CONTRIBUTION OF PROTECTED AREAS TO MITIGATE THE EFFECT OF LANDSCAPE FRAGMENTATION IN SLOVAKIA

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ABSTRACT

The main aim of the research is to identify landscape fragmentation (LF) in Slovakia with special emphasis on the contribution of protected areas (PAs) to mitigate the effect of LF. Results are presented in the final raster output (10 m grid). The raster contains 490,321,151 individual 10 m raster grids, with the LF average value of 59.12 % (where 0 represents fragmented landscape, 100 represents fully connected landscape by natural or semi-natural ecosystems) on the national level. Most of the territory of Slovakia falls within the range of values 55 – 65 %, which confirms the presence of significant continuous unfragmented areas. Based on the Ordinary Least Square (OLS) statistics results, there is a positive correlation of lower LF within the PAs network ($p < 0.05$, Table 1) in comparison to the unprotected part of Slovakia. The results of geographically weight regression (GWR) proved a medium positive correlation ($r2=0.36$; $r2adj=0.36$; $n=49,003$), thus confirming to a certain extent the role of PAs in the mitigation of the effect of LF. On the other hand, the level of protection does not correlate significantly with fragmentation values, where a higher level of protection is not significantly connected with a lower level of LF. For each category of PA, individual statistics of quality and quantity of LF are estimated and subsequently compared with unprotected parts of Slovakia. The comparison of all PAs with each other resulted in 1,132 unique assessments. The overall average value of LF of unprotected parts is still rather high (56.42 %) and it shows that there are still significant areas existing, which are situated in unprotected parts of the country. Spatial analysis revealed, that these important parts are covering 93,065 hectares, and are variously spread across the whole of Slovakia. The average value of LF for these newly identified areas is 68.5 %. As output, the results of this research present a comprehensive national map of the level of LF and lists of PAs ranked according to the overall assessment of LF.

INTRODUCTION

The process of habitat fragmentation affects ecological processes on several levels – functionality of habitat is limited by reducing its area, and isolation disrupts natural flow in the ecosystem. The term fragmentation (fragmentation, division) in the scientific community appears more and more often in context with the distribution and reduction of natural and semi–natural habitats and subsequently with the need for the protection of habitats, species, and communities. It is a process (or state) of a division of natural/semi-natural areas, reduction of area, and increase of their mutual isolation. Naturally isolated are e.g. areas of alpine communities. However, the species occurring in such places are adapted to these conditions, or the process of adaptation still continues.

The current landscape is increasingly affected by the progressive construction of roads, highways, and high-speed railway corridors, but also by the development of industrial and residential development. Problems are also related to development of recreational areas including touristic infrastructure (i.e. ski resorts, hotels, restaurants, apartments, chalets, holiday buildings, shopping centers, transportation facilities), commercial buildings, storehouses, agricultural buildings. Regulated sections of rivers, small hydropower plants and reservoirs with concrete and rocky embankments also act as barriers. Linear barriers in combination with the rapid development of buildings cause the disintegration of originally continuously inhabited natural or semi-natural units into individual mutually isolated islands, which by their size often do not meet the requirements for the long-term survival of habitats and species. The fragmentation of the environment by transport infrastructure and expanding buildings is thus becoming a major limit to the survival of several species (Romportl *et al.*, 2013). In a country like Slovakia that is influenced by human activities, new obstacles or barriers are being added very quickly, which disrupt the long-term and established way of life of organisms, daily journeys for food, water, and seasonal migrations. The most serious artificial barriers include motorways, expressways, railways, built-up areas of settlements, and fenced industrial zones, fenced agricultural and forested land (including pastures, game enclosures, gardens, orchards, etc.). (Ružičková & Lehotská, 2008).

The documentation (specific for Slovakia and the Czech Republic) of territorial ecological stability systems in Slovakia (TSES), from the supra-regional to the local level, should capture important landscape connectivity features and reflect them in the design of bio-corridors (Ružičková & Lehotská, 2008). However, the TSES is currently insufficiently implemented in practical terms, because the LF constantly continues, although there is legislative support for TSES implementation. Increasing urbanization, and progressive development of roads but also geomorphological conditions negatively affect the habitat distribution in Slovakia. In particular, the mentioned anthropogenic elements cause fragmentation of ecosystems and habitats in which species naturally occur.

The EUNIS habitat classification (European Union Nature Information System) developed by the European Environment Agency, has been used in nature conservation as a tool for describing habitat units. The system is hierarchical, and covers all types of habitats from natural to artificial, from terrestrial to freshwater and marine. This classification is useful for the national nature conservation authorities to place and assess habitats in a European context (EEA, 2017). This classification is also very useful as a baseline for the identification of particular habitat types for the assessment of LF.

Knowing that continuous large-scale ecosystems and habitats have a positive effect on habitat conservation and indirectly also to landscape connectivity, e.g. areas of national parks, protected landscape areas, Ramsar sites, and Natura 2000 sites, we used these attributes as input data for the analysis of habitat fragmentation in Slovakia.

PAs function mainly as core areas, but also as so-called stepping-stones and corridors provide structural connectivity between them (Stewart et al., 2019). Not only structural but also functional connectivity plays an important role in preserving the biodiversity of habitats (Kimberley et al., 2021). Functional connectivity is essential for maintaining ecological processes (Berti & Svenning, 2020), due to its natural dynamic (Zeller et al., 2020). However, ecological fragmentation is known to increase the edge effect (Fahrig et al., 2019), contributing to the decay of an ecosystem by reducing processes in smaller and more isolated habitat patches, in which more species are lost than would be expected from the loss of the habitat itself (Chase et al., 2020; Haddad et al., 2016). In Slovakia, there are several categories of PAs present, mainly national parks, landscape protected areas, Natura 2000 sites, nature reserves, and others. The total area of PAs in Slovakia is cca 12,536 km^2, unprotected part covers 36,485 km^2. There is 5 basic various levels of protection, 1 is an unprotected part, 5 is a strictly protected non-intervention area and the levels in between represent the medium level of protection. Level 2 covers 8,452 km^2, level 3 covers 2,776 km^2, level 4 covers 333 km^2 and level 5 area is 973 km^2.

