Ekológia (Bratislava) - Journal of the Institute of Landscape Ecology, Slovak Academy of Sciences Vol. 43, No. 2, p. 183–191, 2024
DOI:10.2478/eko-2024-0019

GLOBAL MEGATRENDS IMPACTS ON THE LANDSCAPE, ANALYSIS BASED ON KEY DRIVERS OF THE MEGATRENDS AND LANDSCAPE CHANGE: CASE STUDY OF DANUBIAN LOWLAND, SLOVAKIA

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Received: 7 May 2024 / **Accepted:** 14 July 2024

Abstract

Raniak A., Izakovičová Z.: Global megatrends impacts on the landscape, analysis based on key drivers of the megatrends and landscape change: case study of Danubian lowland, Slovakia. Ekológia (Bratislava). Vol. 43, No. 2, p. 183–191, 2024.

Global megatrends (GMTs) reshape landscapes worldwide, posing challenges for sustainability. This study delves into the complex interplay between GMTs and landscape changes in the Danube Lowland region of Slovakia, a microcosm of broader trends. Leveraging the concept of representative potential geoecosystems (REPGES), we assess historical landscape transformations and correlate them with key GMT drivers. Results reveal significant urban expansion linked to GMT2, primarily impacting the Bratislava area. Simultaneously, GMT5-driven economic growth manifests in agricultural land expansion and the total loss of one REPGES type. Notably, these changes coincide with a decrease in ecological stability across the region. Spatial analysis further unravels the interplay of GMTs, highlighting areas under intense urban and agricultural pressure. Our findings not only shed light on specific GMT impacts in the Danube Lowland but also offer valuable insights for landscape management across diverse regions facing similar megatrends. By understanding these complex interactions, we can develop informed strategies to navigate the challenges and opportunities presented by a globalized world, promoting sustainable landscapes for the future.

Key words: landcover, landscape change, representative potential geoecosystems, global megatrends, Getis-Ord Gi*, landscape ecology.

Introduction

The state of globalization of our civilization bounds European countries with links that allow constant two-way flow of materials, energy, finances, and information and the resilience and stability of countries will be significantly affected in the upcoming decades by various global megatrends (GMTs) (Ayomitunde et al., 2020; European Environment Agency, 2015a). In the 2015 report, the European Environment Agency (2015a) identified 11 GMTs, which are thematically divided into five clusters: *social, technological, economic, environmental, and a cluster of governance and diversifying approaches to governance*. These trends were subsequently evaluated at the global level in The European environment—state and outlook 2015, the basis of which was the determination of the basic driving forces of individual GMTs and the definition of trends. Based on these findings, implications for Europe were drawn up, including impacts on the economy, the environment and the social sphere.

Thematic diversity and extensiveness are difficult obstacles to the assessment of GMT impacts. This fact led to studies focused on GMTs to often examine their impact on specific, narrowly specified areas, such as their impact on the spread of microscopic fungi in the Pannonian biogeographic region (Magyar et al., 2022), development of food security for populations (King et al., 2017), or natural resources and ecosystems (Dmitrieva, Kliems, 2010; Izakovičová et al., 2022b). Evaluating the impacts of GMTs on the landscape level, which is a complex system because it requires an interdisciplinary approach, is all the more difficult. Lorenz and Haraldsson (2014) assessed the impact of GMTs on selected aspects of the country at the regional and local level using qualitative models, with the aim of predicting the future development of GMTs. A different approach to assessing the impact of megatrends on the country was brought by Day et al. (2014), where based on already available studies from individual sectors, he made an overview study that focused on trends in the USA regarding climate change, energy shortages, the development of the provision of ecosystem services, the economy, agriculture, food, and the development of settlement patterns and population distribution. There is also an overall evaluation of GMTs in Slovakia carried out in the study by Lubyová and Filčák (2016). This evaluation was carried out analytically for each GMT. However, it is emphasized that these megatrends are interrelated, and their impacts are usually the product of multiple megatrends. Hence, there is a strong suggestion for the avoidance of isolated analysis of individual megatrends (Retief et al., 2016). The purpose of this paper is therefore to approach these issues with a focus on the fundamental driving forces behind these trends, and consider their impact on the landscape in an interrelated nexus of individual GMTs and their spatial characteristics. Also, it tries to bridge the gap of knowledge in the holistic landscape ecology approach in GMTs assessments.

Material and methods

We based our assessment of GMT's impact on the landscape, on drivers behind the changes that can be detected in the landscape, as well as the key drivers of GMTs. The drivers behind the landscape change were identified based on the representative potential geoecosystems (REPGES) that have been changed and the current land cover as a final product of these changes. The land cover data of the area were mapped in 2018 and had been further updated in 2020 and 2021 (ESRI, 2011).

