randomly selected sample area only. For the subsequent analyses, the 150 m raster output was vectorised in order to calculate areal statistics per municipality, to overlay the result with the changing areas and to prepare the maps. Vectorisation did not alter the areal shares of the categories; the 150 m values in Table 2 are therefore identical to those reported in Section 3.

Table 2. Sensitivity of matrix categorisation to the moving-window radius for the entire study area: areal shares of the land use strategy categories (30/70% thresholds) and total length of internal category boundaries.

Indicator/Radius	100 m	150 m	200 m
Sustainable (≥70%)	53.57%	52.47%	51.55%
Transitional (30–70%)	13.73%	15.73%	17.40%
Conventional (≤30%)	32.70%	31.80%	31.05%
Total internal category boundary length	2739.69 km	2077.94 km	1717.0 km

The matrix identification and grouping of the output layer was run separately on the current (2022) and the expected (planning-corrected) two-function layers, allowing comparison of the current and expected matrix structure and of the sustainable and conventional land use strategies they define.

2.5. Comparative and Statistical Analysis

From the continuous, three-class and two-class moving window result layers, datasets were compiled per municipality and for the agglomeration as a whole, based on the official administrative boundary polygons; the minor mismatch between these polygons and the extent of the rasters had a negligible effect on the results. The current and expected states were compared at two levels: (i) as the general, agglomeration-level relationship system of territorial functions and land use strategies, and (ii) as a detailed transition analysis restricted to the changing areas, derived from a full attribute-level intersection of the current land cover categories and the planned land use categories, in both the original three-function system (production–consumption–protection) and the simplified two-function system (protection vs. non-protection) relevant to landscape sustainability.

3. Results

3.1. Current Relationship System of the Territorial Functions

Based on the 2022 HNHRL, the territorial functions of the Miskolc agglomeration show a markedly polarised west–east spatial pattern (Figure 6). The protection function covers 60.5% of the agglomeration, the production function 32.4% and the consumption (settlement) function only 7.1%. In the western half—characterised by the Bükk Mountains and the surrounding hill country—the protection function forms a single, largely contiguous block, interrupted only locally by the consumption function. This pattern is most pronounced around Miskolc, but, with the help of urban green infrastructure elements, the agglomeration's other towns are also able, at a smaller scale, to embed

themselves into the protection function of their wider surroundings. East and south of Miskolc, by contrast, the production function dominates, but heterogeneously: here the protection function is present not as a contiguous block but, as indicated by the map (Figure 6), as narrow corridor-like strips and smaller, isolated patches. It is most extensive and most contiguous in the Bükk foothills, the Hernád valley, the southern Cserehát and the southern Sajó–Hernád Plain. The boundary between the two structurally distinct halves of the agglomeration runs approximately along the Sajószentpéter–Nyékládháza line and is sharp: there is no intermediate transitional belt in the land cover pattern.

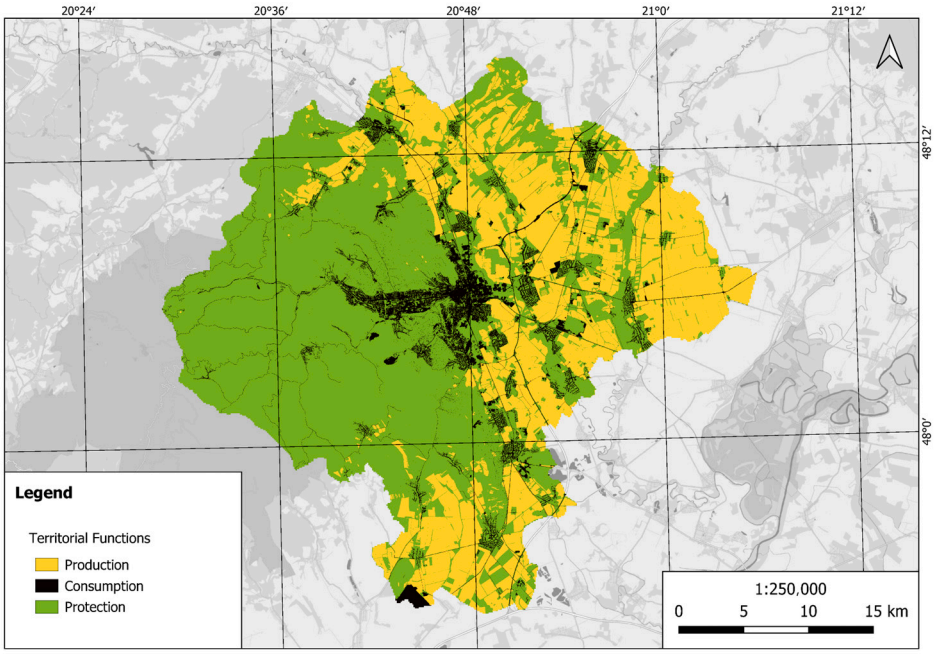


Figure 6. Current relationship system of the territorial functions (production, consumption, protection) in the Miskolc agglomeration, 2022. Source: own compilation based on HNHRL 2022.

3.2. Current Land Use Strategies (Matrix Identification)

Applied to the simplified two-function (protection vs. non-protection) layer, the moving window method confirmed this polarisation at the level of the dominant landscape element, i.e., the matrix. The continuous [0, 1] result—the local share of the protection function—has a strongly polarised distribution: across half of the agglomeration's area, the protection share in the assessed pixel neighbourhoods exceeds 76.3% (median), while the standard deviation (≈40.4 percentage points) indicates considerable spatial heterogeneity. Classified with the 30/70% thresholds, 52.5% of the agglomeration is characterised by a sustainable, 31.8% by a conventional and 15.7% by a transitional land use strategy; with a simple 50% threshold, the shares of sustainable and conventional land use almost exactly follow the areal share of the protection function (60.5% and 39.5%, respectively) (Figure 7).

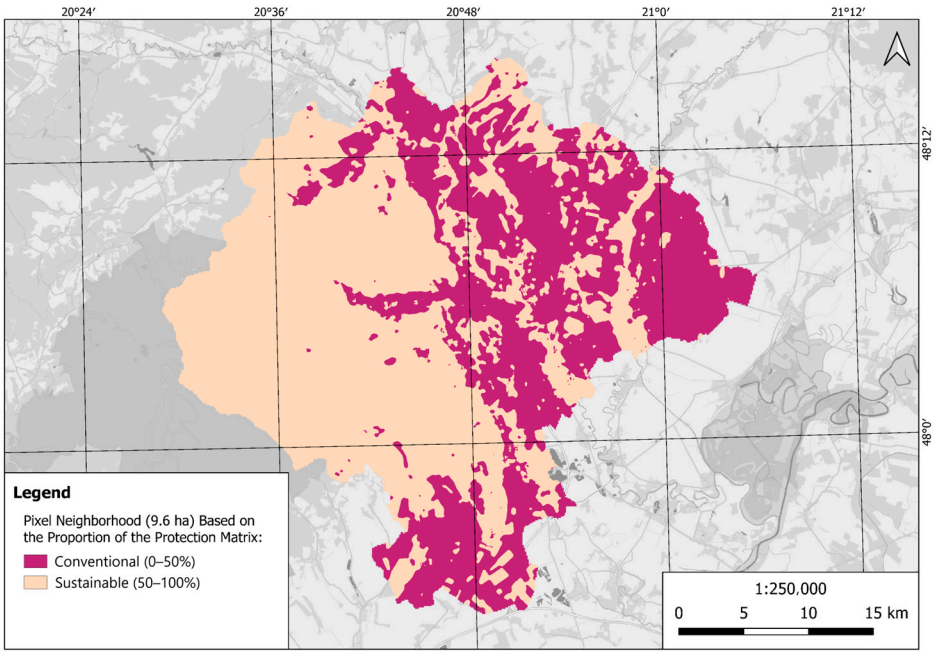


Figure 7. Current land use strategies (sustainable vs. conventional) in the Miskolc agglomeration, identified with the moving window method (50% threshold). Source: own compilation based on HNHRL 2022.