Ensuring spatio-temporal connectivity is also important for the maintenance of migratory species (Howard et al., 2020) but also for species that are expected to shift range due to ongoing climate change (Huang et al., 2020; Zurell et al., 2018). Improving connectivity is therefore one of the commonly recommended adaptation strategies in nature conservation (Costanza & Terando, 2019; Vanneste et al. 2020). For all the above-mentioned reasons, increasing numbers of national and international conventions, laws, and regulations set goals and requirements that lead to the preservation and restoration of ecological networks and the development of "green infrastructure" (Leitner et al., 2016). Many studies focus on tracking animal mortality on the roads (Tejera et al., 2018) and telemetry (Hays, 2014), but these parameters are usually rather local and out of the overall national and international contexts. From the point of view of the understanding species occurrence, maintaining or restoring connectivity among wildlife populations is a primary strategy to overcome the negative impacts of habitat fragmentation and ensure wildlife survival (Ghoddousi et al., 2021). Ecosystems are maintained within a regime through the internal dynamics of variables, such as the interaction between populations of species that coexist therein. Therefore, natural dynamics do not interfere with the possibility of species dispersal, as species are largely adapted to these natural changes (Mayer & Rietker, 2004). The division and reduction of habitats (fragmentation) and the creation of barriers to dispersal weaken populations, through the reduction in abundance and therefore potential extinction of species (Fahrig, 2003). In places where movement routes intersect with busy roads, collisions often occur. Collisions of animals with vehicles can result in injury or damage, also human death. Many authors (Psaralexi et al., 2017; Talty et al., 2020) agree on the conservation importance and value of areas without roads and transport infrastructure. It is currently estimated that around 194 million birds and 29 million mammals die each year on European roads (Grilo et al., 2020). One way to improve connections between habitats of wild animals fragmented by human activity is to improve connectivity (Teixeira et al., 2020; Seidler et al., 2018). Measures can also be formulated to reduce traffic or speed on roads (Whittington et al., 2019; Lamb et al., 2018; Collinson et al., 2019). The study (Clair et al., 2020), analyzing the mortality of some mammalian species on the railway, showed that train speed, proximity to a water source, and track curvature increase mortality.

Fragmentation of natural areas and landscapes is a process that, after reaching and exceeding beneficial and bearable borders negatively affects the biota, but also the quality of human being.

There are several methods for assessment of LF (i.e. Gustafson, 1998; Leitão *et al*., 2006), using usually GRID-based assessment (i.e. effective mesh density) however very few consider spatial density and its spatial cumulative effect into account.

The aim of this research focuses on the assessment of LF at the national level, with special emphasis on the contribution of PAs to mitigate the effect of LF. Based on the analytical part the focus is also to assess the level of contribution of PAs to the overall landscape connectivity in comparison to the unprotected part of Slovakia. In addition, the results provide identification of important unfragmented areas, which are not presently protected, and propose adequate conservation measures. This kind of national assessment based on detailed national spatial data set analysis is actually missing and it was never performed in the past by using such detailed spatial data sets, in fact, recent and up-to-date assessments of LF on the national level based on more precise data than Corine land cover data set are completely missing. The level of precision of input data and advantageous methods used for the measurement of LF in our research is rather unique as in the past only less precise input spatial data for assessment were used, where small-scale features were barely taken into account. Results can be used not only in spatial planning but also in the field of nature conservation, preparation of national strategies for the protection of landscape connectivity, and many other practical applications.

MATERIALS AND METHODS

The preparation of the spatial analysis was based on data from the ecosystem/landscape type map (Černecký *et al*., 2020). This data set consists of detailed data, which identifies individual landscape types in form of ecosystems and their spatial distribution. For the preparation of a landscape type map, the most precise available data from the nature protection, agricultural, and forestry sector were used. The spatial precision of the data was determined by that of the field data, which was mostly created at scales between 1:10,000 and 1:5,000. The data was stored in the form of a geodatabase containing more than 1,000,000 polygons (in the case of splitting polygons of individual buildings it is more than 2,000,000 polygons). The data in the map was streamlined and identified the ecosystem distribution in a unified ecosystem classification. EUNIS classification from the year 2017 (EEA, 2017) was used for this purpose, thus the individual hierarchical habitat classes could be extracted and divided into suitability classes for the identification of landscape types. We decided to use this data instead of other data (i.e. Corine Land Cover – CLC) due to its higher precision on a national, regional, and local level. The data set was prepared in vector form and, most importantly, the polygons were not restricted to a certain size (as in the case of CLC); therefore even small and important features are present and considered in the analysis. Ecosystems, their distribution, and overall composition have a significant influence on landscape connectivity and fragmentation. Based on spatial data, ecosystems have been divided into those categories, that support landscape connectivity, and those that affect LF.

Ecosystems were transferred from vector data set to raster in the precision of a 10 m grid. The raster images were calculated by using the "Kernel density" tool in ArcGIS 10.3. The 2 divided input data sets when processed by the Kernel density, generated clusters of landscape connectivity (ecosystems supporting the connectivity data set) and landscape fragmentation (ecosystems affecting landscape fragmentation data set). This method of measuring landscape connectivity is not very common, however, it has many advantages in comparison

to other well-established methods for the measurement of landscape fragmentation. Mainly, the tool itself has implemented spatial weighting, where the clusters of features and distance play an important role. Therefore the cumulative effect of spatial distribution is taken into account, which is not the case in many other existing methods.