The REPGES are complex landscape units that represent what geoecosystems would be present if there was no human interference in a landscape. These landscape units are specified by the zonal (altitudinal zonation of vegetation) and azonal landscape characteristics (geological background, soils, hydrological conditions, etc.). There were 120 types of REPGES identified in Slovakia (Miklós, Izakovičová et al., 2006).

The current state of the identified REPGES types was assessed by calculating the area of each REPGES that is still present in the landscape today and the state of nature protection on these preserved parts of each REPGES type. For this step, the following forms of natural protection currently present in the study area were taken into consideration: protected landscape areas, national parks, national nature reserves, nature reserves, national nature monuments, nature monuments, protected sites, and Natura 2000 areas.

These changes are complex and difficult to assess at the regional scale. Therefore, we used the hot spot identifying statistical method Getis-Ord Gi* to identify statistically significant changes by their spatial association. A simple form of the Gi* statistical method is

$$G_i* = \frac{\sum_{j=1}^{n} w_{ij} x_j}{\sum_{j=1}^{n} x_j} , \qquad (1)$$

where G_i*is the statistic that describes the spatial dependency of incident *i* over all *n* events, x_j is the magnitude of variable *x* at incident location *j* over all *n* (*j* may equal *i*), and w_{ij} is the weight value between event *i* and *j* representing their spatial interrelationship. This statistical approach allows the identification of clusters of temporal changes with the effect on the landscape and streamlines the process of evaluation of landscape change (Getis, Ord, 1992).

Significance was achieved by weighting the polygons of change in two ways, capturing both high-risk areas and milder decreases of ecological stability happening on large areas. Polygons that show the highest decrease in ecological stability were identified by setting the weight of change in indices of ecological stability based on the difference between REPGES and current land cover. Changes with a lower decrease of ecological stability with significant area span were identified by using their area as a weight for the statistical analysis, and their self-potential was set to be the decrease of ecological stability indices. The ecological stability indices were assigned based on Miklós (1996), which uses a simple integer scale based on land cover units. Detected areas of significant land cover changes were then individually examined, and the drivers of these changes were assessed. Based on these data, we were able to compare these key drivers to the key drivers of GMTs. The drivers of GMTs were identified in a technical report carried out by the European Environment Agency (2015b).

On top of these data, we analyzed the elements of the landscape with negative environmental presence to further understand the spatial relations in the region and the presence of potential GMT impacts (mainly the environmental cluster trends). These aspects consisted of spatial data about photovoltaic power plants, hydropower plants, environmental burdens (current, sanitized, and potential), biogas plants, waste incinerators, other small stationary sources of air pollution, sources of water pollution, sewage treatment sites, urbanization, intensive agriculture areas, road infrastructure, railroad infrastructure, electrical infrastructure, gas pipelines, and crude oil pipelines. These data were then supplemented by data on river water and air pollution, data available at national departmental databases, and land cover data (Lieskovská, Lényiová, 2023; SAŽP, 2022; SHMÚ, 2023). The above mentioned negative impacts were then analyzed based on their spatial characteristics to create a kernel density heatmap, which helped better understand the spatial distribution of the environmental pressures.

Key drivers of GMTs

These drivers allowed us to make the connection between the landscape changes and the theory of GMTs. The GMTs, being the general trends with multiple drivers behind them, do not manifest completely in isolation. Their synergies and relations can also be seen through the shared drivers. The commonly shared key drivers between almost all GMTs are economic growth and population trends (European Environment Agency, 2015b) (Table 1).

The specification of the main drivers behind changes in the study area was carried out by an expert assessment in the form of a discussion. Based on the consensus of experts in the area, basic relevant drivers were identified, which had a significant impact on the use of the land and, consequently, on the quality of the components of the environment. However, the high interconnectivity of key drivers of the GMTs (Fig. 1) based on the shared key drivers causes difficulty in finding the impacts of individual GMTs. Shared drivers show that GMTs can manifest their impacts in synergy and, therefore, their evaluation shouldalways consider these relations. Also, there is a visible higher interconnectivity of the megatrends of the environmental cluster.

Study area

The study area is located in the southwestern part of Slovakia – Danube Plain (Fig. 2) and spans between the cities of Bratislava and Gabčíkovo, following the Danube River and the national border. The total area of the territory is 46132.5 ha. Its northern part, where Bratislava city is situated, has a prevalent urban character. The rest of the study area is significantly more agricultural with smaller rural municipalities (Fig. 2). Being a sub-basin of the Danube River, which includes urban, rural, and natural environments, it forms a naturalsocio-economic complex typical

Table 1. Key drivers of GMTs (European Environment Agency, 2015b).

