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SPATIAL ENTROPY CHANGES FOR BUILT-UP AREAS IN THE VICINITY OF KRAKÓW IN THE YEARS 2014–2020

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Summary

Information on landscape structure is an important issue for sustainable development and for making correct spatial planning decisions. Therefore, studies providing information on the diversity and changes of land cover and land use in a selected area are currently an important research topic. In addition to quantitative-qualitative statistics, spatial entropy is increasingly used to assess the degree of diversity of land cover and land use. This paper aim was to determine the diversity of objects within the land cover classes in the years 2014, 2017 and 2020, with a focus on built-up areas, in three districts bordering the city of Kraków, i.e. the Wieliczka, Kraków and Proszowice districts, located in the Małopolskie Voivodeship in Poland. In order to perform the analysis with the appropriate spatial resolution, a hex grid was used to determine the diversity of objects in the built-up area class. For this reason, data on land cover from the BDOT10k national database of topographic objects were used. The analyses followed the division into classes and objects defined in the structure of the BDOT10k database. The degree of diversity was determined using the Entropy Index and Herfindahl-Hirschman Index. Changes in the diversity of built-up areas were observed especially in areas located in close proximity to the border of Kraków, as well as on its eastern and south-eastern sides. A significant relationship was also observed between the increase in diversity of objects in the built-up area class and the immediate proximity of roads.

Keywords

built-up areas • BDOT10k • entropy • land cover • hexagons

1. Introduction

Changes in land cover and land use are currently among the most frequently discussed issues due to their significance for sustainable development, as well as for appropriate land management. The notion of land cover refers to the actual cover of land's area [Di Gregorio and Jansen 2000], while land use refers to the actual use of the Earth's surface by human or the condition of such surface caused by human activity [Bičík et al. 2015]. Land use includes, for instance, settlement, agricultural and industrial areas, while land cover will include the type and quality of vegetation, waters and minerals that occur on land's surface [Meyer et al. 1994]. However, in some cases an unambiguous distinction between classes of land cover and land use is not possible, and thus they are analysed together [Luc and Bielecka 2018].

Currently, the research on changes in land cover and land use in Poland most often uses two databases, i.e. CORINE Land Cover (CLC) and Topographic Objects Database (BDOT10k). The CLC database belongs to a sub-program of the CORINE program run by the European Environment Agency – EEA, to which Poland joined in 1993. The purpose of the CLC sub-program is to provide information on land cover and its changes on the territory of Europe at regular intervals. Under the CLC, land cover has been classified into 44 classes, which correspond to all types of cover that exist in Europe. On the other hand, the BDOT10k database is a vector database containing information on the spatial location of topographic objects, including their characteristics. The content and detail of the BDOT10k database corresponds to a topographic map in the scale 1: 10,000 and includes information contained in 10 categories of objects, including 58 classes, which are divided into 267 objects. Among the categories of the BDOT10k database there is the land cover (PT) category. The following 12 classes of objects have been distinguished under the land cover category: surface water (PTWP), buildings (PTZB), forests or wooded areas (PTLZ), shrub vegetation (PTRK), permanent land cultivation (PTUT), grasslands and agriculture (PTTR), communication areas (PTKM), unused land (PTGN), squares (PTPL), landfills (PTSO), excavation and dumping sites (PTWZ) and other undeveloped areas (PTNZ) [BDOT 2021]. The classes of the land cover category in the BDOT10k database were further divided into 31 distinct objects. Thus, the structure of BDOT10k database comprises three levels of detail, i.e. categories – 1st level of detail, classes – 2nd level of detail, and objects – 3rd level of detail. Therefore, it can be noted that, in accordance with the commonly accepted definitions of land cover and land use, the land cover category identified in the BDOT10k database also includes classes that should be qualified as land use. Thus, in the further part of the paper, the nomenclature is adopted in accordance with the names in the BDOT10k database, i.e. land cover (PT). A similar situation occurs within the CLC database, where land cover classes predominate in the nomenclature, but classes representing a type of land use have also been distinguished [Bielecka and Ciołkosz 2008, Mierzwiak and Całka 2019]. It is also worth noticing that the CLC is a European database, which makes it possible to study the changes in land cover and land use at both regional and local levels. In case of BDOT10k, which is a national database, only the changes in land cover and land use on the territory of Poland can be considered.