The basic setup for Kernel density values was set to 10 m output cell size and 3,000 m search radius for best possible precision, but still with the relevant surrounding area for correct interpretation of broader ecosystem context. The scheme presenting the main steps in the process of analysis and data production is provided in Figure 1.

Fig. 1: Flowchart of the main steps and data preparation for the analysis of LF
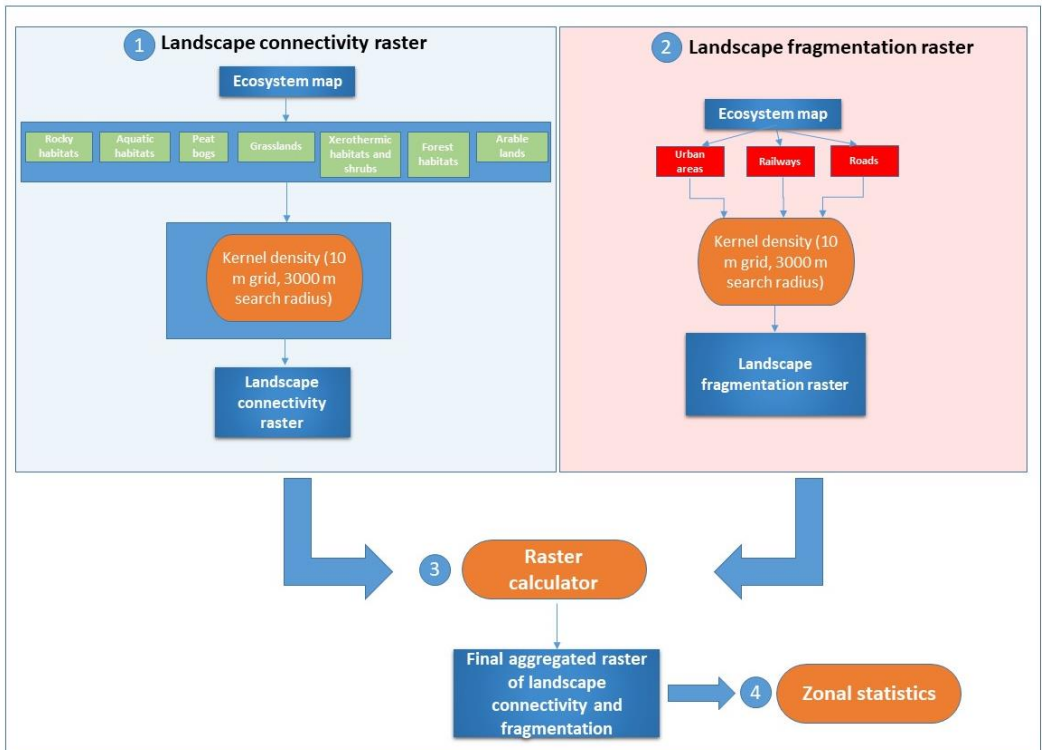
Based on the combination of all data from 2 prepared raster images, the data were grouped by using the ArcGIS function raster calculator and provided an overall picture of LF within Slovakia. Values were recalculated to the percentage on the scale of 0–100 % based on minimal and maximal values calculated by the Kernel density, where 0 means a totally fragmented landscape and 100 % represents a connected landscape without any obstacles. Final values of the raster were reclassified by using rounding into 20 categories (0, 5, 10, 15…, 95, 100) for easier map presentation and overall clear interpretation of the results.

After the initial preparation of data identifying landscape fragmentation, analyses began to be prepared concerning the evaluation of the contribution of individual categories of PAs in terms of landscape connectivity/landscape fragmentation and their comparison with the unprotected parts of Slovakia. The analyses included all relevant categories of PAs in Slovakia, namely large-scale protected areas (national parks – NP, protected landscape areas – PLA), small-scale protected areas (nature reserves – NR, natural monuments – NM,

protected sites – PS, etc.), Sites of Community Importance (SCIs), Special Protected Areas (SPAs), Ramsar Sites and Biosphere Reserves (BR). Unique values were calculated individually for each protected area. The value (in %) for LF was calculated based on previously calculated raster images processed by the raster calculator.

The resulting layers and final LF raster image were analyzed by using ArcGIS 10.3 tool "Zonal statistics" to obtain statistical summaries and values. This tool allows the calculation of values such as min, max, ranges, standard deviations, mean values, median, etc. The values, in addition to the pure ranking of best values of connectivity in individual PAs, were weighted according to the total area of the territory of the particular protected area itself, as the acreage has a high influence on contribution to the overall landscape connectivity. The result of this process is a tabular overview of ranking according to the quality of provided landscape connectivity without taking into account the total area of the protected area and the second ranking takes into account its area as well.