GMT	Key drivers
GMT1 – diverging global population trends	Economic growth, fertility trends, mortality trends, education levels, human health, and climate change
GMT2– towards a more urban world	Population trends, economic growth, industrialization, globalization, and employment opportunities
GMT3– changing disease burdens and risks of pandemics	Population trends, economic growth, consumption patterns, life expectancy, technological innovation, and environment and climate change
GMT4– accelerating technological change	Population trends, economic growth, education levels, urbanization, information and communication technologies, and research and development
GMT5– continued economic growth	Population trends, labor availability, education levels, technological innovations, market globalization, and consumption patterns
GMT6– an increasingly multipolar world	Population trends, economic growth, structural economic change, foreign direct investment, trade liberalization, education levels, and international cooperation
GMT7 – intensified global competition for resources	Population trends, economic growth, consumption patterns, structural economic change, technological innovation, and international cooperation
GMT8– growing pressures on ecosystems	Population trends, economic growth, climate change, urbanization, bioenergy demand, and consumption patterns
GMT9– increasingly severe consequences of climate change	Population trends, economic growth, fossil fuel combustion, deforestation, technological innovation, international cooperation, and consumption patterns
GMT10–increasing environmental pollution	Population trends, economic growth, consumption patterns, fossil fuel combustion, agricultural practices, and chemicals
GMT11– diversifying approaches to governance	Population trends, economic growth, globalization, social innovation, and information and communication technology

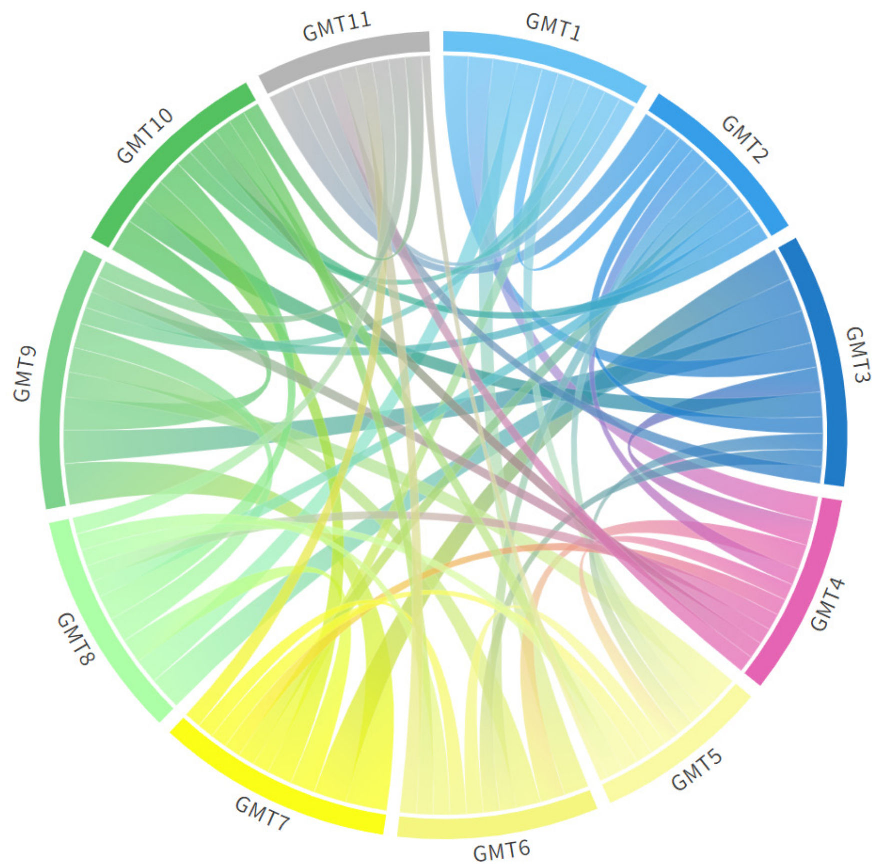

Fig. 1. Chord diagram of interconnectivity of GMTs based on their shared key drivers.