In the western block, matrix identification showed that the protection function forms a spatially contiguous, protection-dominated (sustainable) matrix in the dominance layer, rather than merely a locally dominant land cover; here, transitional areas appear only along the narrow margins of the block, mainly where production function patches intrude. In the western block, matrix identification showed that the protection function forms a spatially contiguous, protection-dominated (sustainable) matrix in the dominance layer, rather than merely a locally dominant land cover, let alone to counterbalance the conventional character of its surroundings. The homogenising effect of the moving window therefore applies only to the smallest patches, such as compactly built-up settlements and agricultural areas with an impoverished biotope network. As a result, a single, fully conventional enclave appears in the easternmost block, while most of the transitional category is concentrated in the central, structurally still "undecided" belt between the Sajószentpéter–Nyékládháza line and the Hernád (Figure 8).

At the local scale, matrix identification also revealed relationships not visible on the three-function map: for example, the network along the Sajó, Hernád and Kis-Sajó rivers emerges as a distinct, protection-dominated local matrix, while the Cserehát, previously known as mosaic-like, resolves into clearly separated sustainable and conventional blocks.

3.3. Expected Relationship System of the Territorial Functions

Based on the changes enabled by the collected settlement plans, the areal share of the production function decreases by 3.4 percentage points (a relative decrease of 10.4%), almost exclusively in favour of the consumption function, which grows by 3.8 percentage points (a relative increase of 53.4%). The areal share of the protection function remains essentially unchanged (−0.4 percentage points; relative change −0.7%) (Figure 9).

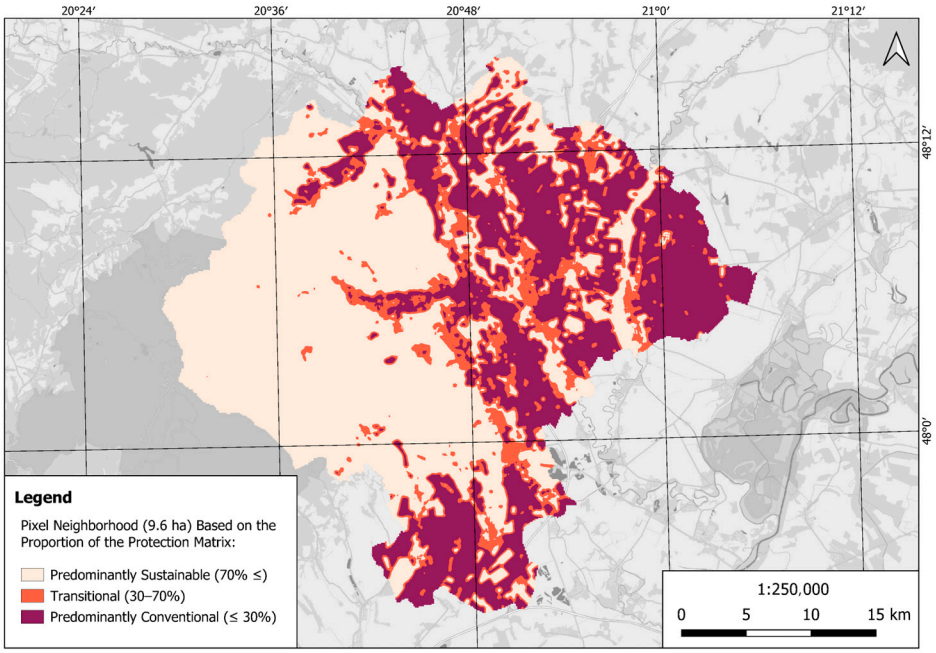


Figure 8. Current land use strategies (sustainable vs. conventional) in the Miskolc agglomeration, identified with the moving window method (30/70% thresholds). Source: own compilation based on HNHRL 2022.

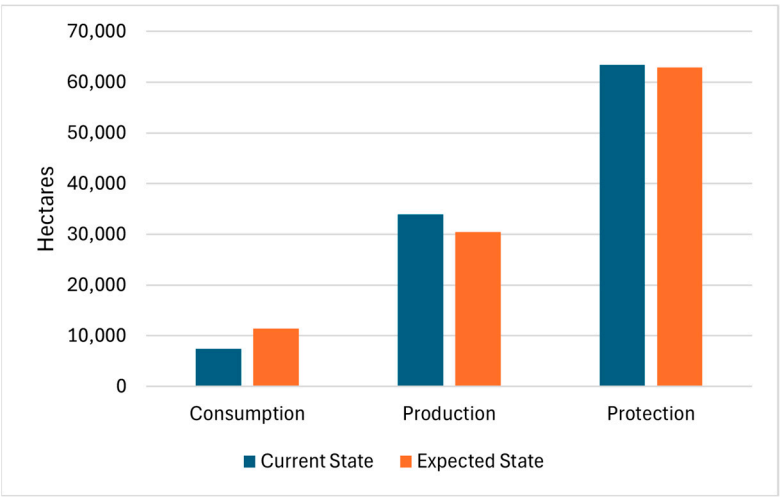


Figure 9. Change in the areal extent of the territorial functions (current vs. expected state), Miskolc agglomeration. Source: own compilation.

The spatial pattern of change is highly uneven: new consumption function areas typically appear as compact patches adjoining existing built-up areas, expanding at the expense of peri-urban agricultural land currently in production or protection function, thereby weakening the direct spatial link between the protection and production functions. Newly designated consumption function areas are most densely concentrated precisely within the Sajószentpéter–Nyékládháza dominance-boundary belt; the largest contiguous change is expected south-east of Miskolc and at Hernádkak, where arable land may be converted to industrial/commercial and transport (road) land use (Figure 10).

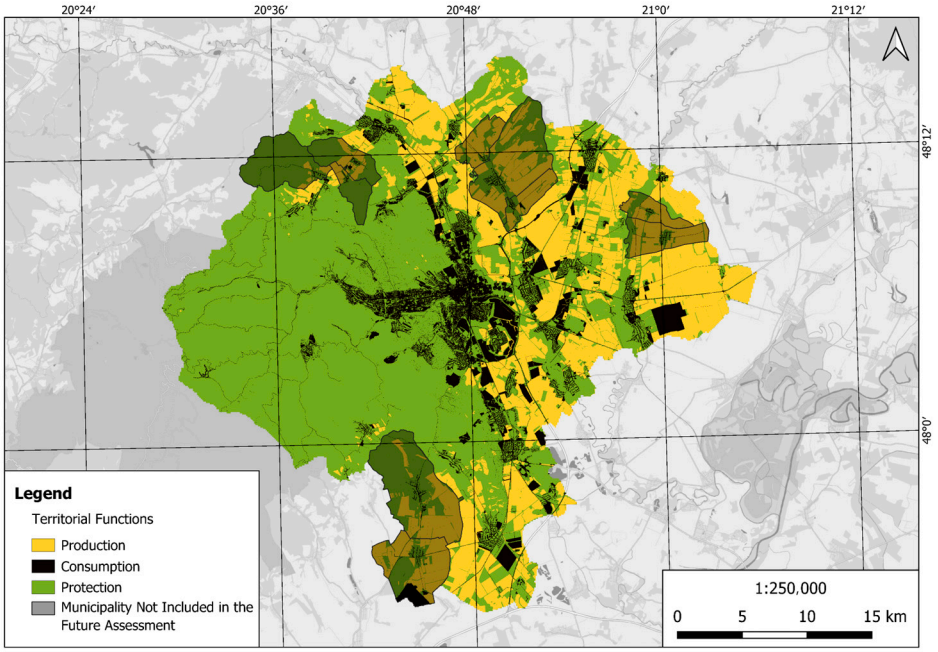


Figure 10. Expected relationship system of the territorial functions in the Miskolc agglomeration, based on the collected settlement plans. Source: own compilation based on HNHRL 2022, the collected settlement plans and the OTAB administrative boundaries.

