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FULL ARTICLE

Changes in spatial discontinuity in settlement patterns in the Czech-Polish border area: A case study of Těšín Silesia

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Abstract

The paper presents a discontinuity-based analysis of the settlement pattern changes in the Czechia–Poland cross-border historical region of Těšín Silesia. An approach based on a well-known and popular method (regression discontinuity design) was applied to measure spatial discontinuity. To describe the spatiotemporal changes, a combination of spatial, statistical and cartographic methods was used. The observed differences have been developing for more than 150 years; at the start, this area belonged to the territory of one state, and later it was divided by a national border. The division of the region resulted in areas following different development trajectories.

KEYWORDS

Czechia, discontinuity, Poland, settlement pattern

1 | INTRODUCTION

The differences in socio-economic and territorial conditions (economic factors, planning traditions, population changes and the availability of land for development) between continents, countries and regions have fundamental roles in shaping settlement structure, including urban sprawl. In post-socialist metropolitan and medium-sized urban areas, urban sprawl, which is expressed by a chaotic positioning of new buildings, has been the most dominant spatial growth model (Lityński, 2021). Housing and traffic sprawl are not restricted to urban areas alone. Mann (2009) defines 'rural sprawl' as construction activities in rural landscapes which degrade the scenic or environmental quality of the area. A typical expression of urban sprawl in rural areas is termed 'leapfrog', which depicts housing development within agricultural areas, creating a patchwork that does not resemble a compact city (Lityński, 2021).

Urban development is influenced by different spatial planning policies, on each side of the border. As a result, the spatial pattern can be biased due to the spatial discontinuity caused by administrative border (Kopczewska et al., 2021). The word continuous refers to something 'unbroken' or 'uninterrupted'; that is, a continuous entity has no 'gaps'. Commonly, it is expected that space and time are continuous and that natural processes occur continuously. The opposite of continuity is 'discreteness', consisting of separate elements (Bell, 2010). Continuity can be applied, e.g., to meteorological phenomena such as air temperature or pressure because we can measure it at any point in space. However, most socio-economic phenomena are discrete by their nature. To be interpreted and measured, they are related to units of area, e.g., population density or unemployment in LAU2 units that seamlessly cover an area. This perception of continuity is more concerned with the types of phenomena, how they are captured as data and how they can be visualised. Our concept of spatial cross-border (dis)continuity differs from this approach.

The literature does not contain many examples which examine cross-border spatial continuity. Pászto et al. (2019) define this continuity as 'the smoothness or trend in which the change in the indicators' values occurs in the direction from the inner part of the country: from country A through its borderlands, across the border and to the inner part of country B'. This concept of continuity is based on the typology of borderlands and their interactions. Regression discontinuity design (RDD), however, uses regression to quantify the extent of discontinuity based on a threshold. One specific type – geographic (or boundary) regression discontinuity design (GRDD, Keele & Titiunik, 2015) – exploits spatial discontinuities, using geographic or administrative boundaries as discontinuity thresholds. Usually, the discontinuity threshold is a national border (labour market districts, Lalive, 2008; media-market border, Keele & Titiunik, 2015) or historical border (former border between West and East Germany, Ehrlich & Seidel, 2018). This methodology has been applied to estimate the impact of an intervention or treatment; for example, Ehrlich and Seidel (2018) explain that the persistent spatial pattern of economic activity in the former West Germany area adjacent to the Iron Curtain is supported by investment subsidies and tax deductions, and Cerqua et al. (2022) assess the causal relationship between reception of subsidies and migration in EU-15 regions. According to Cunningham (2021), this design is currently extremely popular.

We build on the concept described by Pászto et al. (2019) and extend it with elements of GRDD. The discontinuity is the difference between the border values approximated by regression. The trend in which the change in the indicators' values occurs towards the border is the relationship between the indicator and the distance from the border, which can affect discontinuity size (if the relationship is statistically significant). In this concept, we do not see discontinuity as the opposite of continuity. Rather, the size of the discontinuity is how far the phenomenon is from being continuous across the border. Unlike GRDD, we do not aim to quantify the outcome of a particular treatment.