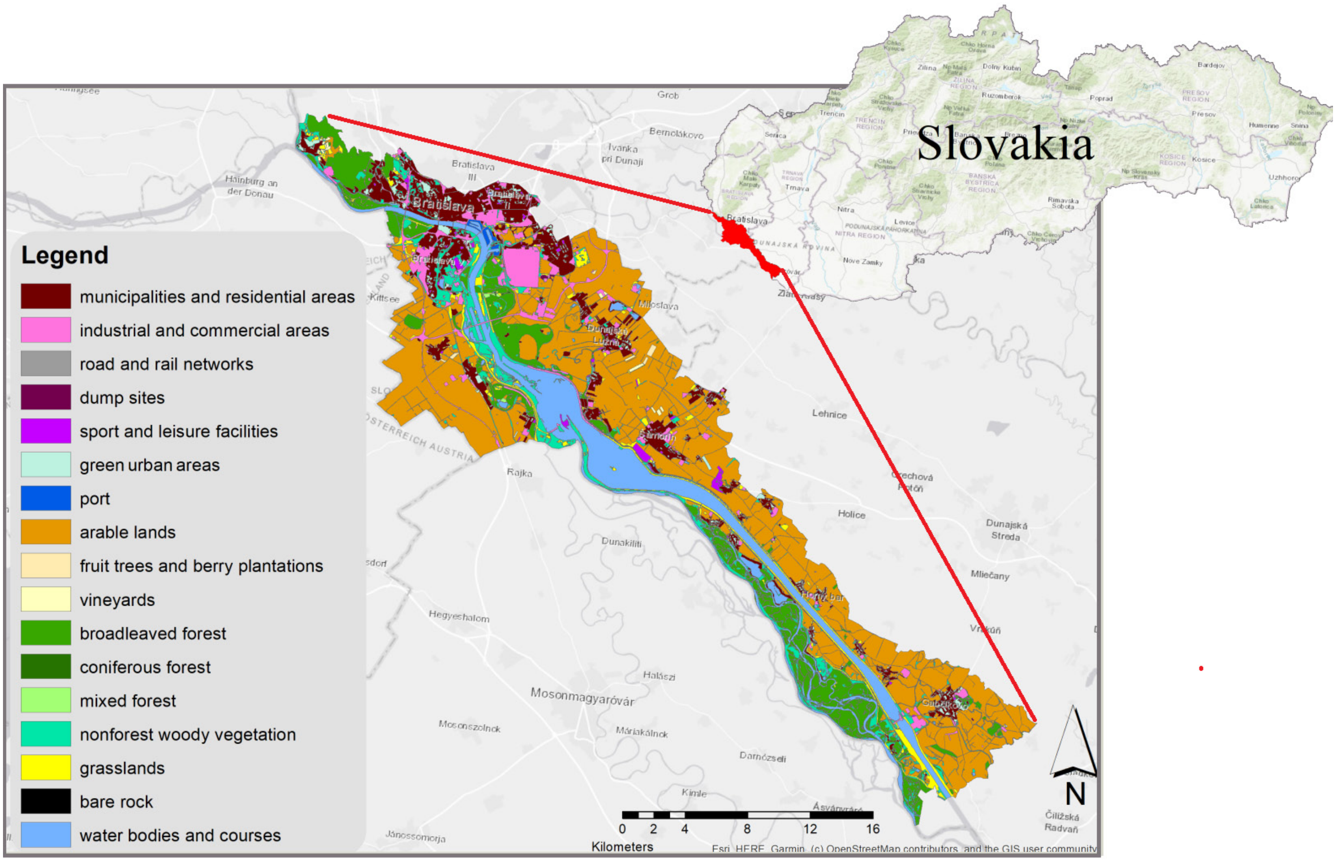

Fig. 2. Study areaand its current (2021) land cover.

for Slovakian lowlands,therefore providing a better understanding of GMT's impacts on these agricultural pillars of Slovakia, which are already facing global challenges concerning their sustainability(Bartošová, Buday, 2013).

Results

There were 10 types of REPGES present in the study area (Table 2), of which the *REPGES riparian forests on river floodplains in lowlands* and the *REPGES riparian forests on the rugged meandering plane* would cover the majority ofthe region of interest, following the Danube River from northwest to southeast.

We identified 4131 individual polygons of change from the REPGES baseline to the current land cover. The most changed were the *REPGES oak-hornbeam forests on river terraces or proluvial fan* that were eradicated completely and overtaken by the urban sprawl of Bratislava city and the adjacent commercial and industrial sites. There is a visible correlation shown between a higher percentage of preserved REPGES types and increased levels of natural protection, which suggests effective conservation of representative ecosystems (Table 2).

From these changes, 625 polygons showed the highest decrease in ecological stability, and their mean area was 11.29 ha per polygon. Areas with a medium decrease in ecological stability were identified at comparable 593 features; however, their mean area was 48.72 ha. This difference underlines our choice of two-way statistical analysis. The statistical hotspots weighted by ecological stability loss are correlated with urban areas and adjacent infrastructure, where there is a visible increase in significance in small municipalities closer to Bratislava city. The result of the statistically important decrease in ecological stability weighted by the area of change points mostly toward large-scale agricultural production land, artificial dam Gabčíkovo, and continuous built-up areas (centers of municipalities) (Fig.3).

The key drivers of these landscape changes were mainly population trends and economic growth, which are shared by the majority of the GMTs. Even though impacts of GMTs are the product of the synergy of multiple GMTs, the specific spatial distribution and type of landscape change help point to impacts of specific GMTs. *GMT2 towards a more urban world* impacts are significant in Bratislava city since it is the capital city of Slovakia; however, there is also significantly higher urbanization in adjacent municipalities, which might point to a potential trend of suburbanization of Bratislava city.

The economic cluster of GMTs had visible impacts on both statistical outcomes of land cover changes. Mainly, the GMT5 considers continuous economic growth, since the high decrease in ecological stability statistics shows areas of industrial zones adjacent to the city of Bratislava as well as such areas near other cities, even though these areas span only 6.03% of the region of interest. Furthermore, the second statistical approach reflects the agricultural aspect of this particular landscape. Agricultural ar-

Table 2. Types of REPGES identified in the study area and their respective areas.