3.4. Expected Land Use Strategies

According to the prospective matrix identification, the agglomeration's matrix structure remains quantitatively close to the current one but changes structurally. With the 30/70% thresholds, the sustainable share of the agglomeration decreases slightly, from 52.5% to 51.5%, the transitional share increases from 15.7% to 16.7%, and the conventional share remains essentially stable (31.8% → 31.9%). With the simple 50% threshold, the conventional share of the agglomeration rises from 39.54% to 40.26%, a total shift of 0.72 percentage points (≈748 ha) in favour of conventional land use (Figure 11).

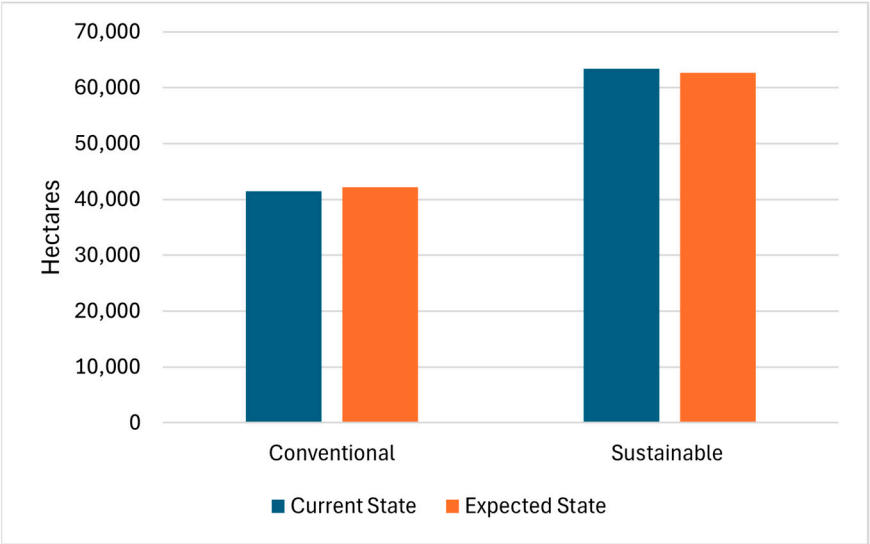


Figure 11. Change in the areal extent of sustainable and conventional landscape structure (current vs. expected state), Miskolc agglomeration. Source: own compilation.

The relatively small net change conceals a genuine structural reorganisation. In the western block, several new, patch-like conventional fragments—mainly associated with

the expansion of settlement peripheries—perforate the previously homogeneous sustainable matrix without breaking up the block itself. Meanwhile, further north, the protective areas along the Sajó expand and, as indicated by the maps, form a more spatially contiguous band (Figure 12). North of Miskolc, by contrast, the conventional area expands around Szirmabesenyő at the expense of the sustainable matrix. In the eastern half of the agglomeration, protection-dominated areas around Emőd expand and become locally more contiguous in the dominance layer, extending sustainable land use towards the agglomeration boundary, while the conventional core between the Hernád and the Sajó becomes further consolidated as the smaller sustainable patches within it disappear (Figure 12).

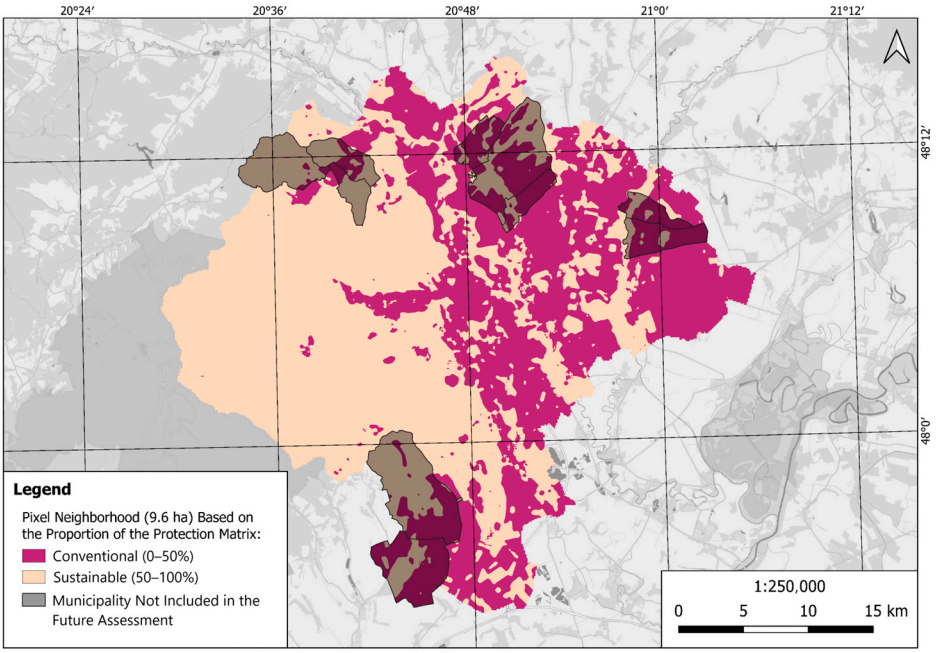


Figure 12. Expected land use strategies (sustainable vs. conventional) in the Miskolc agglomeration, identified with the moving window method (50% threshold), based on the collected settlement plans. Source: own compilation based on HNHRL 2022, the collected settlement plans and the OTAB administrative boundaries.

3.5. Detailed Transition Analysis of the Changing Areas

Based on the collected planning documents, land use change is expected on 6427.3 ha, i.e., 6.13% of the agglomeration's area (the "changing areas"). Classified by direction of change, the function of the changing areas remains conventional on 46.4%, becomes conventional on 24.4% and becomes sustainable (protective) on 17.5%, while only 11.8% remains protective. The changes are spatially concentrated, following the agglomeration's radial, valley-aligned spatial structure and development axes. The largest number and the greatest extent of changes occur east of Miskolc, in the Sajó, Hernád and Hejő valleys and towards Hernádkak (Figure 13).