The idea behind this research is that the demarcation of the Czech-Polish boundary was the cause of settlement pattern changes in a region that previously functioned as a cohesive whole. The main aim of the paper is to describe the cross-border discontinuity in the settlement pattern and its change in the cross-border region of Těšín Silesia, using a combination of spatial, statistical and cartographic methods. It is also very important to construct settlement pattern metrics from the available (historical) data so that the differences and discontinuities are detectable.

2 | LITERATURE REVIEW

Settlements entail one of the most persistent changes in land use. Although settlements are generally characterised by relatively small footprints, they nonetheless have a huge impact (Meyfroidt et al., 2022) and influence on both neighbouring areas and more distant land systems. Local settlement triggers the loss of natural areas (van

Vliet, 2019); increases road network development, landscape fragmentation (Ibisch et al., 2016), light (Hölker et al., 2010) and noise pollution (Merrall & Evans, 2020); and adversely impacts connectivity among habitats (Kaim et al., 2019).

Although urbanisation around the world has experienced high rates of change over the past 50 years (Melchiorri et al., 2018), the specificity of the process suggests that very often development occurs at the fringes of already-existing built-up patches. As a result of a high degree of persistence, this is perhaps why settlement patterns have strong legacy effects over long periods. This may not only impact patterns and processes, but it may also define or prevent the potential trajectories of landscape development in the future (Tappeiner et al., 2021).

Despite the wide application of monitoring settlements over short periods, e.g., to observe the development of agglomeration (Huang et al., 2017) or suburbanisation processes (Kovács et al., 2019; Pazúr et al., 2017; Wnęk et al., 2021), less attention is given to the changes in rural areas (Song & Li, 2020). This is potentially partially also due to uncertainties in settlement products, which are usually of high quality, to monitor urban, yet not particularly rural, areas (Kaim et al., 2022). Detailed, long-term changes in settlements are also rare due to a lack of consistent and reliable data. Only recently have such products become available in various parts of the world, including the USA (Leyk & Uhl, 2018), Central Europe (Kaim et al., 2021) and China (Xue et al., 2021), and enabled the long-term study of development patterns over large areas (Leyk et al., 2020).

Similarly, the impact of the border existence and influence was so far mainly considered in the urban and metropolitan context of, e.g., US and Mexico (Herzog, 2016), Western Europe (Fricke, 2014; Sohn et al., 2009, 2022), Eastern Europe (Hardi, 2012) and Asia (Kopczewska, 2022; Mikhailova & Wu, 2016). However, it seems clear that border existence or appearance can shape settlement patterns also far from the urban centres, e.g., by transforming transportation systems, local markets, job opportunities. Such processes, however, require usually longer time spans to be manifested in spatial patterns (Eskelinen & Kotilainen, 2011). Although currently Poland is known for its scattered settlement and problems with spatial planning enforcements, it is hard to say to which extent it is a result of the recent socio-economic processes, or was already visible in landscape patterns in the past (Niedziałkowski & Beunen, 2019; Śleszyński et al., 2021). Studying the changes in the settlement pattern in the area divided by the border could shed new light on this phenomenon.

Borders can be examined through different aspects: geographical, economic, political, cultural, military-strategic and others (Dokoupil, 2000). With regard to the function of borders, their negative or positive nature is evaluated (Šerý & Šimáček, 2013). From a geographical and political perspective, borders appear as barriers that prevent or complicate the movement of people and goods (Liberato et al., 2018). The type of border effect depends on the permeability and openness of the border, while its intensity depends on the symmetry (if the economic situation of the regions is comparable, the border between them is symmetric) and the nature of the neighbouring regions (Balaguer & Ripollés, 2018). Martinez (1994) defines four types of cross-border interaction based on the permeability of border: alienated borderlands, coexistent borderlands, interdependent borderlands and integrated borderlands.

Regions with long and diverse political histories, where boundaries, institutions or even political systems have changed over time, have had a diverse impact on land use (Bičík et al., 2001), triggering forest disturbance (Main-Knorn et al., 2009; Munteanu et al., 2015), patterns of agricultural land abandonment (Munteanu et al., 2017) and demographic processes (Kladivo et al., 2012). Because the impact of national policies on settlement patterns is usually assessed over short periods (Gennaio et al., 2009; Grădinaru et al., 2020), little is known about how various institutional drivers have influenced the current settlement patterns over a longer time. The current study delivers an evaluation of the settlement patterns (both rural and urban) for more than 150 years in the Czech-Polish border area, which was part of the same territory under the Habsburg Empire at the beginning of this period but fell under the control of two independent states after World War I (WWI). The detailed data sets we used in the study allowed us to compare the extent to which the evolution of the settlement pattern in this area followed a different trajectory, starting from similar conditions and evolving into similar environmental and socio-economic conditions, i.e., where the cross-border discontinuity might evolve over time.