REPGES	Area [ha]	Part of total area [%]	Area of preserved REPGES [ha]	Area of preserved REPGES currently with natural protection [ha]
Oak forests with *Quercus cerris* on plains	1958.575	4.25	21.348	0
Oak forests with *Quercus cerris* on river floodplains	2349.423	5.09	15.506	0.0853
Oak-hornbeam forests on polygenic Hügelland or broken pediments	19.683	0.04	8.218	8.218
Oak-hornbeam forests on river terraces or proluvial fan	620.687	1.35	0	0
Oak-hornbeam forests on jagged highlands on crystalline basement	1263.019	2.74	524.405	254.651
Oak forests on jagged highlands on Mesozoic rocks	387.183	0.84	198.431	151.661
Riparian forests on lowlands or depressions in foothill basins	1303.876	2.83	64.542	0
Riparian forests on river floodplains in lowlands	19925.539	43.19	795.029	110.827
Riparian forests on rugged meandering plane	17387.243	37.69	5675.196	4836.402
Alder moors forests on lowlands or depressions in foothill basins	917.267	1.99	71.547	1.795

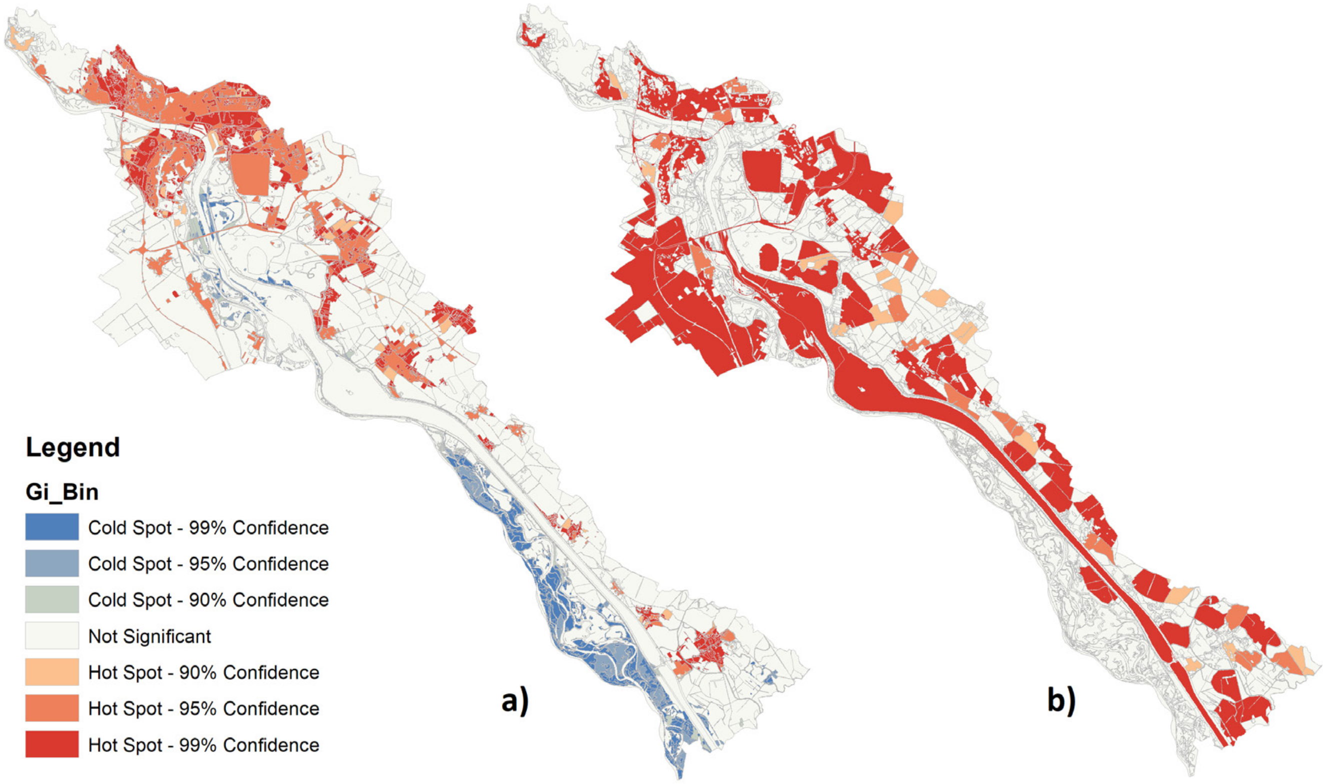

Fig. 3. Statistically significant hotspots of changes weighted by highest ecological stability loss (a) and by area of change connected to the loss of ecological stability (b).