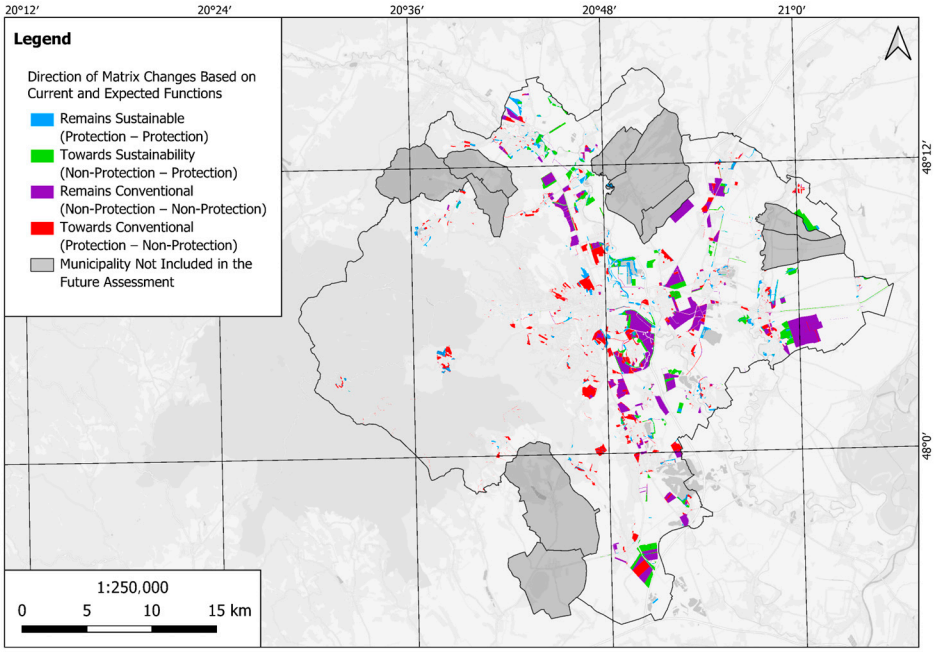


Figure 13. Direction of the effect of the changing areas on the matrix, based on the current and expected territorial functions. Source: own compilation based on collected settlement plans and the OTAB administrative boundaries.

Specifically, within these areas—in contrast to the agglomeration as a whole—the shift from the production towards the consumption function is far more pronounced: the production function almost disappears (3975.1 ha → 434.8 ha), the consumption function becomes dominant (125.9 ha → 4114.1 ha), and the area of the protection function within the changing areas decreases by 19.2% (2326.3 ha → 1878.4 ha) (Table 3).

Table 3. Transition matrices of the changing areas (hectares and number of distinct transition relations).

Three-function transition matrix			
From\To [1]	**Consumption**	**Production**	**Protection**
Consumption	99.76 ha (55)	0.83 ha (2)	25.34 ha (41)
Production	2482.78 ha (16)	395.81 ha (3)	1096.50 ha (19)
Protection	1531.58 ha (145)	38.16 ha (20)	756.54 ha (134)
[1] Function change: 5175.19 ha (243 relations) · No function change: 1252.11 ha (192 relations).			
Two-function transition matrix (relevant to landscape sustainability)			
From\To [2]	**Non-Protective**		**Protective**
Non-protective	2979.18 ha (76)		1121.84 ha (60)
Protective	1569.74 ha (165)		756.54 ha (134)
[2] Function change: 2691.58 ha (225 relations) · No function change: 3735.72 ha (210 relations) · Total changing area: 6427.3 ha (435 relations).			

In the simplified two-function system relevant to landscape sustainability, the conventional (production + consumption) area within the changing areas grows by 447.8 ha at the expense of sustainable areas (4101.2 ha → 4549.0 ha). This is smaller than the 748.3 ha net agglomeration-level shift detected by matrix identification (Section 3.4), confirming that the moving window method also captures structural (neighbourhood) effects extending beyond the directly delineated areas. In terms of land cover, arable land accounts for 61.8% of the current land cover affected by change, 42.1% of which becomes

industrial/commercial land (77.2% of all newly designated industrial/commercial land is converted from arable land); grasslands and urban green areas are the second and third most affected current land cover categories.

4. Discussion

4.1. Territorial Functions and Land Use Strategies in the Light of the PLES Framework

The results confirm that Ángyán's [6] domestically rooted classification, based on production, consumption and protection territorial functions, closely parallels the international Production–Living–Ecological Space (PLES) concept and offers an applicable framework for studying the landscape structure of a Hungarian post-industrial agglomeration. Beyond mere areal proportions, moving window-based matrix identification carries more substantial information: the spatial structure of areas with almost identical functional composition can differ markedly. When smaller foothill and riverine areas of equal extent are compared, the areal shares of the two land use strategies may be nearly identical; yet, at the level of processing that follows matrix identification, sustainable areas in the foothills can form a homogeneous matrix, whereas in the eastern and southern parts of the agglomeration they typically form an island- or corridor-like pattern embedded in a conventional matrix. This difference may matter because the potential capacity of the protective matrix to support ecosystem services, and its resilience to further transformations, is expected to depend not only on its extent but also on the spatial arrangement of green infrastructure [28]; the dominance-based matrix captures this arrangement only indirectly (Section 4.3). Because the protection function comprises the land cover types that primarily support natural ecosystems and their services, the sustainable matrix identified here can be interpreted as a potential landscape-structural framework for these ecosystems; whether it functions as such also depends on connectivity, which was not assessed in this study. The results therefore also bear on the natural, and not only the land use, dimension of sustainability, even though ecosystem condition and service supply were not measured directly. Such a finding supports the view, widespread in the landscape-ecological literature, that production–living–ecological (or production–consumption–protection) proportions alone are insufficient to describe territorial sustainability.

The sharp east–west polarisation identified along the Sajószentpéter–Nyékládháza line, without a transitional zone, illustrates how sharply a single, spatially concentrated functional boundary can divide an otherwise contiguous agglomeration into structurally distinct halves. The eastern and southern half—heterogeneous and nominally dominated by conventional land use—in fact accounts for a larger share of the agglomeration than the compact western (Bükk) block forming a homogeneous protective matrix. At the same time, the conventional land use category itself currently covers barely 40% of the agglomeration's total area, since the eastern–southern zone is also interlaced with protective patches running along river corridors or occurring as islands. These spatial components of green infrastructure are able to prevent the eastern half from consolidating into a uniformly conventional matrix. Accordingly, it is the smaller western half, where protection-dominated areas form a spatially contiguous matrix in the dominance layer, that lends the agglomeration as a whole its overall, essentially sustainable character (excluding transitional areas, 52.5% sustainable versus 31.8% conventional at the agglomeration level). This asymmetry—a spatially larger conventional zone interspersed with protective patches versus a smaller, contiguous protection-dominated zone—suggests that the spatial configuration of the matrix may be a more informative indicator of territorial sustainability at the agglomeration scale than areal extent alone.

4.2. Comparison with Previous Research

Direct quantitative comparison with previous studies is limited, because no assessment of territorial functions based on settlement plans has been carried out for a Hungarian study area, and international approaches differ from ours in classification, data and analytical units. We therefore compare our findings at the level of patterns and processes, and point out the main methodological differences.

PLES-based studies of urbanising regions consistently report a decline of ecological space and an expansion of production and living space [31]. In the Chaohu Lake Basin, agricultural production space was the main source of urban expansion, and landscape-pattern indices indicated weakening dominance and increasing fragmentation between 2000 and 2020 [32]. In Nanchong, the conversion of production space to living space was concentrated around the urban core [16]. Our prospective results show a similar pathway: the settlement plans reduce the production function by 3.4 percentage points, mainly in favour of the consumption function, and the changes are concentrated around Miskolc and along radial development axes. Unlike in most PLES studies, however, the areal extent of the protection function remains practically unchanged, whereas the matrix-level shift towards conventional land use (≈748 ha) exceeds the net areal loss of protective land (447.8 ha). This is consistent with the observation in PLES research that changes in spatial pattern can be more pronounced than changes in composition [32]. The comparison should be read with caution: PLES studies are typically retrospective, rely on multi-indicator classifications and aggregate results to administrative or grid units, whereas our assessment is prospective, uses a single dominance-based rule and works at the pixel level.