3 | METHODS AND DATA

3.1 | Study area

The cross-border area of Těšín Silesia (2283 km^2; in Czech Těšínské Slezsko, in Polish Śląsk Cieszyńskii), a part of the historical region of Austrian Silesia, was selected as the study area (Figure 1.). In the compared periods, there is a large difference between spatial delimitation of the administrative level of municipalities (Table 1). Because of this difference, it was necessary to use customised artificial units (hexagons) for comparison. There is also a huge difference between the sizes of current Czech and Polish LAU 2 units. The position of its centroid determined the affiliation of hexagons crossed by the border. In this case, the result is the same as if the larger part of the hexagon had been used.

The borders of Těšín Silesia were shaped after the Seven Years' War (1756–1763) as a result of the division of Silesia into Austrian and Prussian territory. It became part of Austrian Silesia along with Opava Silesia as crown land

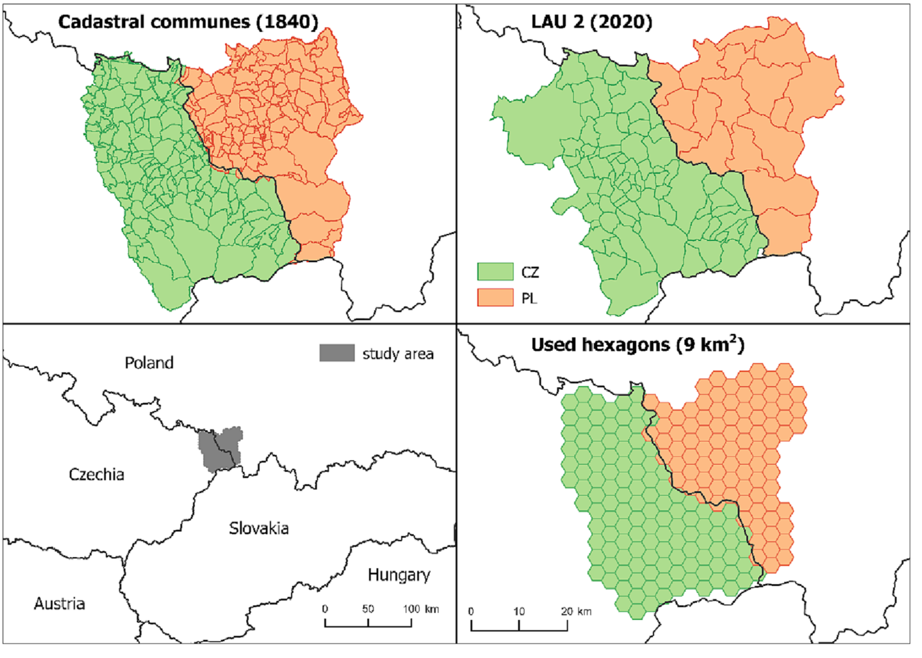

FIGURE 1 Study area along the current national border.

TABLE 1 Comparison of administrative spatial units.

Area	Number of units	Average size (km^2)
Cadastral communes, Czech side 1840	142	8.95
Cadastral communes, Polish side 1840	112	9.04
LAU 2, Czech side, 2020	76	19.97
LAU 2, Polish side, 2020	17	63.63
Hexagons, Czech side	123	9
Hexagons, Polish side	90	9

under the Habsburg Monarchy (until 1804), Austrian Empire (1804–1867) and Austro-Hungarian Empire (1867–1918).