The correlation of values calculated for landscape connectivity in relationship with protected areas was tested by linear regression, particularly OLS statistics. The final raster was recalculated to a 1,000 m grid (recalculate function in ArcGIS) and centroids of grids were created (raster to point). This was necessary for reducing the data set for calculations as a basic raster contains more than 400 million grids and it would be impossible to calculate statistics on such a large data set. In this way, generalized 49,003 point data set was the basis for the statistics. As a dependent value LF value was chosen (0–100 %). As an explanatory value, the placement of the grid inside or outside of PAs was used (value 1 or 0). By using a similar approach also the level of protection in protected areas was tested (values in the range 1 – 5, where 1 – non-protected area, 5 – strict protection). By using this analysis the correlation between the level of fragmentation and level of protection in each protected area was tested in order to confirm if a higher level of protection correlates with a lower level of landscape fragmentation. After testing of significance/non-significance of the relationship by OLS, the statistics continued by using GWR. As dependent values again the LF values were set and as explanatory values, the relationship to PAs was used. In process of performing the model of GWR only those explanatory values were used, for which significant correlation in OLS previously was confirmed. GWR model, in addition to OLS analysis, calculates the spatial relationship of individual values, which is very relevant for our case. The main expected outcome of GWR was the calculation of the r^2 value, thus proving the value of significance/non-significance of the relationship of lower LF inside of the PAs network.

In the overall interpretation of the resulting values, the values for all categories of protected areas were compared together followed by a comparison of the individual PAs categories separately, and, above all, they were compared to the average value of LF in the unprotected part of Slovakia.

One of the final outputs is the detailed geodatabase of LF in Slovakia as well as the ranking of protected areas according to the overall LF.

RESULTS

National assessment of LF and role of the PAs in mitigating the LF in Slovakia

Results are presented in the final raster output (10 m grid). The raster contains 490,321,151 individual 10 m raster grids (Figure 2), with the average value for landscape fragmentation of 59.12 % (where 0 represents a totally fragmented landscape, 100 represents a fully connected landscape by natural or semi-natural ecosystems) on the national level. The calculated median value is 60 %. Most of the territory falls within the range of values 55 – 65 %, which confirms the presence of significant continuous unfragmented areas.

Fig. 2: Map of the LF in Slovakia, national, regional, local view, and additional statistics (count of 10 m raster grids for each value of landscape fragmentation)
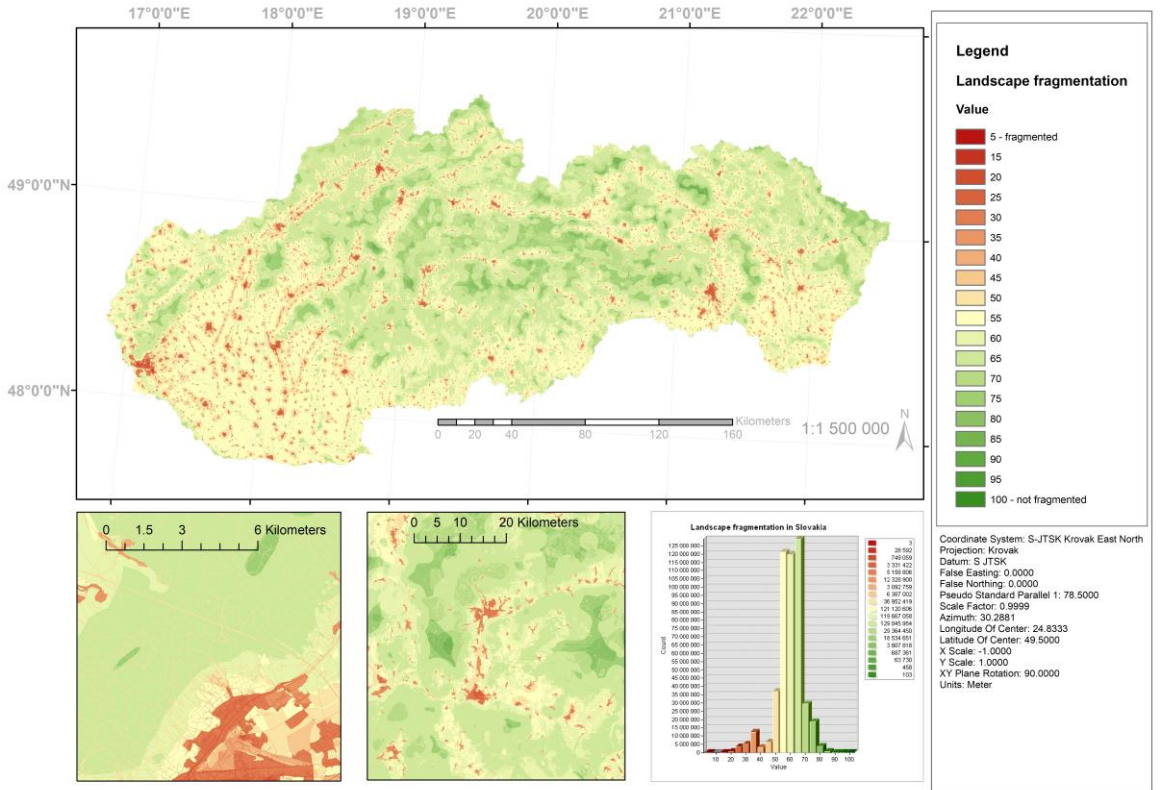
The lower level of LF is particularly evident in the middle and northern part of Slovakia (Figure 2). In principle, the landscape is relatively well connected from the north to the south of Slovakia and from the east to the west by more or less interconnected parts, but further fragmentation, development, urban sprawl and construction of transport infrastructure can also worsen the current situation in close future. The southern part of Slovakia is much more affected by a higher level of LF (Figure 2).

On the local level, it is possible to identify significant landscape connectivity features, which are based on the precision of the prepared data set. It can help to identify often small, but highly relevant elements important for the connectivity (Figure 2, bottom middle and left part).