In the European context, the closest conceptual counterpart is the Land Use Functions (LUF) framework, developed for the *ex ante* sustainability impact assessment of policy-driven land use change [50]. It aggregates a large set of impact indicators into nine land use functions balanced across the three pillars of sustainability [51]. Our approach shares the *ex ante* orientation, but uses statutory settlement plans as the scenario and evaluates the spatial structure of three territorial functions rather than aggregated indicator values. The two approaches are therefore complementary: LUF assessments indicate which functions are enhanced or hindered, while matrix identification shows where and in what spatial configuration these changes occur.

Moving-window methods have long been used to characterise landscape pattern around each pixel, most prominently in global forest-fragmentation assessments, which showed that the resulting categories depend strongly on window size [52]. Hagen-Zanker [42] generalised this approach into a computational framework for landscape pattern analysis. Our sensitivity analysis agrees with these findings: across window radii of 100–200 m, the areal shares of land use strategies remained stable, while the spatial detail of category boundaries changed considerably (Table 2). Studies of agricultural landscapes in Central Europe have emphasised the role of small-scale and linear landscape structures in green infrastructure connectivity [28]. Our results are compatible with this: in the eastern and southern part of the agglomeration, riverine corridors and protective patches prevent the consolidation of a uniform conventional matrix. Since connectivity was not measured directly in this study, this correspondence should be regarded as indicative. The intensification of conventional land use observed in Miskolc and immediately south of it is consistent with the findings of Kristóf [53] on the functional, sectoral and regional transformation of the Miskolc agglomeration's economy, which likewise identifies the city and its southern surroundings as the locus of the strongest post-transition economic and land use transformation. This convergence between an economic geography assessment and our land cover-based structural analysis provides independent confirmation of the conventional–sustainable boundary delineated here, and suggests that the observed spatial

pattern reflects a persistent, multi-decade development trajectory rather than an incidental bias of the 2022 HNHRL snapshot.

At the same time, since, according to the prospective (settlement-plan-based) layer, the planned land use changes reinforce rather than fundamentally redraw this pattern—concentrating further conventionalisation in the same eastern–south-eastern belt, while the newly designated protective areas, as indicated by the maps, remain largely scattered rather than forming contiguous bands —the results suggest that, in the absence of deliberate planning intervention, the agglomeration's current east–west structural divide is more likely to consolidate than to dissolve.

4.3. Methodological Considerations and Limitations

Several methodological choices influence the interpretation of the results. Landscape-ecological studies have shown that patch- and landscape-level metrics, including moving-window outputs, are sensitive to the size of the analysis window and to the resulting modifiable areal unit problem (MAUP). We therefore selected the window size (31 × 31 pixels, ≈150 m radius) based on a sensitivity analysis comparing radii of 100, 150 and 200 m (Section 2.4, Table 2). Across this range, the share of sustainable areas varied only between 53.6% and 51.6%, and that of conventional areas between 32.7% and 31.1%. The main effect of window size was on spatial detail: total internal category boundary length decreased by 37.3% from the 100 m to the 200 m radius, while the transitional category expanded. The overall land use strategy pattern is therefore robust to the choice of window size, whereas the delineation of local boundaries depends on it. The classification thresholds (the three-class 70%/30% rule and the two-class 50% dominance rule) were not varied and should be regarded as one possible parameterisation adapted to the research questions and the data; a data-driven threshold-selection procedure is a natural direction for further development. Although the moving windows can be applied on the basis of several other properties, we chose quantitative dominance because, of the available options, this provided the most reliable means of determining one of the matrix's most important fundamental properties. The method calculates values for individual pixels based on the quantitative dominance of environmental characteristics; it does not take connectivity into account as a separate characteristic. When evaluating the results, it must therefore be considered that the connectivity factor of the matrix may influence the structure of the areas identified by the matrix. The significance of this problem is mitigated by the fact that the concept of the matrix can be defined in many ways; what these definitions generally have in common is that they interpret the matrix as a dominant, background-like component of the landscape, which is closely related to its quantitative dominance. At the same time, where neighbouring protective patches grow closer or merge, the share of the protection function within the window increases. The method therefore responds indirectly to changes in spatial contiguity, although it does not measure connectivity itself. Although no conclusions regarding connectivity can be drawn from the study's results, the significance of the resulting local structural changes has become observable through quantitative matrix identification. As shown in Section 4.1, spatial arrangement can differ markedly between areas of similar functional composition, incorporating landscape-connectivity or fragmentation metrics (e.g., contiguity, patch cohesion, effective mesh size) alongside the dominance-based matrix would probably separate more sharply the areas that are merely function-rich from those that are genuinely structurally coherent.

The prospective land use layer could be produced for only 31 of the agglomeration's 41 municipalities, since ten municipalities either did not respond to the freedom-of-information request or did not have a digitisable planning sheet in force; the agglomeration-level prospective picture should therefore be regarded as a partial, lower-bound estimate of expected land use change, and the actual extent of planned conventionalisation or

protective function gain may be larger. The settlements not included in the future analysis, with a total area of 16,249.9 ha, represent 15.5% of the agglomeration (Figure 2b). In terms of their location, these are small settlements lying outside the typical spatial development corridors, and their position within the agglomeration is also balanced. The two poles of the agglomeration each comprise five settlements: in the west, covering a total of 9629.2 hectares (9.2%of the conurbation), and in the east, covering 6620.8 hectares (6.3% of the agglomeration). In settlements of similar size within the agglomeration, the proportion of areas undergoing change is relatively low. In view of all this, the lack of data may have distorted the results to a small extent, in a manner that was spatially and functionally balanced across the two parts of the agglomeration.

Since settlement-planning regulations are themselves projective planning instruments rather than realised land cover, the timing and extent of their implementation are inherently uncertain; the "changing areas" analysed here should therefore be interpreted as a plausible planned trajectory rather than a forecast.

4.4. Potential Implications for Ecosystem Services

The structural changes revealed may also have implications for the conditions under which ecosystem services are provided. As ecosystem services were not measured directly in this study, these effects should be regarded as potential rather than demonstrated outcomes. A primarily structural weakening of the protection function and of green infrastructure could affect supporting, provisioning and regulating services alike. The conversion of protection function areas into consumption function and the increasing dispersion of protection-dominated areas are likely to pose the greatest risks, whereas the local expansion and merging of protective areas may create more favourable conditions for the persistence of these services.

4.5. The Spatial Organisation of Territorial Functions and Land Use Strategies

The current state of land use functions can, of course, be traced back to the local landscape history. Based on the landscape development processes outlined in the introduction, the regulatory environment (spatial planning) is only a partial cause of this current state of affairs, having only emerged in an institutionalised form in Hungary at the end of the 20th century. We have therefore used planning documents in our studies to examine anticipated future landscape changes, as land use concepts, through the regulatory framework, can provide a reference point for the direction of anticipated landscape formation. Although our study did not extend to investigating the causes of the situation in 2022, a detailed consideration of the local historical background is necessary to interpret the current pattern of land use. Although the current pattern of land use is related to the topography, the specific characteristics of the landscape's history must not be overlooked. The spatial expansion and intensification of agriculture, the history of farming and their broader economic and social causes—which can ultimately be traced back to natural potential and the region's location—have, within a complex system, resulted in the defensive function and sustainable land use being confined primarily to the low mountain and hilly areas, as well as to riverine environments.