In 1920, Těšín Silesia was divided into Polish and Czech territory (at that time, Czechoslovakia). The western Czech territory covers an area of 1276 km^2 (56%), and the eastern part belonging to Poland covers 1007 km^2 (44%). Both the Polish and Czech territories have the same patterns of physico-geographical regions (Figure 2). The north contains lowland valleys (min. 188 m.a.s.l. at the mouth of the Olza River into the Odra River), and the south comprises foothills and the Beskidy Mountain range (max. Lysa Hora 1323 m.a.s.l.) – the Carpathian Flysch Belt. The natural environment therefore has a much larger gradient of natural changes in a north–south direction than an east–west direction (Dorda, 2012). The settlement pattern has adapted to this significantly over time. In the lowlands and foothills, large towns have developed (Těšín, Bielsko, Frýdek, Ostrava). In the mountains, settlement has concentrated along the axis of the river valleys, with hamlets at higher elevations. The southern area was largely covered with forests with pastures along its ridges, while the northern area, mainly agricultural, became increasingly industrialised from the mid-19th century because of hard coal resources in the Ostrava-Karviná region used in processing iron ore initially mined in the Beskidy Mountains (Myška, 2013). The historical region of Těšín Silesia largely overlaps with the Euro region of the same name (established 1998) and supports cross-border cooperation and development.

Těšín Silesia, from the point of view of the capitals of superior political entities, was perceived as a peripheral region, in the times of both the Austro-Hungarian monarchy and after WWI. For Vienna, Prague and Warsaw, it was one of the most remote regions, with an uncertain political status for quite a long time (interwar period, armed conflicts between Poland and Czechoslovakia). After 1945, the tight state border significantly limited economic links within the region, but the regional identity of the society remained strong (Matykowski, 2021). The socio-economic breakthrough of the 1980s and 1990s clearly influenced the renewal of socio-economic contacts and enabled the formation of a cross-border identity and a solid foundation of regional affiliation built in the Habsburg times (Nowak, 2015).

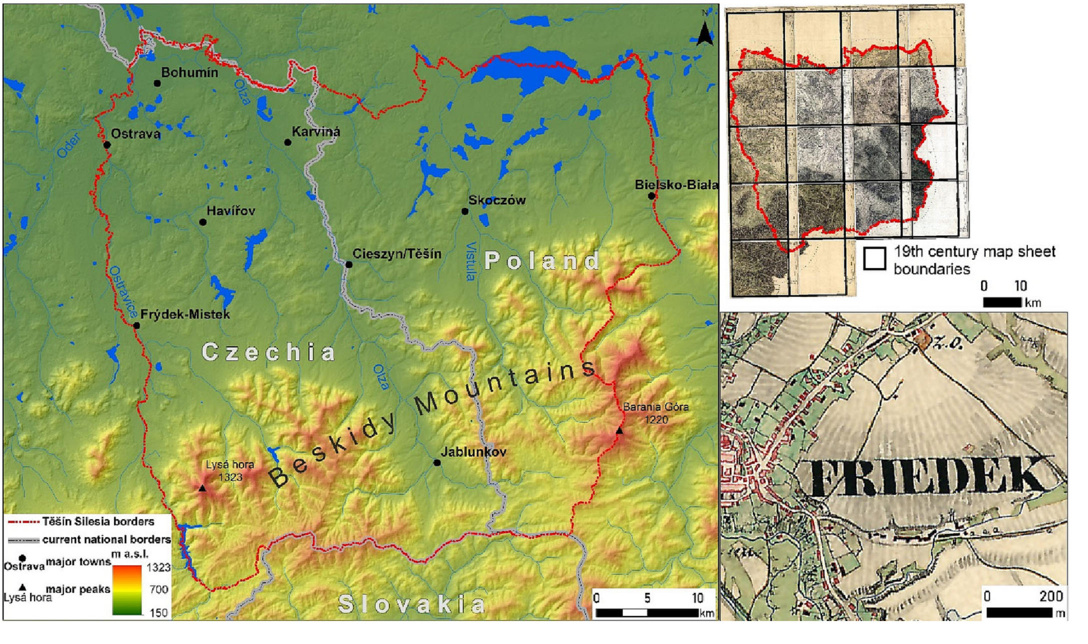

FIGURE 2 Study area (left) and historical maps used in the research (right).