eas make up to 42% of the entire area of the region of interest and are significant in the local economy, but statistically important are mainly the large-scale agricultural production zones (mainly arable land), which also have a slightly greater decrease in ecological stability compared to small-scale patches of arable lands. The large-scale land cover change that is quite specific for this region is the ar-

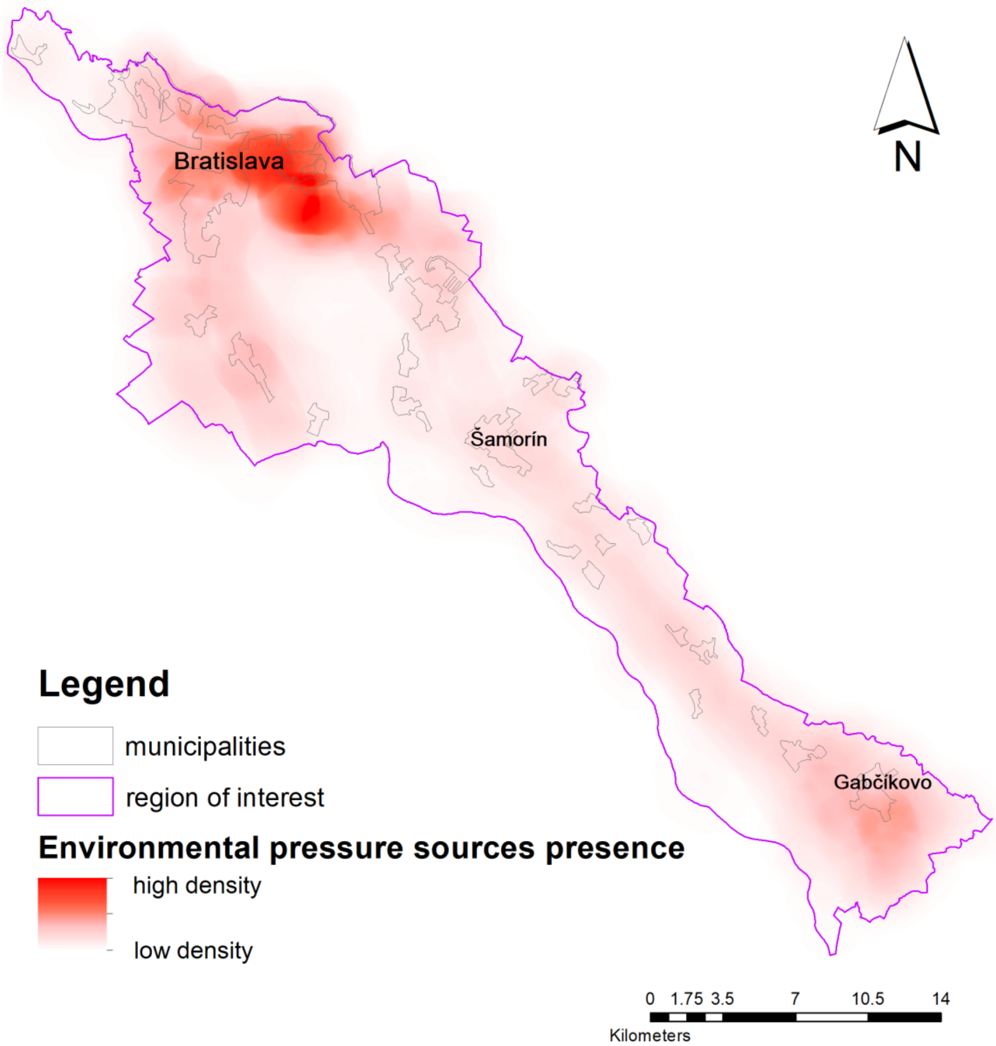

Fig. 4. Kernel density heatmap of environmental pressure sources.

tificial dam Gabčíkovo. This multipurpose project except the flood prevention ensures river navigability and production of electricity, which both lead to continuous economic growth of the region.

The interconnectivity of GMTs based on their key drivers reveals that GMTs of environmental clusters show a stronger connection with other GMTs, especially the *GMT9 – increasingly severe consequences of climate change* – which has the highest interconnectivity among the GMTs (Fig. 1). We can see that the decrease in ecological stability is present more in the northern part of the area, which is caused by the urban character of the landscape. This part of the study area also shows the highest density of anthropogenic environmental pressure (Fig. 4). The pressure source analysis heatmap shows the highest values of pressure source density in the area south of Bratislava city, exactly in the industrial area of a crude oil refinery. However, we can see that nearly the whole region of interest is under anthropogenic pressure since it underwent high levels of anthropization. This fact reflects the impacts of GMT8 – *growing pressures on ecosystems*, which is not only seen through the mentioned strong anthropogenic change of landscape but also through the comparison with REPGES. This comparison shows the intense loss of representative ecosystems.