Based on the OLS statistics results, there is a positive correlation of lower LF within the protected areas network ($p < 0.05$, Table 1) in comparison to the unprotected part of Slovakia. For individual levels of protection, there was no significant correlation confirmed in any of the tested levels (1–5) and it seems that a higher level of protection does not automatically mean lower LF. Therefore for GWR, only the parameter inside/outside of the protected network was used. The results of GWR proofed medium positive correlation ($r2=0.36$, $r2adj=0.36$; $n=49,003$). PAs in Slovakia to a certain extent are contributing to mitigating the effect of LF. On the other hand, it seems that the levels of protection (1–5) are not appropriately established as an actually higher level of protection from a national

perspective does not generally represent lower LF and the other way round. Also, there are important parts of Slovakia, which are not actually protected in which a low level of LF is present.

Table 1: Summary of OLS Results – Model Variables

Variable	Coefficient [a]	StdError	t-Statistic	Probability [b]	Robust_SE	Robust_t	Robust_Pr [b]
Intercept	57.280798	0.043789	1,308.106758	0.000000*	0.046663	1,227.532887	0.000000*
Protected areas network	7.180304	0.086676	82.840402	0.000000*	0.074553	96.311703	0.000000*

A positive correlation of lower LF can be visible also in the spatial output of GWR analysis, where positive values (darker color) are more frequent inside of the PAs network (Figure 3). This represents the fact that in PAs it is a higher expectation of the model to maintain lower levels of LF. Places of darker color in Figure 3 also suggest that there is a significant area outside of the PAs network, where a higher value of connectivity is expected and indirectly shows the need for additional protection in the future. The spatial distribution also reveals a more positive std. (standard deviation) residuals in close vicinity of the PAs. This suggests that PAs network also positively affects the surrounding areas from an ecological point of view.

Fig. 3: Results of the model of GWR residual values, where positive values represent higher expected values of landscape connectivity (dependent value) and negative values represent lower expected values of landscape connectivity in spatial form
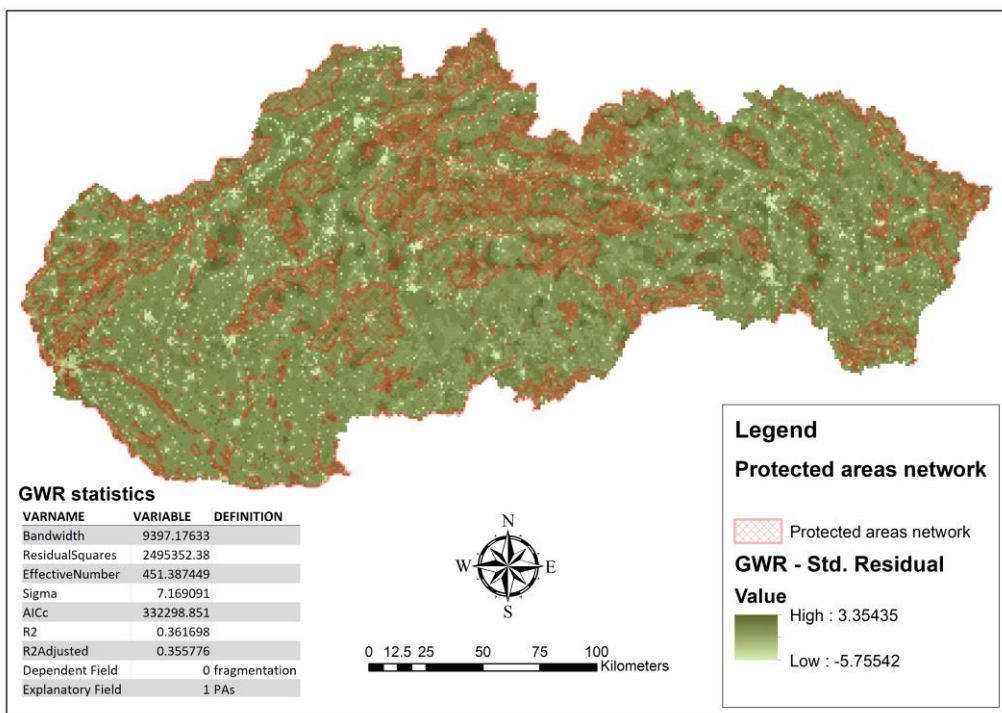
The comparison of all PAs with each other results in 1,132 resultant assessments. The resulting data contains an assessment of the overall LF level in %, the average, and the total assessment of each PA individually. When comparing all PAs, large-scale sites logically dominated among the others when not only quality but also the size of the PAs was taken into account. In NPs and PLAs there are 44,629,971 grids (substantial size) and high-quality of landscape connectivity (mean 61.19 %) present. The 5 best PAs providing the best overall connectivity (taking into account the total area of protected area) are SPA Volovské vrchy, SPA Nízke Tatry, SPA Laborecká vrchovina, PLA Štiavnické vrchy and buffer zone of NP Nízke Tatry. On the other hand, when purely quality was assessed the small-scale PAs dominated, especially the category of NR. Without taking the acreage of PA the best values of landscape connectivity were reached in NR Mláčik, SCI SKUEV0186, SCI SKUEV0384, NR Klenovské blatá, NR Debšín.

Generally, there is a substantially more unfragmented landscape inside of the network of PAs in comparison to the area, which is not protected (Figure 4).