Land cover and land use databases provide information in the form of landscape representations for large areas, in which land cover and land use are described by surfaces of various sizes and shapes. Therefore, when analysing land cover and land use, it is necessary to consider the relations through geometrically standardised surface units, which allow for the assessment. For this purpose, a suitably selected surface grid is usually adopted. The most commonly used grids include the square grid [Feranec et al. 2000, 2010, Bagan and Yamagata 2014] due to its symmetry and ease of division into a lower resolution grid [Birch et al. 2007]. Besides the square grid, the hex grid is also becoming increasingly popular. The grid of hexagons makes it possible to cover an area without overlapping surfaces and gaps. Additionally, all adjacent cells are at the same distance from the centre of the hexagon, and the individual hexagons have a symmetrical topology, invariant surface, and can be recursively divided into smaller grids [Richards et al. 2000, Goldblatt et al. 2018]. The hex grid has been used, among others, for developing a method for mapping surfaces covered with vegetation [Molnár et al. 2007], studying the cover of built-up areas [Goldblatt et al. 2018], analysing the suburban landscapes [Cegielska et al. 2019], as well as in research on land use changes in protected areas [Terra et al. 2014]. Moreover, Shoman et al. [2019] recommends a hex grid to minimise surface errors for urban areas. In addition to grids of squares and hexagons, land cover and land use can also be analysed by dividing the area with buffer zones in relation to the boundaries of an agglomeration unit [Cegielska et al. 2017a] or ring-shaped polygons [Wnęk et al. 2019], where the changes in the land cover and land use are considered in relation to the motion from a central point, which may be an agglomeration centre, for example. In the case of urban areas, the role of the area in which land use changes are considered may also be played by the so-called Functional Urban Area (FUA) [Wnęk et al. 2021, Iváncsics and Kovács 2021, Micek et al. 2020].

Land cover and land use analyses are part of the landscape structure research. In this type of research, it is important to determine the diversity of the existing conditions in a given area, as well as the size, direction and rate of changes in land cover and land use. Due to the use of different land cover class divisions in different land cover and land use mapping projects, it becomes necessary to describe land cover diversity in a consistent way and reduced to a single value. For this reason, spatial entropy [Batty 1974], which can also be applied to measure the disorder of landscape structure, is an increasingly used method in land cover research [Cushman 2016, Zhang et al. 2020, Bitner and Fialkowski 2021]. The use of spatial entropy is especially useful for urban and suburban areas, as it makes it possible to assess the urban growth [Deka et al. 2011, Rahman 2016, Fenta et al. 2017] and the transformation of suburban areas [Cegielska et al. 2019].

The aim of this paper is to determine the degree of land cover diversity, with particular emphasis on built-up areas in the Wieliczka, Kraków and Proszowice districts, located in Poland in the Małopolskie Voivodeship, in 2014, 2017 and 2020. The research was carried out on two spatial levels, i.e. with regard to the area of an entire district, as well as the division of the districts' area into a hex grid, which enabled the assessment. These counties were selected due to their direct border with the city of Kraków. The research used data on the land cover category from the BDOT10k database at two levels of detail, i.e. for classes (2^{nd} level of detail) and objects (3^{rd} level of detail). The degree of diversity of land cover and land use was determined on the basis of the Entropy Index and the Herfindahl – Hirschman Index for all land cover classes and objects as well as separately for the buildings class (PTZB).

2. Materials and methods

The research covered three districts located in the Małopolskie Voivodeship and in immediate proximity of the city of Kraków, i.e. the Wieliczka district (TERYT 1219), the Kraków district (TERYT 1206) and the Proszowice district (TERYT 1214), which due to their location can be understood as a functional area of the city of Kraków. The location of the research area in relation to the city of Kraków and administrative borders is presented in Figure 1.