5. Conclusions

This study assessed the sustainability of the landscape structure of the Miskolc agglomeration on the basis of the relationship system of territorial functions, and projected its expected change from statutory settlement plans. In 2022, the protection function covered 60.5% of the agglomeration, the production function 32.4% and the consumption function 7.1%. Matrix identification showed that 52.5% of the agglomeration has a sustainable, 31.8% a conventional and 15.7% a transitional land use strategy, with a sharp

east–west divide along the Sajószentpéter–Nyékládháza line. The settlement plans enable land use change on 6427.3 ha (6.13% of the agglomeration). This would reduce the production function by 3.4 percentage points, mainly in favour of the consumption function, while the protection function would remain practically unchanged. At the matrix level, the plans imply a net shift of 0.72 percentage points (≈748 ha) towards conventional land use, which exceeds the 447.8 ha net loss of protective land within the changing areas.

In answer to the two research questions, the agglomeration's landscape structure is currently sustainable overall, but this rests on the western block around the Bükk Mountains, where protection-dominated areas form a spatially contiguous matrix. The planned changes are modest in extent, yet they reinforce rather than redraw the existing divide. In the absence of deliberate planning intervention, this divide is therefore more likely to consolidate than to dissolve. More generally, the results suggest that the spatial configuration of the matrix may be a more informative indicator of landscape sustainability at the agglomeration scale than areal proportions alone.

These findings have direct relevance for planning practice. The transitional areas along matrix boundaries often coincide with existing green-space elements, so municipal green infrastructure development could build on them to link agricultural and near-natural biotopes into networks. The territorial function and land use strategy layers can also help to prioritise areas for integration into the Natura 2000 network and Hungary's National Ecological Network. Finally, because even a modest net areal shift may cause a locally decisive reorganisation of the matrix, the structural and not merely the areal impact of planned land use change should become a routine part of impact assessment for settlement plans and for the related compensation measures.

The results should be read in light of several limitations. The window size and classification thresholds represent one possible parameterisation, although the share of sustainable areas varied only between 53.6% and 51.6% across window radii of 100 to 200 m. Planning documents were unavailable for ten municipalities (15.5% of the agglomeration), so the prospective results are a lower-bound estimate. The changing areas describe a planned trajectory rather than a forecast, and ecosystem services were not measured directly.

Future research could extend the approach in three directions. Landscape metrics such as patch cohesion or effective mesh size could complement the dominance-based matrix and quantify connectivity directly. The multi-temporal HNHRL series would allow a retrospective component to be added, so that past and expected drivers of landscape change could be examined within a single framework. Linking the territorial function layers with the Ecosystem Map of Hungary [54] and with ecosystem service indicators would allow the potential effects of matrix change on ecosystem services to be tested empirically. The method relies on nationally available land cover data and on settlement plans that every Hungarian municipality is required to prepare, so it can be transferred to other city-regions in the country.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/land15122323/s1: Table S1: Crosswalk between the planned land use categories of the collected settlement plans and the territorial functions.

Author Contributions: Conceptualization, all authors; methodology, B.K.; software, B.K.; validation, all authors; formal analysis, C.C.; investigation, all authors; resources, B.K.; data curation, B.K.; writing—original draft preparation, B.K., G.O.; writing—review and editing, all authors; visualisation, B.K., G.O., I.M. and R.P.; supervision, G.O.; project administration, B.K. and G.O.; funding acquisition, none. All authors have read and agreed to the published version of the manuscript.

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References

1. Vidal de la Blache, P. Personnalité géographique de la France. In *Histoire de France Depuis les Origines Jusqu'à la Révolution*; Lavisse, E., Ed.; Hachette: Paris, France, 1911; Volume 1, 5–54.
2. Li, S.; An, W.; Zhang, J.; Gan, M.; Wang, K.; Ding, L.; Li, W. Optimizing limit lines in urban-rural transitional areas: Unveiling the spatial dynamics of trade-offs and synergies among land use functions. *Habitat Int.* **2023**, *140*, 102907. https://doi.org/10.1016/j.habitatint.2023.102907.
3. Li, S.; Zhu, C.; Deng, X. Exploring the urban–rural gradient effects of construction land expansion processes on land use function trade-off/synergy in rapidly urbanizing areas. *Land Degrad. Dev.* **2024**, *35*, 46–61. https://doi.org/10.1002/ldr.4896.
4. Liu, J.; Jin, X.; Xu, W.; Yang, F.; Wang, S.; Zhou, Y. Assessing trade-offs and synergies among multiple land use functional efficiencies: Integrating ideal reference and key indicators for sustainable landscape management. *Appl. Geogr.* **2023**, *158*, 103037. https://doi.org/10.1016/j.apgeog.2023.103037.
5. Ren, J.; Ma, R.; Huang, Y.; Wang, Q.; Guo, J.; Li, C.; Zhou, W. Identifying the trade-offs and synergies of land use functions and their influencing factors of Lanzhou-Xining urban agglomeration in the upper reaches of Yellow River Basin, China. *Ecol. Indic.* **2024**, *158*, 111279. https://doi.org/10.1016/j.ecolind.2023.111279.
6. Ángyán, J. *A Növénytermesztés Agroökológiai Tényezőinek Elemzése (Gazdálkodási Stratégiák, Termőhelyi Alkalmazkodás) [Analysis of the Agroecological Factors of Crop Production (Farming Strategies, Site Adaptation)]*; Candidate of Sciences Dissertation; Gödöllő University of Agricultural Sciences: Gödöllő, Hungary, 1991. (In Hungarian)
7. Feng, C.; Zhang, H.; Xiao, L.; Guo, Y. Land Use Change and Its Driving Factors in the Rural–Urban Fringe of Beijing: A Production–Living–Ecological Perspective. *Land* **2022**, *11*, 314. https://doi.org/10.3390/land11020314.
8. Hu, M.; Yigitcanlar, T.; Li, F.; Deng, S.; Yang, Y. Sustainable Development of Production–Living–Ecological Spaces: Insights from a 30-Year Remote Sensing Analysis. *Sustainability* **2024**, *16*, 9585. https://doi.org/10.3390/su16219585.
9. Xia, N.; Hai, W.; Tang, M.; Song, J.; Quan, W.; Zhang, B.; Ma, Y. Spatiotemporal evolution law and driving mechanism of production–living–ecological space from 2000 to 2020 in Xinjiang, China. *Ecol. Indic.* **2023**, *154*, 110807. https://doi.org/10.1016/j.ecolind.2023.110807.
10. Filepné Kovács, K.; Dubois, S.; Thill, M.; Valánszki, I.; Jombach, S.; Mikházi, Z.; Kollányi, L. A francia tájpolitika tanulságai a hazai gyakorlat számára [Guidance of the French Landscape Policy for Hungary]. In *A VIII. Magyar Földrajzi Konferencia, a XVI. Geográfus Doktoranduszok Országos Konferenciája és az Oktatás-Módszertani és Földrajztanári Konferencia Konferenciakötete [Proceedings of the 8th Hungarian Geographical Conference]*; Pajtókné Tari, I., Tóth, A., Eds.; Eszterházy Károly University: Eger, Hungary, 2016; 452–469. (In Hungarian)
11. Fodor, L. A környezetvédelem helyi szintje egy dél-borsodi kistelepülés, Bogács példáján [The local level of environmental protection: The example of Bogács, a small settlement in southern Borsod]. *Miskolci Jogi Szemle* **2016**, *11*, 5–28. (In Hungarian) Available online: https://ojs.uni-miskolc.hu/index.php/jogiszemle/issue/view/359/221 (accessed on 25 November 2026).
12. Filepné Kovács, K.; Valánszki, I.; Sallay, Á.; Jombach, S. A tájtervezés és a tájvédelem helyzete az európai országok területi tervezésében [The status of landscape planning and landscape protection in the spatial planning of European countries]. *Tájökológiai Lapok* **2013**, *11*, 279–290. (In Hungarian) https://doi.org/10.56617/tl.3754.
13. Filepné Kovács, K.; Dancsokné Fóris, E.; Valánszki, I. Tájfunkció elemzés, mint megalapozó munkarész a vidékfejlesztési stratégiákban [Landscape function analysis as a groundwork for rural development strategies]. In *Interdiszciplináris Tájkutatás a XXI. Században. A VII. Magyar Tájökológiai Konferencia Tanulmányai [Interdisciplinary Landscape Research in the 21st Century: Proceedings of the 7th Hungarian Landscape Ecology Conference]*; Blanka, V., Ladányi, Z., Eds.; University of Szeged, Department of Geography and Earth Sciences: Szeged, Hungary, 2017; pp. 163–170. (In Hungarian)
14. D'Amico, G.; L'Abbate, P.; Liao, W.; Yigitcanlar, T.; Ioppolo, G. Understanding Sensor Cities: Insights from Technology Giant Company Driven Smart Urbanism Practices. *Sensors* **2020**, *20*, 4391. https://doi.org/10.3390/s20164391.
15. Liu, H.; Qin, L.; Xing, M.; Yan, H.; Shang, G.; Yuan, Y. Effects of Production–Living–Ecological Space Patterns Changes on Land Surface Temperature. *Remote Sens.* **2023**, *15*, 3683. https://doi.org/10.3390/rs15143683.
16. Xu, H.; Zhang, F.; Li, W.; Shi, J.; Johnson, B.A.; Tan, M.L. Spatial-temporal pattern of change in production-living-ecological space of Nanchong City from 2000 to 2020 and underlying factors. *Environ. Monit. Assess.* **2023**, *196*, 94. https://doi.org/10.1007/s10661-023-12249-8.