Fig. 4: Relationship of LF and PAs network
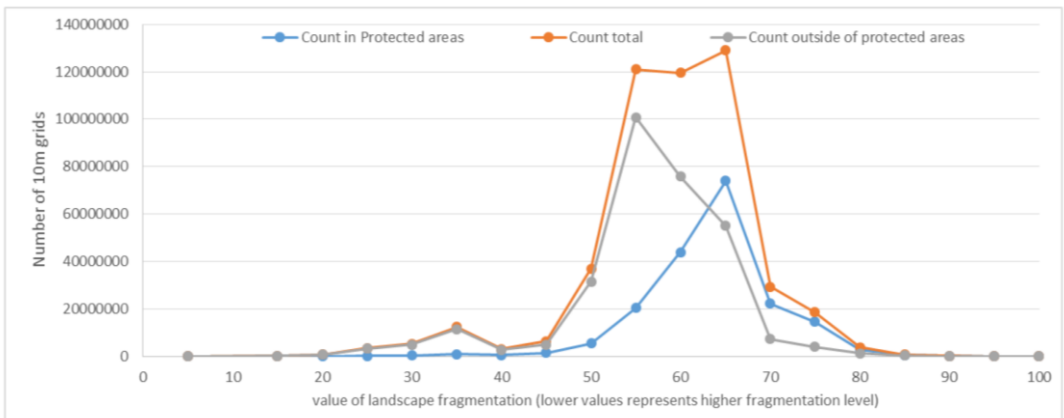
All categories of PAs scored higher than the unprotected part of Slovakia (Table 2). The analysis also reveals that on average also unprotected part plays a significant role in maintaining the landscape connectivity, however it varies a lot in each region.

Table 2: Overview of the level of LF in PAs network by PA categories

PA category	COUNT of GRIDs	The minimum value (%)	The maximum value (%)	Mean values (%)
Biosphere Reserves	3,160,283	15	75	60.83
Large-scale protected areas	44,629,971	20	85	61.19
Natura 2000 – SCIs	3,707,835	15	95	59.97
Natura 2000 – SPAs	130,893,532	20	100	61
Ramsar Sites	808,641	20	70	57.21
Small-scale protected areas	3,624,845	15	85	58.73
Unprotected areas	303,232,907	15	95	56.42

Identification of the important unprotected parts of valuable unfragmented areas in Slovakia

An important part of our results is the identification of specific valuable unfragmented areas that possibly require strengthened protection as some of those are actually unprotected. The overall average value of landscape connectivity of unprotected parts is still rather high (56.42 %) and it shows that there are still significant areas existing, which are situated in unprotected parts of the country. Spatial analysis revealed, that these important parts are covering 93,065 hectares, and are variously spread across the whole of Slovakia (Figure 5). The average value for these newly identified areas is 68.5 %.

Fig. 5: Areas not listed in any protection category important for landscape connectivity (red)
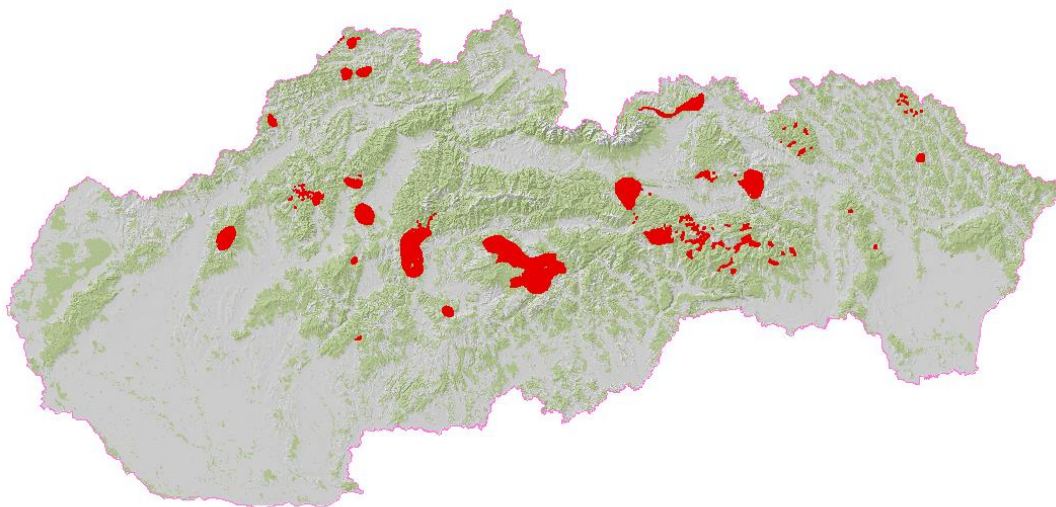

DISCUSSION

Assessment of LF in Slovakia by using various data has also been carried out in the past, but on a broader and less detailed scale (Miklós *et al.*, 2019). Legislatively implemented TSES in Slovakia is one of the important sources dealing with the connectivity of the landscape, however, it misses the necessary national electronic spatial data set and does not focus purely on LF. The majority of the national territory in local TSES does not have an electronic version yet, although there are steps taken to digitalize the paper maps and non-digital content. Overall progress in process of digitalization is rather slow and there are only a few districts available in electronic spatial form so far. Additional problem of the TSES is the quality of outputs, where various experts working on individual districts often use the non-streamlined approach in the assessment and the general outputs vary a lot. All these facts are rather limiting in the possibility of the use of this data set for the recent national LF assessment. Mentioned gaps provide an opportunity to use a new innovative approach by using different kinds of data sets, which was also the case in our research.

Electronic spatial national streamlined data set is crucial for the preparation of appropriate LF assessment.