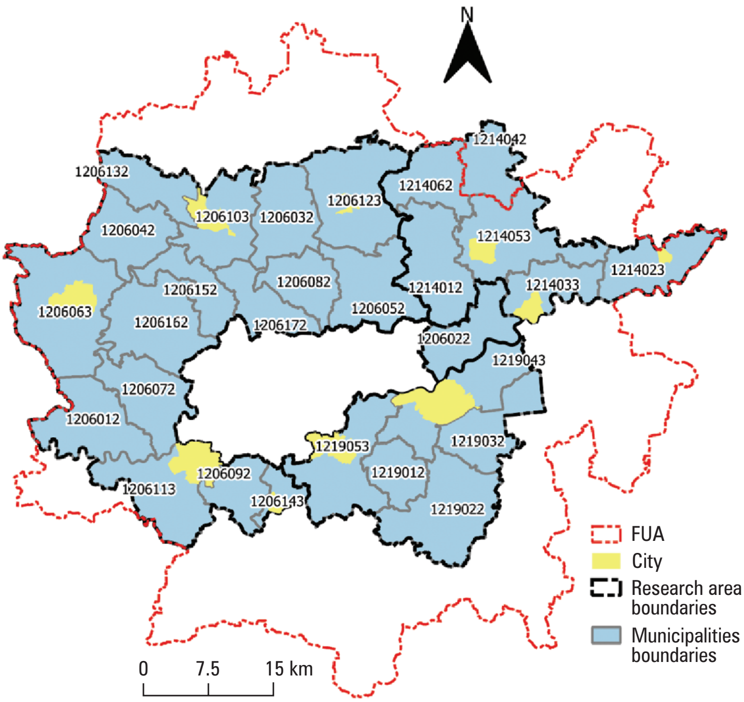

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Fig. 1. Location of districts, municipalities and towns in the research area

The Wieliczka district consists of 5 municipalities, including 3 rural municipalities: Biskupice (1219012), Kłaj (1219032) and Gdów (1219022) and 2 urban-rural municipalities: Wieliczka (1,219,053) and Niepołomice (1,219,043), while the Proszowice districts consists of 3 rural municipalities: Koniusza (1,214,012), Pałecznica (1,214,042), Radziemice (1,214,062) and 3 urban-rural municipalities: Koszyce (1,212,023), Nowe Brzesko (1,214,033) and Proszowice (1,214,053). The Kraków district consists of urban-rural municipalities: Krzeszowice (1206063), Skała (1206103), Skawina (1206113), Słomniki (1206123), Świątniki Górne (1206143), and rural municipalities: Czernichów (1206012), Igołomia-Wawrzeńczyce (1206022), Iwanowice (1206032), Jerzmanowice-

Przeginia (1206042), Kocmyrzów-Luborzyca (1206052), Liszki (1206072), Michałowice (1206082), Mogilany (1206092), Sułoszowa (1206132), Wielka Wieś (1206152), Zabierzów (1206162), Zielonki (1206172). There were 10 towns in the area of research, i.e. Koszyce, Nowe Brzesko, Proszowice, Niepołomice, Wieliczka, Krzeszowice, Skała, Skawina, Słomniki and Świątniki Górne. The area of the Kraków district is approx. 1,228.96 km^2, the Wieliczka district – 410.10 km^2, and the Proszowice district – 414.40 km^2. According to the definition of functional urban areas defined under the Urban Atlas [UA 2021] project, 100% of the area of the Kraków and Wieliczka districts belongs to the functional area of the city of Kraków, while in the case of the Proszowice district it is 88.33%.

The rural area of the Wieliczka municipality (33,913 inhabitants), located in the Wieliczka district, was one of the two most populated rural areas in Poland in 2014 [GUS 2021]. In 2017, the most densely populated rural areas in Poland were in the following municipalities: Świątniki Górne (Krakow district) and Wieliczka (Wieliczka district), respectively 467 and 406 people/km^2 [GUS 2021]. In 2014, there were 118,553 inhabitants in the Wieliczka district, 43,864 inhabitants in the Proszowice district, and 266,649 inhabitants in the Krakow district, thus the population density was 289 people/km^2, 106 people/km^2 and 217 people/km^2, respectively. However, in 2017, the Wieliczka district was inhabited by 123251 inhabitants, i.e. 300 people/km^2, in the Proszowice district there were 43648 inhabitants, i.e. 105 people/km^2, in the Kraków district – 272591 inhabitants, i.e. 222 people/km^2. As a result, the population of Wieliczka district increased by 3.96% between 2014 and 2017, in Kraków district by 2.23%, while in Proszowice district it decreased by 0.49%.

The research used the archival data of the BDOT10k database for the land cover category at the end of 2014, 2017 and 2020 provided by GUGiK at the government website [Geoportal 2021] for the area of the three districts under analysis. The analysis applied the division of the land cover categories (level 1 of the BEDOT10k database) into two levels of detail, i.e. 12 classes (level 2 of the BDOT10k database) and 31 objects (level 3 of the BDOT10k database). Spatial analyses were carried out with the use of the QGIS program.