17. Jiang, M.Q.; Liu, Y. Discussion on the concept definition and spatial boundary classification of "production-living-ecological" space. *Urban Dev. Stud.* **2020**, *27*, 43–48. https://doi.org/10.3969/j.issn.1006-3862.2020.04.007 (In Chinese)
18. Lin, G.; Jiang, D.; Fu, J.; Zhao, Y. A Review on the Overall Optimization of Production–Living–Ecological Space: Theoretical Basis and Conceptual Framework. *Land* **2022**, *11*, 345. https://doi.org/10.3390/land11030345.
19. Maucha, G.; Belényesi, M.; Friedl, Z.; Kerékgyártó, É.; Kristóf, D.; Lehoczki, R.; Pacskó, V.; Pataki, R.; Petrik, O.; Vaszócsik, V. *Felszínborítás Vizsgálata az UNCCD Országjelentés Felülvizsgálata Keretében [Land-Cover Assessment in the Review of the UNCCD National Report]*; Presentation at the World Day to Combat Desertification and Drought; Ministry of Agriculture and General Directorate of Water Management: Budapest, Hungary, 2019. (In Hungarian) Available online: https://vpf.vizugy.hu/reg/ovf/doc/Lechner_Maucha_Gergely_UNCCD_felszinboritas.pdf (accessed on 4 June 2026).
20. Belényesi, M.; Pacskó, V.; Lehoczki, R.; Pataki, R.; Tanács, E.; Kristóf, D.; Szekeres, Á.; Zsembery, Z.; Mikus, G. Országos gyeptérképezés Magyarországon: Helyzetkép [National grassland mapping in Hungary: Current status]. *Tájökológiai Lapok* **2025**, *23*, 3–45. (In Hungarian) https://doi.org/10.56617/tl.6660
21. Süli-Zakar, I. A roma integráció kérdőjelei társadalomföldrajzi megközelítésben [Open questions of Roma integration from a social-geographical perspective]. In *A Tudás Szolgálatában—Földrajzi Tanulmányok Pál Ágnes Tiszteletére [In the Service of Knowledge: Geographical Studies in Honour of Ágnes Pál]*; Győri, F., Ed.; Közép-Európai Monográfiák 5; Egyesület Közép-Európa Kutatására: Szeged, Hungary, 2012; 163–178. (In Hungarian)
22. Englund, O.; Berndes, G.; Cederberg, C. How to analyse ecosystem services in landscapes—A systematic review. *Ecol. Indic.* **2017**, *73*, 492–504. https://doi.org/10.1016/j.ecolind.2016.10.009.
23. Portman, M.E. Ecosystem services in practice: Challenges to real world implementation of ecosystem services across multiple landscapes—A critical review. *Appl. Geogr.* **2013**, *45*, 185–192. https://doi.org/10.1016/j.apgeog.2013.09.011.
24. Costanza, R.; d'Arge, R.; de Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'Neill, R.V.; Paruelo, J.; et al. The value of the world's ecosystem services and natural capital. *Nature* **1997**, *387*, 253–260. https://doi.org/10.1038/387253a0.
25. de Groot, R.S.; Wilson, M.A.; Boumans, R.M.J. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecol. Econ.* **2002**, *41*, 393–408. https://doi.org/10.1016/S0921-8009(02)00089-7.
26. European Commission. *Green Infrastructure (GI)—Enhancing Europe's Natural Capital*; COM(2013) 249 final; European Commission: Brussels, Belgium, 2013. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52013DC0249 (accessed on 25 November 2026).
27. Máté, K. Agrárterületek Zöldinfrastruktúrájának Tájökológiai Vizsgálata [Landscape-Ecological Assessment of the Green Infrastructure of Agricultural Areas]. Ph.D. Thesis, Hungarian University of Agriculture and Life Sciences, Budapest, Hungary, 2024. (In Hungarian) https://doi.org/10.54598/005150.
28. Skokanová, H.; Netopil, P.; Havlíček, M.; Šarapatka, B. The role of traditional agricultural landscape structures in changes to green infrastructure connectivity. *Agric. Ecosyst. Environ.* **2020**, *302*, 107071. https://doi.org/10.1016/j.agee.2020.107071.
29. Tóth, A. Greenways as Linear Components of Green Infrastructure in Rural Agricultural Landscapes of South-Western Slovakia. *Fábos Conf. Landsc. Greenway Plan.* **2016**, *5*. 195–201. https://doi.org/10.7275/fabos.646
30. Ángyán, J. A térstruktúra, ökológiai infrastruktúra [Spatial structure, ecological infrastructure]. In *Védett és Érzékeny Természeti Területek Mezőgazdálkodásának Alapjai [Foundations of Agriculture in Protected and Sensitive Natural Areas]*; Ángyán, J., Tardy, J., Vajnáné Madarassy, A., Eds.; Mezőgazda: Budapest, Hungary, 2003; 190–192. (In Hungarian)
31. Xu, N.; Chen, W.; Pan, S.; Liang, J.; Bian, J. Evolution Characteristics and Formation Mechanism of Production-Living-Ecological Space in China: Perspective of Main Function Zones. *Int. J. Environ. Res. Public Health* **2022**, *19*, 9910. https://doi.org/10.3390/ijerph19169910.
32. Zhang, R.; Li, S.; Wei, B.; Zhou, X. Characterizing Production–Living–Ecological Space Evolution and Its Driving Factors: A Case Study of the Chaohu Lake Basin in China from 2000 to 2020. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 447. https://doi.org/10.3390/ijgi11080447.
33. Wu, Z.; Mu, D.; Sun, M.; Xiong, Q.; Xiao, S. Evaluating rural tourism landscapes in world heritage buffer zones using PLES (Production–Living–Ecological Space) theory. *npj Herit. Sci.* **2025**, *13*, 464. https://doi.org/10.1038/s40494-025-02033-x.
34. Li, S.; Chen, Y.; Huang, Q. Spatial allocation and sustainable development: A study of production-living-ecological spaces in the Yangtze River Delta. *Front. Environ. Sci.* **2025**, *12*, 1481186. https://doi.org/10.3389/fenvs.2024.1481186.
35. Wen, S.; Cao, S.; Du, M.; He, Z. Aligning territorial spatial planning with sustainable development goals: A comprehensive analysis of production, living, and ecological spaces in China. *Ecol. Indic.* **2024**, *160*, 111816. https://doi.org/10.1016/j.ecolind.2024.111816.