Fig. 6: Comparison of precision of outputs in various LF research studies; 1. Results of our research in the Banská Bystrica region (central Slovakia); 2. Results of assessment on European level performed by EEA (2011) in Banská Bystrica region (central Slovakia); 3. Results of assessment performed by Slovak Environmental Agency (2016)
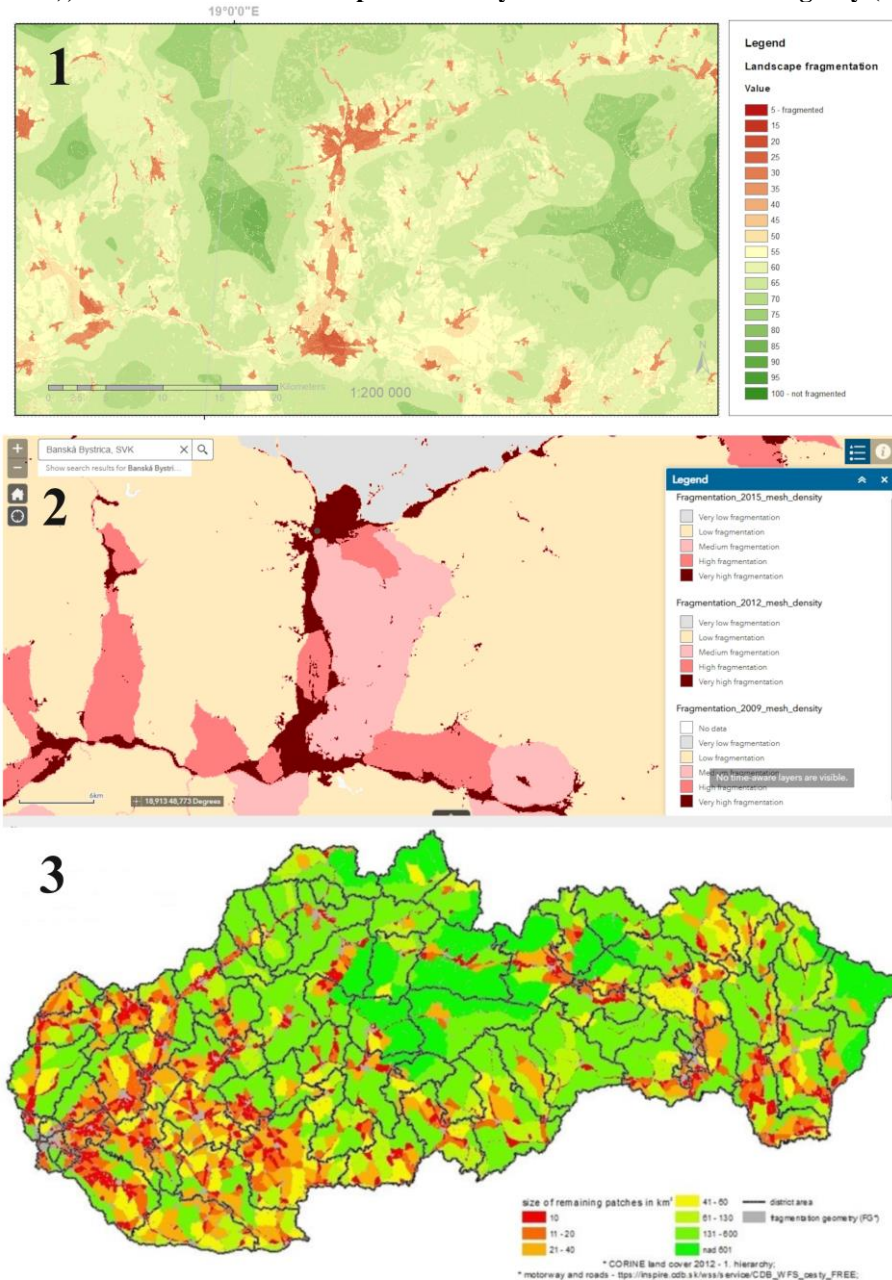
Another important assessment on the European level was performed by the EEA (2011), which covers also the territory of Slovakia. This assessment was a few times updated and it used the new version of the Effective Mesh Density 2016 dataset with improved input data, specifically for the years 2009, 2012, and 2015. This dataset is based on the Copernicus Imperviousness and the TomTom TeleAtlas data sets as fragmenting geometries. CLC data set was the baseline and therefore the outputs are less precise in comparison to our research, where the more detailed map of the ecosystem was used as a baseline. CLC data set generally does not sufficiently cover small-scale important connectivity features as the polygon in the data set is not allowed to cover less than 25 ha. A similar approach of assessment was performed in 2016 by Slovak Environmental Agency by using Effective Mesh Density, however, the outputs also use purely the Corine Land Cover data set as a baseline and the final outputs are generalized on the district level, thus the outputs miss the overall precision, especially on a local level. A comparison of the precision of outputs in our research and other mentioned research studies is presented in Figure 6.

Based on the comparison to other research studies we assume that recent spatial data, their combination, and interpretation provided valuable input for our research, from which it was possible to identify key landscape connectivity areas in a more precise way than ever before.

Another important aspect, which is barely considered in other methodologies for measuring LF is the cumulative effect. While the identification of coverage/length of urban areas/roads defined by a certain index or by acreage is the most important parameter, also the cumulative effect of fragmentation in specific areas should be considered as well. The areas which possess important connectivity features close to each other create important clusters of interconnected natural/semi-natural features and are more beneficial in the overall aspect. The same rule applies for the LF, where not only the area of fragmentation is important, but also the spatial pattern of accumulated fragmentation features and their distance from each other plays an important role. For measurement of this cumulative effect is the GIS Kernel density very viable as it has implemented weighting of features by density and assesses not only the acreage of features but also the accumulation of similar features in a particular area. This is one of the main reasons why we decided to use this particular method of measurement over the other existing methods. There are existing research studies, which use Kernel density in partial identification of LF i.e. to assess the spatial pattern of road density and its impact on landscape fragmentation (Cai *et al.*, 2013). In this research, the authors state that previous studies have shown that road density, estimated by grid computing, has a weak correlation with LF (i.e. by using FRAGSTATs). Therefore instead of grid computation, they prefer to use the Kernel density tool and by using it the regional spatial pattern of road density and the prediction of the impact of the road on LF could be effectively acquired. From this research is also evident that for effective identification of the LF not only the length of the road network is important, but also the density of the road network has a significant impact on LF. In our research, we applied a similar approach, not only for the road network but for all landscape types/fragmentation features in order to assess the LF/connectivity comprehensively.