For each of the analysed administrative units, the value of the Entropy Index (EI) was determined based on data on classes and objects of the land cover category for each of the adopted time moments, according to the formula [Song et al. 2013]:

$$EI = \frac{-\sum_{j=1}^{k} P^j \ln P^j}{\ln k} \tag{1}$$

where:

- k – the number of considered classes or objects of the land cover category in the BDOT10k database,
- j – class or object of the land cover category,
- p^j – the percentage share of the area of a given class or object of the land cover category in the analysed area.

The EI can take values between 0 and 1, low EI values indicate that there is little variety of classes or objects of land cover occurring in the analysed area, while high EI values indicate that there is high diversity of classes or objects of land cover, and their surfaces are essential. The applied EI is an adaptation of the Shannon entropy for land use and land cover. The determination of EI made it possible to assess in general way the entropy value of the spatial share of classes and objects of land cover in areas of the districts and at selected times, as well as the changes in entropy of the system of classes and objects of built-up areas over time.

In order to confirm the obtained values of the EI, the value of the Herfindahl-Hirschman index (HHI) was also calculated for the studied administrative units in order to indicate whether one of the land covers does not have a monopoly feature in the analysed area, according to the following formula [Song et al. 2013]:

$$HHI = \sum_{j=1}^{k} \left(P^{j}\right)^{2} \tag{2}$$

where:

p^j – the percentage share of the area of a given class or object of the land cover category in the analysed area.

HHI determines the value of concentration, and thus monotonicity of land cover, and takes values from 0 to 10000, which in case of normalisation are from 0 to 1, where a value of 1 means that the analysed area is covered by only one type of land cover.

In order to proceed research with higher spatial resolution, the studied administrative units were covered with a regular hex grid with an area of 1 km^2 each. In this way, the EI can be applied to the hexagon surface, and its spatial variability in the district area can be studied.

The EI was also determined for objects separated within the buildings class (PTZB) in relation to the area of hexagons. In the case of the BDOT10k database, the built-up areas class includes 5 objects, and the minimum area of an object belonging to this class is 1000 m^2. Built-up areas have been divided into the following objects: multi-family housing (PTZB01), single-family housing (PTZB02), industrial and storage development (PTZB03), commercial and service development (PTZB04) and other buildings (PTZB05). Therefore, for the objects in the built-up areas class, the formula (1) has been transformed into the following form:

$$EI_{ZB} = \frac{-\sum_{i=1}^{m} P^{i} \ln P^{i}}{\ln m} \tag{3}$$

where:

m – number of objects in the built-up areas class in the land cover category of the BDOT10k database,

i – objects in the built-up areas class,

p^i – percentage share of given objects of the built-up area class in the total of the built-up areas class in the hexagon area.

3. Results and discussion

First, the research was focused on the second level of detail (PT02), i.e. it involved data from the BDOT10k database on land cover divided into 12 classes. The conducted research showed that in 2014 at this level of detail the Wieliczka district obtained the highest EI value, while the Proszowice district the smallest. Thus, it can be concluded that the Wieliczka district had the most diverse land cover, exceeding the Kraków and Proszowice districts in this regard (Table 1). These results repeated in 2017 and 2020. This is also confirmed by the analysis of the EI determined at the 3rd level of detail (PT03), i.e. with the division of the land cover classes of the BDOT10k database into 31 objects. The analysis of changes in the EI between individual years indicated that the entropy value at the PT02 level of the BDOT10k database increased between 2014 and 2020, which the most noticeable in the Proszowice and the Wieliczka districts, and the least in Kraków. However, a more detailed analysis at the PT03 level indicates a decrease in entropy between 2014 and 2020, which means there is a decrease or even that objects of some land cover classes distinguished at the PT03 level of the BDOT10k database in the studied area have disappeared.

Table 1. Changes in the EI determined for the analysed districts

District	BDOT10k detail level					
	PT02			PT03		
	2014	2017	2020	2014	2017	2020
Wieliczka	0,4548	0,4563	0,4605	0,5163	0,5168	0,5134
Kraków	0,3932	0,3930	0,3938	0,4529	0,4510	0,4508
Proszowice	0,1972	0,1973	0,2077	0,2680	0,2681	0,2604

Table 2. Changes in the HHI determined for the analysed districts

District	BDOT10k detail level					
	PT02			PT03		
	2014	2017	2020	2014	2017	2020
Wieliczka	0,4323	0,4308	0,4257	0,2346	0,2342	0,2364
Kraków	0,5165	0,5165	0,5156	0,3122	0,3163	0,3173
Proszowice	0,7938	0,7936	0,7822	0,6043	0,6042	0,6299