Discussion

The long-term changes that manifested themselves in the country on the largest scale are agricultural activities, the expansion of which was initially caused mainly by population trends. The sudden change in their character was caused by the change of political regime after the Second World War. Collectivization resulted in a significant reduction of small-scale farming and a transition to intensive farming on large conglomerated areas of arable land, which are still in the country today (Izakovičová et al., 2022b; Kozelová et al., 2020; Bezák, Petrovič, 2006). Population trends are also closely linked to the growth of residential buildings and the associated new production areas, commercial buildings, and operations. The driving force of population trends works here with the synergy of the driving force of economic growth and the related patterns of resource consumption, which were significantly manifested in the post-transformation period.

GMT3 – Changing disease burdens and risks of pandemics – impacts were present on a global scale since the start of the COVID-19 pandemic; however, our methodology of long-term landscape changes did not clearly reflect its impact. Habib and Anik (2021) and Ramani and Bloom (2021) suggest that an increase in home office work supports moving working people further from the downtown area of the cities to suburban areas. Our results show slight suburbanization of Bratislava city, which is in line with the results of multiple papers on this subject (Šveda, 2011; Šveda et al., 2016); however, further research would be needed to see if this trend of suburbanization increased after the pandemic outburst.

The megatrends *GMT4 – Accelerating technological change* –and *GMT11 – Diversifying approaches to governance* –proved difficult to assess by our methodology since their impacts were not as straightforward as other GMTs. However, the important role these megatrends played in the landscape changes is heavily connected to the governance of the socialist regime and its abovementioned agriculture-intensifying efforts. This intensification of agriculture was also possible thanks to the state of accelerating technological advances in heavy machinery, which could effectively farm such large-scale arable lands (Izakovičová et al., 2022b).

In terms of a synthetic spatial assessment of the impacts of GMTs on the landscape and its components, three basic spatial units can be distinguished (Fig. 4) as follows:

- The northern part of the territory where the capital city of Bratislava is located. Here, we can see mainly the negative impacts of GMT related to the development of industrialization and urbanization after the Second World War when there was a rapid growth of industrial production, which gradually gained a leading position in the economic structure (Górka, Kušnírová, 2021). Several important industrial plants were built here, especially, chemical and food processing plants (e.g. Slovnaft, Matador, Figaro, Palma, and many of them intensified production –Dimitrovka, etc.). Mass industrial production was based on the unbearable exploitation of natural resources and energy. Many industrial plants placed an unreasonable burden on the environment, producing excessive amounts of emissions that contaminated the various components of the environment, depleting natural resources to an unacceptable degree, and deteriorating the overall quality of the environment (Barnovský, 2007). Insufficient attention has been paid to the assessment of environmental quality. Environmental quality has not been regularly monitored and evaluated, and much information on the state of the environment has not been made public and has remained a secret. The building of industrial enterprises was aimed only at economic profits and strengthening the economic aspect of the population's standard of living. Many new job opportunities were created, resulting in a gradual migration of the rural population to the cities and a consequent unbearable concentration of the population in the cities (Izakovičová et al., 2022a). Major changes occurred during the transition. The transition to a market economy led to the disappearance of many industrial plants, which in turn led to a decline in the production of pollutants. Slovakia's accession to the EU entailed obligations in the field of environmental legislation. Slovakia has adopted a number of EU-compatible environmental laws. New technologies were introduced, and ecological and environmental limits were applied, which reduced the intensity of the burden on individual landscape components. However, many negative impacts of old environmental burdens still remain in the territories.
- Gabčíkovo area located in the southern part of the study area, where in the 80s, a hydroelectric dam was built in order to protect the area from the high waters of the Danube. It alsoenabled virtually year-round ship access on the entire stretch of the Danube from Bratislava to Budapest, while ensuring a navigational depth of 3.5 m to exploit the energy potential of the Danube on the stretch Bratislava–Budapest and enabled the sports and recreational use of the adjacent territories. The Gabčíkovo–Nagymaros waterworks system was originally intended to be a waterworks system, but the Hungarian side eventually withdrew from the contract in 1989, and the waterworks were built only on the territory of the Slovak Republic. In addition to the implementation of technical objects, the construction was also associated with several negative impacts on natural resources and ecosystems,such as the loss of high quality soils, the loss of floodplain forests and wetlands, the change of the water regime of the territory, the disappearance of part of the Danube river arms, the disappearance of habitats, the impaired infiltration and self-cleaning capacity of the waters, and the pollution of the Danube watercourse (Oszlányi, 2001; Lisický et al., 1991; Šomšák, 1999).Theoperation of Gabčíkovo Waterworks on the Danube River in Slovakia has significantly impacted the localwater regime and ecosystems (Petrášová-Šibíková et al., 2017).
- The central part of the study area is represented by the rural agricultural landscape, which was mainly affected as a result ofcollectivization and normalization, when collectivization occurred, coupled with the confiscation of private farmers' property and the establishment of cooperatives. Collectivization was seen primarily as a political problem, with no regard for social, cultural, or psychological issues. Traditional forms of farming and traditional ways of rural life were being dismantled (Slavkovský, 2002). The creation of cooperatives started the process of land consolidation and gradually began the creation of a monofunctional agricultural landscape. Boundaries were ploughed up, and terraced fields, meadows, and pastures were liquidated. A similar process of "nationalization" was observed in forestry, where forest land began to change hands and the area of state-owned forests gradually increased. Intensive logging began, inappropriate forms of forest management were applied, threatening the naturalness and species composition of forest ecosystems, and poplar monocultures were planted intensively. The desire of socialist agriculture to continually increase per-hectare yields led to the establishment of new agricultural colossi, which were created by merging individual farms within given regions. With the division of labor and the modernization of cooperatives came new pressures on land take. The last remnants of woods, hedgerows, and permanent grassland were taken; swamps and ponds were drained; watercourses were restored; meanders, valuable wetlands, and riparian vegetation were destroyed; roadside avenues were cut down, etc. There has also been increas-