36. Tian, F.; Li, M.; Han, X.; Liu, H.; Mo, B. A Production–Living–Ecological Space Model for Land-Use Optimisation: A case study of the core Tumen River region in China. *Ecol. Model.* **2020**, *437*, 109310. https://doi.org/10.1016/j.ecolmodel.2020.109310.
37. Gou, M.M.; Liu, C.F.; Li, L.; Xiao, W.F.; Wang, N.; Hu, J.W. Ecosystem service value effects of the Three Gorges Reservoir Area land use transformation under the perspective of "production-living-ecological space". *Chin. J. Appl. Ecol.* **2021**, *32*, 3933–3941. (In Chinese)
38. Wang, R.J.; Zhao, X.M.; Guo, X.; Ye, Y.C.; Li, Y.; Zhou, Y. A Study on Land Use Transformation and Ecological Environment Effects from the Perspective of "Production-Living-Ecological Space": A Case Study of Yingtan City, Jiangxi Province. *Acta Agric. Univ. Jiangxiensis* **2021**, *43*, 681–693. (In Chinese)
39. Zhou, J.X.; Zhang, Q.J. Study on the Relationship between Land Use Transformation and Ecological Environment Change in Tianjin Based on "Ecological-production-living Spaces". *J. Tianjin Chengjian Univ.* **2021**, *27*, 333–339. (In Chinese)
40. Tóth, G. Agglomerációk, településegyüttesek és vonzáskörzetek Magyarországon, 2024 [Agglomerations, settlement clusters and catchment areas in Hungary, 2024]. *Területi Stat.* **2024**, *64*, 356–397. (In Hungarian) https://doi.org/10.15196/TS640304
41. Marosi, S.; Somogyi, S. (Eds.) *Magyarország Kistájainak Katasztere I–II [Cadastre of Hungary's Micro-Regions I–II]*; MTA Földrajztudományi Kutató Intézet: Budapest, Hungary, 1990. (In Hungarian)
42. Hagen-Zanker, A. A computational framework for generalized moving windows and its application to landscape pattern analysis. *Int. J. Appl. Earth Obs. Geoinf.* **2016**, *44*, 205–216. https://doi.org/10.1016/j.jag.2015.09.010.
43. Šímová, P.; Gdulová, K. Landscape indices behavior: A review of scale effects. *Appl. Geogr.* **2012**, *34*, 385–394. https://doi.org/10.1016/j.apgeog.2012.01.003.
44. Huang, Q.; Huang, J.; Yang, X.; Ren, L.; Tang, C.; Zhao, L. Evaluating the Scale Effect of Soil Erosion Using Landscape Pattern Metrics and Information Entropy: A Case Study in the Danjiangkou Reservoir Area, China. *Sustainability* **2017**, *9*, 1243. https://doi.org/10.3390/su9071243.
45. Zhang, S.; York, A.M.; Boone, C.G.; Shrestha, M. Methodological Advances in the Spatial Analysis of Land Fragmentation. *Prof. Geogr.* **2013**, *65*, 512–526. https://doi.org/10.1080/00330124.2012.700501.
46. Zhang, L.; Zhao, Y.; Yin, S.; Fang, S.; Liu, X.; Pu, M. Gradient analysis of dry valley of Minjiang River landscape pattern, based on moving window method. *Acta Ecol. Sin.* **2014**, *34*, 3276–3284. https://doi.org/10.5846/stxb201310312639.
47. Paluch, J. On the Consequences of Using Moving Window Segmentation to Analyze the Structural Stand Heterogeneity and Debatable Patchiness of Old-Growth Temperate Forests. *Forests* **2021**, *12*, 96. https://doi.org/10.3390/f12010096.
48. Feng, B.; Yang, H.; Ren, Y.; Zheng, S.; Feng, G.; Huang, Y. Study on Change of Landscape Pattern Characteristics of Comprehensive Land Improvement Based on Optimal Spatial Scale. *Land* **2025**, *14*, 135. https://doi.org/10.3390/land14010135.
49. Russo, L.F.; Andrello, M.; Giuliani, M.; Ancillotto, L.; Carboni, M.; La Bella, G.; Martelli, F.; Santini, L. Mapping the urban landscape at multiple ecological scales. *Urban For. Urban Green.* **2025**, *110*, 128849. https://doi.org/10.1016/j.ufug.2025.128849.
50. Pérez-Soba, M.; Petit, S.; Jones, L.; Bertrand, N.; Briquel, V.; Omodei-Zorini, L.; Contini, C.; Helming, K.; Farrington, J.H.; Tinacci Mossello, M.; et al. Land use functions—A multifunctionality approach to assess the impact of land use changes on land use sustainability. In *Sustainability Impact Assessment of Land Use Changes*; Helming, K., Pérez-Soba, M., Tabbush, P., Eds.; Springer: Berlin/Heidelberg, Germany, 2008; 375–404.
51. Paracchini, M.L.; Pacini, C.; Jones, M.L.M.; Pérez-Soba, M. An aggregation framework to link indicators associated with multifunctional land use to the stakeholder evaluation of policy options. *Ecol. Indic.* **2011**, *11*, 71–80. https://doi.org/10.1016/j.ecolind.2009.04.006.
52. Riitters, K.; Wickham, J.; O'Neill, R.; Jones, B.; Smith, E. Global-scale patterns of forest fragmentation. *Conserv. Ecol.* **2000**, *4*, 3. https://doi.org/10.5751/es-00209-040203.
53. Kristóf, A. Functional, sectoral and regional transformation of the economy of the Miskolc agglomeration revisited. *Analele Univ. Oradea Ser. Geogr.* **2017**, *27*, 84–97. Available online: https://geografie-uoradea.ro/Reviste/Anale/Art/2017-1/9.AUOG_737_Andrea.pdf (accessed on 6 May 2025).
54. Tanács, E.; Belényesi, M.; Lehoczki, R.; Pataki, R.; Petrik, O.; Standovár, T.; Pásztor, L.; Laborczi, A.; Szatmári, G.; Molnár, Z.; et al. Országos, nagyfelbontású ökoszisztéma-alaptérkép: Módszertan, validáció és felhasználási lehetőségek [A national, high-resolution ecosystem basemap: Methodology, validation and possible uses]. *Természetvédelmi Közlemények* **2019**, *25*, 34–58. (In Hungarian) https://doi.org/10.20332/tvk-jnatconserv.2019.25.34.

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