3.2 | Data and software

As a historical building footprint, a database which contained mid-19th-century building structure locations for two Habsburg Empire provinces was used (Kaim et al., 2021). The data set was originally based on second military survey maps, which were a generalised form of cadastral map prepared for military purposes (Ostafin, Kaim, Troll, & Maciejowski, 2020). The survey maps depict two building types – houses and farm-related – although other types (e.g. churches, restaurants and mills) are also included. It was found that, on average, 85% of the structures visible on the cadastral maps (1:2880) were also present on the second military survey maps; therefore, the military maps represent reliable source documents of historical settlement. The original, second military map sheets for the entire area of study were created in 1840. A detailed description of data collection and an evaluation of the uncertainty in the database are given by Kaim et al. (2021).

Data on the current buildings in Czechia were obtained from the Czech Office for Surveying, Mapping and Cadastre from the RÚIAN (Register of Territorial Identification, Addresses and Real Estates) database. The data are valid for 2020. The current building locations in Poland were taken from the official Polish topographic database (BDOT10k), which also contains the shapes of structures, but for the aims of the analysis, it was converted into points representing structure centroids. The data are valid for 2019. The current LAU2 unit geometry and international borders were obtained from Eurostat.

The data were prepared mainly in ArcGIS Pro, but QGIS was also used. Statistical analyses were performed in RStudio, an integrated development environment for programming in R. Maps were created in ArcGIS Pro.

3.3 | Methods

The metrics to quantify spatial settlement pattern according to the same data for the two studied periods first required preparation. The data were then evaluated and interpreted. Three specific types of analyses were performed: the first type of analysis compared the global difference between the Czech and Polish sides and the changes over the studied periods; the second analysis examined the cross-border discontinuity from both global and local perspectives and in terms of the effect of distance from the border; the third analysis looked at local spatiotemporal differences and changes. A combination of statistical and spatial analyses and cartographic visualisations was applied.

3.3.1 | Settlement pattern metrics

A settlement pattern refers to the distribution of buildings and houses in a geographic region and the relationship between one house or building to another. We devised and calculated eight metrics to measure this pattern in a hexagonal layout, which is a suitable spatial representation for the different sizes and number of municipalities (summarised in Table 1; visualised in Figure 1) between the periods we compared and so that the actual municipalities would be incomparable. Each hexagon represents 9 km^2, a size which was derived from the average size of cadastral communes in 1840 (8991 km^2). Hexagons on the edge of the study area were excluded from the analyses and visualisations because the building data do not fully cover them. The aim was not to describe the structure of individual municipalities but to measure across the region without dependence on spatial administrative delimitations.

The first set of metrics aims to catch levels of building density. The number of buildings was converted into a regular grid with a cell size of 250 m, showing areas based on the number of buildings. This fine grid well captures the spatial pattern and covers even the smallest municipalities with enough cells. Three classes of cells were defined according to Jenks' method (according to historical data) to minimise the variability within intervals (by minimising average deviation from the interval mean) and to maximise the diversity among them (by maximising each interval deviation from the means of the rest of the intervals) (Jenks, 1967); a fourth class was added to represent areas without buildings. The first class of areas with low building density includes cells with one and two buildings. The second class contains cells with 3 to 10 buildings representing areas with intermediate building density. The third class with more than 11 buildings represents areas with high building density, and finally, the fourth class shows areas completely without buildings. From this grid, we calculated the percentage of each class area inside the hexagons. The final metrics used for analysis were:

- Proportion of area without buildings
- Proportion of low building density
- Proportion of intermediate building density
- Proportion of high building density

The last four metrics were calculated to measure the compactness and dispersion of buildings in the area. In terms of urban sprawl, continuity is the degree to which space has been built up in a spatially adjacent manner (Lityński, 2021). In Poland, lack of this continuity is perceived as a feature of urban sprawl (Pieniążek & Rogalińska, 2015). We used the distances between buildings to calculate the average distance to the nearest 1, 3, 5 and 10 buildings as a mean of values within each hexagon. It seemed redundant to use all four metrics; therefore the final metrics used for analysis were:

- Average distance to the nearest building
- Average distance to the 10 nearest buildings

The average number of buildings within 100 m was another metric we calculated to reveal building density from a different perspective. Buildings without close neighbouring buildings were selected to calculate the proportion of buildings without neighbours within 100 m in each hexagon. It nicely indicates the proportion of buildings beyond a compact built-up area. We tested different distances: the lower distances in the historical data contained many buildings within the main part of the settlement, and higher distances in the current data showed almost no buildings. The final metrics used for analysis were:

- Average number of buildings within 100 m
- Proportion of buildings with no neighbours within 100 m

All the metrics listed above were calculated in the same way for historical and current data.