In 2014, the highest value of the HHI index for the analysis at the PT02 level of the BDOT10k database was recorded for the Proszowice district, and the lowest for the Wieliczka district (Table 2). The analysis of the HHI value showed that in the Proszowice district the selected classes of land cover categories significantly dominate others and that some classes of land cover are monopolised. This is confirmed in Noszczyk et al. [2017], whose research proved that agriculture dominates in the Proszowice district, covering up to 80–93.2% of its area. As to the Wieliczka district, there is a more balanced share of different land cover classes. This can be caused by urbanization around smaller towns, as observed by Noszczyk et al. [2017] for example in the town of Wieliczka on the basis of data from 2002–2015. It is also worth noting that the HHI value for the PT02 level has slightly decreased in 2020 for all districts, meaning there is a decrease in the share of the dominant land cover categories in the area of the analysed districts (Table 2). The HHI analysis at the PT03 level pointed to an increase in the share of the dominant objects of land cover classes over the years 2014–2020 in the area of considered districts, which is the most noticeable in the Proszowice and Wieliczka districts.

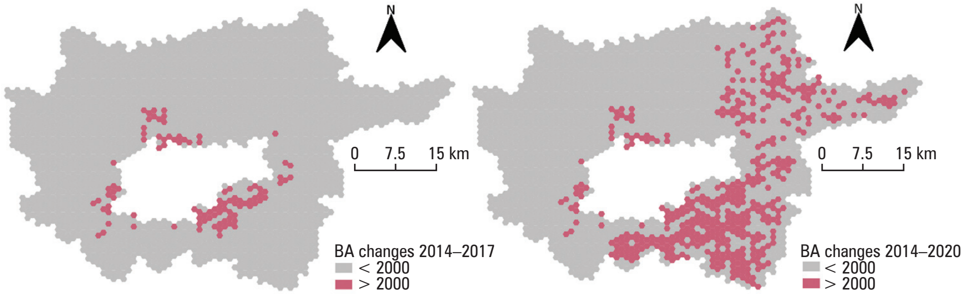
The EI calculated for the objects of the built-up areas class (level 3) indicates that in 2014 their highest diversity occurred in the Wieliczka district, followed by the Kraków district, with the least diversified built-up areas located in the Proszowice district (Table 3). When analysing the changes in the EI value, it can be noted that between 2014 and 2020 there was an increase in entropy for built-up areas in each of the analysed districts, with the highest growth in the Wieliczka district. Therefore, it can be concluded that in the period 2014–2020 there was the greatest diversity of objects in the built-up areas class in the Wieliczka district. Meanwhile, the Proszowice district experienced the lowest diversity within the built-up areas class, which probably stems from an overwhelming predominance of agricultural areas.

Table 3. Changes of the EI for the analysed districts for the objects of the built-up areas class (PTZB)

District	BDOT10k detail level			Increase in entropy value compared to 2014	
	PT03			[%]	
	2014	2017	2020	after 3 years	after 6 years
Wieliczka	0,3200	0,3214	0,3276	0,4276	2,3816
Kraków	0,2977	0,2989	0,2993	0,4032	0,5172
Proszowice	0,2451	0,2451	0,2468	0,0129	0,6753

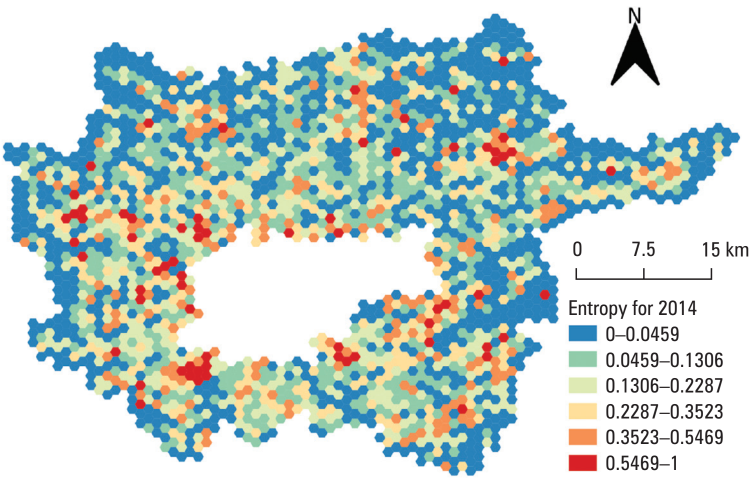
Visualising the results related to the hexagon grid made it possible to conclude that a significant increase of areas in the built-up areas class occurred in 2014–2017 mainly in suburban areas, in the vicinity of the city of Kraków, while in the years 2014–2020 there was an increase in built-up areas in the entire Wieliczka district, the Proszowice district as well as in the southern part of the Kraków district (Fig. 2).