We expect the potential use of our results in many practical applications. Obtained results can help to identify the main priorities for improving PAs connectivity at the national or regional level (Saura *et al.*, 2018; Castillo *et al.*, 2020). The positive aspect of the approach used in this research is its repeatability over time using data that are continuously collected and updated at the national level. The assumption is that the data sources used will continue to be available in the future. The research can be further processed and enriched with additional data sets. Fragmentation itself can be an indicator, e.g. in the USA was included in 2002 among the ten key indicators for assessing the state of national ecosystems.

For improvement of the research in the future, it would be beneficial to search for additional explanatory variables which are significantly affecting the LF level. Our recent GWR model works well in some regions, however not ideally on a national level as such. More explanatory valuables could improve the overall r2 values in GWR in the future.

Implementing measures

Many parts of Slovakia, which provide significant space, continuous and large-scale key areas do not have sufficiently secured protection against further fragmentation. One of the solutions for the improvement of this situation is the creation of a new category of protected areas or the use of existing ones to strengthen the protection. This step is necessary to ensure adequate protection of the continuous unfragmented landscape. Natura 2000 guidelines and implementation of protected areas network seeks to link the various elements, the national system of ecological stability as well, but still insufficiently. For meaningful nature protection, areas need to be truly interconnected, not just close to each other. It is necessary to start with the existing connectivity possibilities to prioritize and interconnect these elements with the protection status and implement practical measures to improve the current situation. In the case of the southern part of Slovakia, it is necessary to preserve all existing PAs and try to connect them by elements of the green/blue infrastructure, which are currently, but insufficiently, present only in some parts of the watercourses, including floodplains. Significant space for landscape connectivity is also provided by some parts of Slovakia, which are not protected by any category of protected area (Figure 5). These areas should receive adequate legal protection.

A separate problem in terms of the country's connectivity is the Danube and East Slovak lowlands. These areas need to be addressed as a matter of priority in terms of a significant lack of green infrastructure. In these areas, the improvement of the current situation is as necessary as changing the uniform management of the landscape in large areas into a mosaic landscape structure with a richer and more diverse occurrence of newly established ecosystems on arable land. The newly created areas would thus ensure not only improved conditions for better connectivity but also greater ecological resistance and resilience of the area and an increase in the value of the provided regulatory and cultural ecosystem services.

The actually established system of levels of protection (1–5) in Slovakia does not adequately reflect the present state of LF. There is a need to reconsider the spatial distribution of levels and review the actual state. Nature protection bodies should propose new spatial distribution of levels of protection for better reflection of actually assessed LF.

CONCLUSIONS

This research provides an alternative overview of the value of PAs, their benefits and quality, the importance of their existence, and the need to strengthen protection in terms of landscape connectivity. It is evident that PAs are one of the most important tools for the current protection against further LF. A complementary benefit of this research is the identification of important locations of large-scale interconnected unfragmented areas of Slovakia, which are still unprotected. These areas are important for maintaining additional landscape connectivity in Slovakia. Each PA has been evaluated from a national perspective with individually calculated data. The results can be used in process of preparation of national strategies, action plans, spatial planning, environmental impact assessments, and many other purposes. Nature conservation could use this material for expert assessments and the preparation of management plans for PAs and for proposals improving/introducing protection of newly identified valuable areas of landscape connectivity. Processed data

present the value and contribution of many already existing PAs, which have been recently underestimated in this field for various reasons. Despite human interventions and degradation of ecosystems, there are parts of the underrated territory, which are crucial in respect of the preservation of landscape connectivity. The added value of the research is to provide an adequate basis for the creation of a real network of interconnected natural and semi-natural large-scale areas in Slovakia. Identified degraded areas can be possibly used as a tool for defragmentation of landscape in future processes dedicated to the strengthening of ecological connectivity in Slovakia.

HIGHLIGHTS

• Conservation Strategies: The research, analyzing 490,321,151 individual 10 m raster grids, confirms the effectiveness of protected areas in mitigating landscape fragmentation, providing crucial insights for conservation strategies globally.

• Biodiversity Preservation: With an average landscape fragmentation (LF) value of 59.12 %, the study underscores the importance of protected areas in preserving biodiversity and enhancing ecosystem resilience on an international scale.

• Climate Change Mitigation: Understanding landscape fragmentation, with most territories falling within the range of 55-65 % LF values, aids in developing effective strategies for climate change mitigation, emphasizing the significance of intact and connected landscapes globally.

• Policy Development: Based on Ordinary Least Square (OLS) statistics, the research emphasizes the need for expanding protected area networks, highlighting the importance of informed land-use policies and conservation priorities internationally.

• Scientific Knowledge Exchange: By sharing methodologies and outcomes, the research promotes knowledge exchange and collaboration within the global scientific community, advancing our understanding of landscape dynamics and conservation strategies worldwide.

AUTHOR CONTRIBUTIONS

Conceptualization, J.Č.; methodology, J.Č.; software, J.Č.; validation, J.Č.; formal analysis, V.Ď. and J.Š.; investigation, J.Č.; resources, J.Č.; data curation, J.Č., J.Š. and V.Ď.; writing—original draft preparation, J.Č., J.Š and V.Ď..; writing—review and editing, J.Š.; visualization, J.Č.; supervision, J.Č.; project administration, J.Č.; funding acquisition, J.Č. All authors have read and agreed to the published version of the manuscript.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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