3.3.2 | Measuring the global differences across the border

We applied a Mann–Whitney *U* test (in cases where the metric for at least one of Czech and Polish side was not normally distributed) and independent samples *t*-test (in cases where the metric for both sides of the border was normally distributed) to check whether the two groups are homogeneous and have the same distribution (Nachar, 2008). In other words, if the difference between the Czech and Polish sides was statistically significant (i.e., p-value <0.05). Four boxplots were created for each of the eight metrics, separated according to the Czech and Polish areas of study for the historical and current data. It was therefore possible to compare the difference across the border and between the observed periods.

3.3.3 | Spatial cross-border discontinuities

To verify cross-border discontinuities and their change over time, we applied a discontinuity analysis based on linear regression. Outliers were removed using the interquartile range (IQR) method. The distance from the border was calculated from the hexagon centroids (to avoid zero distance values) to distinguish the boundaries of the countries; for Poland, we multiplied distances by −1. In addition to the size of discontinuity, it is possible to assess the gradient of the increase or decrease in the phenomenon's value towards the border, whether it is statistically significant, in other words whether the phenomenon is affected by the distance from the border. The form of linear regression model for estimating discontinuity is

$$y = \begin{cases} \beta_{01} + \beta_{11}x + \varepsilon \, if \, x < 0 \\ \beta_{02} + \beta_{12}x + \varepsilon \, if \, x > 0 \end{cases}, \quad (1)$$

where y is the estimated value of the metric and x is the distance from border ($x < 0$ for Poland; $x > 0$ for Czechia). The size of discontinuity is calculated as

$$Discontinuity_y = |\beta_{01} - \beta_{02}|. \quad (2)$$

We also calculated RMSE (root mean square error) for each regression line as

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2}, \quad (3)$$

where n is the number of observations, S_i are predicted values by regression and O_i are observations.

We used a local spatial autocorrelation measurement to test whether the settlement pattern is randomly distributed in space. Specifically, we used the Getis-Ord Gi* statistic with a neighbourhood setting of six closest hexagons. We also applied false discovery rate correction, to control the proportion of false declaration of significance by reducing critical p-value threshold (Caldas de Castro & Singer, 2006). In addition to a usual detection of clusters, the analysis attempted to find two specific types of clusters. The first type of local spatial continuity is clearly cross-border clusters, which reveal areas where the boundary does not disrupt the spatial continuity of phenomena. The second type of cluster is visibly disrupted by the boundary and indicates local spatial discontinuity.

3.3.4 | Local spatio-temporal changes

All metrics were visualised using the choropleth map method. We applied Jenks' method to define classes for visualisation, and the threshold values of classes were rounded according to basic cartographic rules. Classes were determined from historical data and were also used for current data. The maps are therefore more suitable for comparisons between periods and exploring the historical spatial pattern but less for conclusions about spatial differentiation in the current data since they frequently contain mainly values from the highest or lowest interval. If we were to analyse (dis)continuity using these maps visually, we could say that most metrics are continual across the border, especially with the current data. However, that would be an error because the intervals are very wide as a result of these maps simply not being intended for such a purpose. Pászto et al. (2019) mentioned that it is better to use smoother data intervals, e.g., using fuzzy sets and logic before constructing a choropleth map to increase the intuitiveness of evaluating the spatial discontinuity.

Finally, we calculated the index of change for all the applied metrics from the equation:

$$X = \left(\frac{X_c}{X_h} * 100\right), \quad (4)$$

where X_c is the current value and X_h is the historical value of the same metric. The resulting value indicates an increase (if $X > 100$) or decrease (if $X < 100$) in the current value compared to the historical value. If the value of change index $X = 100$, the metric's value remains the same. In the change index maps, we visualised three special situations separately in grey scale, where one of the values is 0 and where both of the values are 0. All other hexagons were separated into classes to illustrate areas of substantial increase (classes up to 200% and over) or decrease (classes up to 50% and over), and where only a small change (up to 10%) occurred in the values between periods. A bipolar colour scale was used to visualise a map with a neutral colour in its centre.