The spatial distribution of the entropy index (EI) for the built-up areas class in 2014 in the area covered by the analysis was diverse (Fig. 3). However, higher values of the EI can be noticed in the hexagons located in the immediate vicinity of the border of the city of Kraków. Additionally, the analysis of spatial change in entropy values indicates the occurrence of higher EI values in the Kraków suburbs located in the studied districts (Fig. 1 and 3).



Source: Authors' own study

Fig. 2. Location of hexagons with an increase in the built-up areas class by over 2,000 m^2 compared to 2014

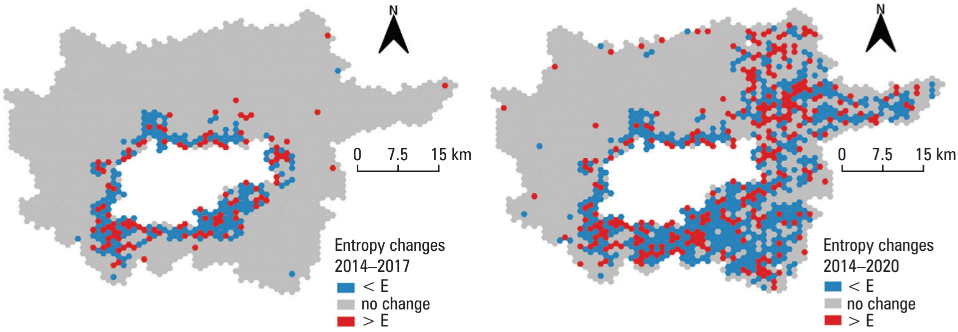


Source: Authors' own study

Fig. 3. The EI value for the built-up areas class according to the hex grid

In 2014-2017, the increase in entropy (>E), and thus the increase in the diversity of built-up areas, occurred mainly in the hexagons located in the vicinity of the city of Kraków, but it cannot be said to be dominant (Fig. 4). There was also a decrease in entropy values (<E) in the vicinity of Krakow city, indicating that in the individual hexagons there was also a decrease in the diversity of the built-up area class objects. However, in the period 2014-2020 the increase in entropy for built-up areas also

occurred in areas further away from the city limits (Fig. 4), with the decrease in entropy in the Wieliczka district, the southern part of the Kraków district and the eastern part of the Proszowice district. The changes in the entropy of built-up areas are mainly caused by the increase in the areas with single-family and multi-family housing.