ing intensification of agricultural production. Hectare yields increased to three times what they were before the Second World War. The desire to achieve the highest possible yields per hectare led to a steady increase in chemicalization, and the modernization of production encouraged the growth of mechanization, which had significant negative effects on the landscape structure, such as manifestations of erosion processes, drying out and easing of the soil, contamination of environmental components, and so on. The development of housing in the countryside was also supported by cooperatives.On the one hand, they started to build cooperative housing for members of the single peasant cooperative, and on the other hand, they provided non-repayable financial loans for the construction of family houses. This started a building boom in rural communities. Construction of new houses and new streets took place, and the construction of cooperative housing blocks, atypical for the rural environment, began. The beautiful scenery of the rural environment began to be disturbed by inappropriately located and environmentally unsuitable uniformed houses. The rural spirit gradually disappeared from the countryside, and rural life took on more and more of the characteristics of urban life (Kristiánová, Adamková, 2010).

Another change came again after the Velvet Revolution. New residential districts are springing up in rural villages, entertainment centers, golf courses, ski slopes, and aqua parks are being built, but also uncoordinated production facilities and large-scale logistics centers, which not only puts a strain on the environment but also changes the traditional character of the countryside. The degree of anthropization of the territory is increasing. Natural ecosystems are being taken over for construction, and often, the best quality soils are also being taken over for the same reason.

Conclusion

In conclusion, our study revealed significant landscape changes in the region of interest, particularly the transformation of REPGES oak-hornbeam forests into urban sprawl in Bratislava city and adjacent areas. We observed a clear correlation between the preservation of REPGES types and increased levels of natural protection, indicating good practice regarding importance of conserving these ecosystems for whole system ecological stability. Our analysis identified polygons with the highest decrease in ecological stability, as expected, primarily located in urban areas and adjacent infrastructure, as well as large-scale agricultural production lands and the artificial dam Gabčíkovo.

The key drivers of these landscape changes were population trends and economic growth, which align with the majority of the identified GMTs. While the impacts of GMTs are complex and multifaceted, the specific spatial distribution and types of landscape change in our study area provided insights into the impacts of specific GMTs. The impacts of GMT2, "towards a more urban world," were particularly significant in Bratislava city and nearby municipalities, indicating a potential trend of suburbanization. Although the impacts of GMTs related to accelerating technological change (GMT4) and diversifying approaches to governance (GMT11) were challenging to assess directly, their role in landscape changes was evident. Technological advances and intensification of agriculture played a crucial role in shaping the landscape, facilitated by the socialist regime's governance and policies.

The spatial assessment of the impacts of GMTs highlighted three distinct areas: the northern part of the territory with negative impacts related to industrialization and urbanization, the Gabčíkovo area affected by the construction of a hydroelectric dam, and the central rural agricultural landscape transformed by collectivization and normalization processes.The dam's operation led to decreased soil moisture and increased nitrogen levels in areas out side the artificial supply system, resulting in the degradation of riparian flood plain forests. Each area exhibited specific landscape changes and environmental pressures. Our findings on the management of waterways and the overall landscape show the possibility of assessing such impacts on a regional landscape scale; however, they also emphasize the importance of understanding the interplay between GMTs and landscape changes for effective environmental management and planning. The results provide valuable insights for policymakers and stakeholders involved in sustainable land use planning, conservation efforts, and mitigation strategies to address the impacts of GMTs and promote ecological stability in the region of interest. Future research should focus on monitoring and assessing the long-term effects of these landscape changes and exploring potential mitigation measures to ensure the preservation of representative ecosystems and sustainable development in the study area.

Acknowledgements

The work was supported by the Integrated Infrastructure Operational Program (OPII)(ITMS2014+313011BVY7 Supporting the R&D activities of a unique research team.).

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