4 | RESULTS

The results are structured according to the three groups and the aim of the methods used. We statistically compared the differences between the Czech and Polish sides in the first section. In the second section, we applied regression to quantify the cross-border spatial discontinuity and cluster analysis to reveal border and cross-border hot spots and cold spots. In the third section, we visually analysed the maps of metrics and their changes.

TABLE 2 Results of statistical tests.

Metric	Difference in (mean) location	95% confidence interval	
Proportion of area without buildings (H)	**−0.57**	**−4.29**	**3.16**
Proportion of area without buildings (C)	9.66***	3.45	16.30
Proportion of low building density (H)	−3.24e-06	−2.069	2.069
Proportion of low building density (C)	6.36***	4.59	8.13
Proportion of intermediate building density (H)	0.15	−2.012	2.73
Proportion of intermediate building density (C)	−6.21***	−9.65	−2.76
Proportion of high building density (H)	−0.34e-05	−4.15e-05	1.35e-06
Proportion of high building density (C)	−10.35***	−14.42	−6.34
Average distance to nearest building (H)	−0.35	−3.3	2.38
Average distance to nearest building (C)	14.95***	13.3	17.35
Average distance to 10 nearest buildings (H)	−0.5	−16.26	13.48
Average distance to 10 nearest buildings (C)	24.39***	15.83	33.27
Average number of buildings within 100 m (H)	−0.17	−0.56	0.23
Average number of buildings within 100 m (C)	−2.55***	−3.76	−1.37
Share of buildings without neighbours within 100 m (H)	0.5	−0.81	1.87
Share of buildings without neighbours within 100 m (C)	3.89***	3.1	5.07

Note: For proportion of area without buildings (H) and proportion of low building density independent samples *t*-test was used instead of Mann–Whitney *U* test.
Abbreviations: C, current data; H, historical data.
***$p < 0.01$.**$p < 0.05$.*$p < 0.1$.

4.1 | Measuring the global differences across the border

We applied a statistical test to check for statistical significance (Table 2) in differences of distributions. The data from 1840 (will be further referred to as historical data) revealed no metrics with any major difference between the current Czech and Polish sides. As mentioned, during that period, there was no interstate border influencing the development of the area. The data from 2020 (will be further referred to as current data) indicated a statistically significant difference in each metric; therefore, we can assume that development in the areas between the observed periods differed substantially.

A much bigger difference in current data is also visible from boxplots (in supplements). A higher proportion of areas have no buildings or low building density on the Czech side, and a higher proportion of areas with intermediate and high building density are clear on the Polish side. The values of the metrics indicate a less compact settlement structure: the average distance to the nearest and to the 10 nearest buildings and proportion of buildings with no neighbours within 100 m are higher on the Czech side, while the average number of buildings within 100 m is higher on the Polish side. The boxplots generally show more compact and densely built-up areas on the Polish side. There are also more high outliers in most metrics on the Czech side. The values between hexagons vary more in the current data, especially on the Czech side. In general, the Czech side of the border was and still is more heterogeneous.

4.2 | Spatial cross-border discontinuities

The discontinuity analysis indicates a considerable increase in the difference between the Czech and Polish sides, as in the previous analysis. It is characterised by an increase in discontinuity size (Table 3; Figure 3) in the current data

TABLE 3 Discontinuity analysis of the metrics.