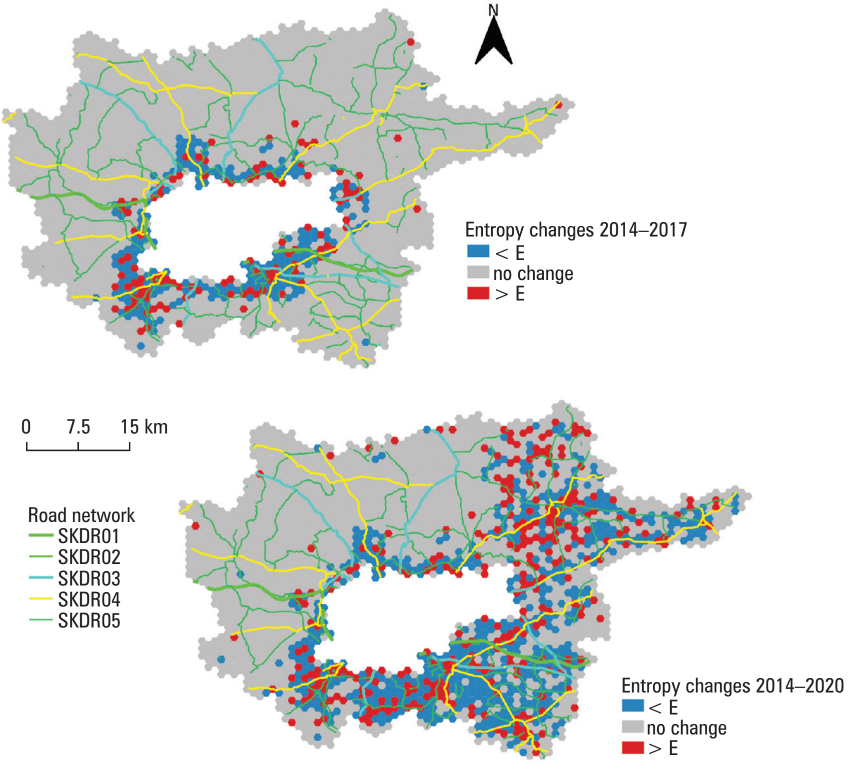
Source: Authors' own study

Fig. 4. Change in the EI value for the built-up areas class in relation to the hexagon area between 2017 and 2014 (left) and between 2020 and 2014 (right)

Considering the data from the BDOT10k database on the communication network (SK) category, it is also possible to analyse the changes in the entropy index in the vicinity of roads. Based on Figure 5, it can be noticed that the changes in the EI occurred in the vicinity of expressways (SKDR02), accelerated main roads (SKDR03), main roads (SKDR04) and service roads (SKDR05). A detailed analysis of the road network and hexagons, where the entropy index has changed, clearly indicates the link between the road network and the location of changes (Fig. 5). This is mainly due to the link between population growth and the technical development of infrastructure [Deka et al. 2011]. Results similar to those recorded in this study were also obtained by other authors such as Cegielska et al. [2019].

The population density of rural areas recorded in 2014 and 2017 in the Wieliczka municipality and the Świątniki Górne municipality [GUS 2021], located south of the city of Kraków, also seems to confirm the obtained locations of entropy changes in built-up areas. The increase in population density is also reflected in recent studies on road traffic, which showed that on the section of the A4 motorway between the Kraków Wieliczka and Kraków Bieżanów junctions (the south of Kraków) in 2015–2021, traffic increased by 100%, and amounts to 77,410 vehicles per day [GDDKiA 2021]. The research also has shown that on the southern ringway of Kraków (A4) vehicle traffic does not fall below 70,000 vehicles per day, which is mainly caused by the commute of residents from areas located south of Kraków to work in the centre of Kraków.

The obtained results allow us to conclude that the changes in entropy and area of built-up areas in districts do not concentrate mainly around towns near Kraków and lead to the conclusion that the built-up development is encroaching on rural areas. Similar conclusions were obtained by Noszczyk et al. [2017], who points to the progress of urbanization outside of large agglomerations, in smaller towns and even municipalities. On the other hand, Cegielska et al. [2019] indicate that although the anthropogenic pressure is greater in urban areas, in the suburbs it is growing in uncontrollable manner. Also, according to the research by Cegielska et al. [2017b], the area of the Proszowice district is under a high anthropogenic impact. Urbanization entering rural areas, caused by urban sprawl, may have a negative impact on the lives of the existing inhabitants of these areas. The increase in the number of inhabitants and the density of buildings may pose a great challenge for local authorities, because it requires a modernisation of the technical infrastructure, e.g. water supply network, sewage network or gas network.



Source: Authors' own study

Fig. 5. Location of changes in the EI of built-up areas in relation to the location of road network

4. Conclusions

The research carried out in this paper on the degree of land cover diversity, with particular emphasis on the built-up areas class for selected three districts of the Małopolskie Voivodeship, located in the immediate vicinity of the city of Kraków, in the years 2014-2020, allows to formulate the following conclusions:

1. The least diverse land cover characterises the Proszowice district, and the most – the Wieliczka district, which is most likely related to the character of land cover and land use dominating in a given area.
2. There was a slight increase in the diversity of land cover at the 2nd level of detail, i.e. at the level of classes within the land cover categories, with a simultaneous slight decrease in the diversity of areas at the 3rd level of detail for objects within the land cover classes.
3. Changes in the diversity of built-up areas were observed in the areas close to the border of the city of Kraków as well as in the Wieliczka district, the southern part of the Kraków district and the eastern part of the Proszowice district. In the case of the western and northern parts of the Kraków district, no major changes in the diversity of built-up areas were recorded.
4. Changes in the diversity of built-up areas in the Wieliczka and Proszowice districts and the southern part of the Kraków district can be particularly observed in the areas in the immediate vicinity of roads.

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