Metric	Slope PL	Slope CZ	Discontinuity size	RMSE PL	RMSE CZ
Proportion of area without buildings (H)	0.60***	−0.77***	0.702	11.14	14.12
Proportion of area without buildings (C)	0.52*	−0.6	9.703	20.77	24.27
Proportion of low building density (H)	−0.29***	0.27*	0.964	6.02	7.37
Proportion of low building density (C)	0.12**	0.12	3.459	3.98	6.78
Proportion of intermediate building density (H)	−0.27***	0.47***	0.288	5.83	8.01
Proportion of intermediate building density (C)	−0.063	0.33	8.134	10.03	11.59
Proportion of high building density (H)	0.0034	0.023	0.318	1.19	1.26
Proportion of high building density (C)	−0.42*	0.12	6.136	14.95	14.69
Average distance to nearest building (H)	−0.28**	−0.14	3.741	8.09	8.22
Average distance to nearest building (C)	0.14**	0.17	11.034	4.37	10.14
Average distance to 10 nearest buildings (H)	1.05	−1.84*	0.277	43.66	55.37
Average distance to 10 nearest buildings (C)	0.84**	0.026	6.817	22.31	29.55
Average number of buildings within 100 m (H)	0.018	−0.0022	0.395	1.35	1.4
Average number of buildings within 100 m (C)	−0.088*	0.14*	2.983	3.52	4.11
Share of buildings without neighbours within 100 m (H)	−0.042	0.011	1.013	3.62	4.49
Share of buildings without neighbours within 100 m (C)	0.047*	0.014	2.988	1.91	3.91

Abbreviations: C, current data; H, historical data.
***$p < 0.01$.**$p < 0.05$.*$p < 0.1$.

compared to the historical data. The change in values towards the border is not statistically significant in most metrics; therefore, they are not strongly related to distance from the border in most cases, but there are several exceptions.

The historical data reveal that two metrics are influenced significantly by the distance from the border in the proportion of area with no buildings and the proportion of area with intermediate building density for both sides. For the Polish side, the relationship between the distance from the border and the proportion of low building density and average distance to the nearest building in both the historical and current periods is also significant and average distance to 10 nearest buildings is significant in current data.

According to the historical data, almost no difference exists between the Czech and Polish parts, and the area close to the border was rather peripheral. In addition to a large increase in discontinuity in the current data, a reduction in the effect of distance from the border is evident in most of the metrics. The analysis indicates a reduction of the border's effect as a barrier in limiting the development of the nearby area.

We calculated the local spatial autocorrelation to identify statistically significant hot spots and cold spots (Figure 4). The first four metrics focused on housing density indicate a greater number of statistically significant clusters, but very few of them are on the Polish side. The most obvious cluster occurred in almost all metrics for the southwestern part of the study area in both the historical and current data. This cluster indicates the sparsely populated mountain area of the Beskidy Mountains. This cluster is more significant in the current data, not appearing in only two of the metrics.

As mentioned earlier, this analysis had the specific aim to detect local cross-border discontinuities. No large cross-border clusters overlap spatially into the inner areas of both countries. The historical data reveals two potential clusters such as this one in the southern part of the study area. The first represents the proportion of area with no buildings, and the second represents the proportion of intermediate building density; however, both are interrupted by a valley located to the west of the border, separating two mountain areas. It is also interesting that clusters in this area remain in the current data on the Czech side but are not statistically significant on the Polish side. One small cross-border hot spot representing the proportion of high building density appears in the area of the town of Těšín, which lies on the Czech-Polish border.

The first three metrics – the proportion of area with no buildings, the proportion of area with low building density and the proportion of area with intermediate building density – indicate a greater number of spatial clusters visibly interrupted by the boundary. The northern area on the Polish side shows a hot spot in the proportion of intermediate building density. Other clusters are located on the Czech side – the historical data reveal these as hot spots in the proportion of low and intermediate building density and a cold spot in the proportion of area with no buildings, all extending from the town of Ostrava across to Havířov and then Těšín on the border. The last hot spot relates to the current data and the proportion of low building density, which spreads from Těšín in the east and the boundary of the study area, where the towns Frýdek-Místek and Frýdlant nad Ostravicí are located.

4.3 | Local spatio-temporal changes

Using map visualisations, we can assess the phenomena in greater detail and look for specific areas which disagree with the more general conclusions from our statistical analyses. The first map (Figure 5.), which shows building density (classes described earlier) in a 250-m grid for both compared periods, at first glance reveals a large increase in areas with high density in the current data. The smallest change is in the southwestern area of the Beskidy Mountains, where housing remains sparse. A significant loss of buildings has occurred in the mining area between the towns of Ostrava, Karviná and Havířov, near the border on the Czech side.

As noted earlier, we created maps for the current values to match the intervals derived from historical values and to improve their suitability in comparing the periods and exploring the historical spatial pattern, but less for drawing conclusions about spatial differentiation based on the current data. Due to the large change in values, most

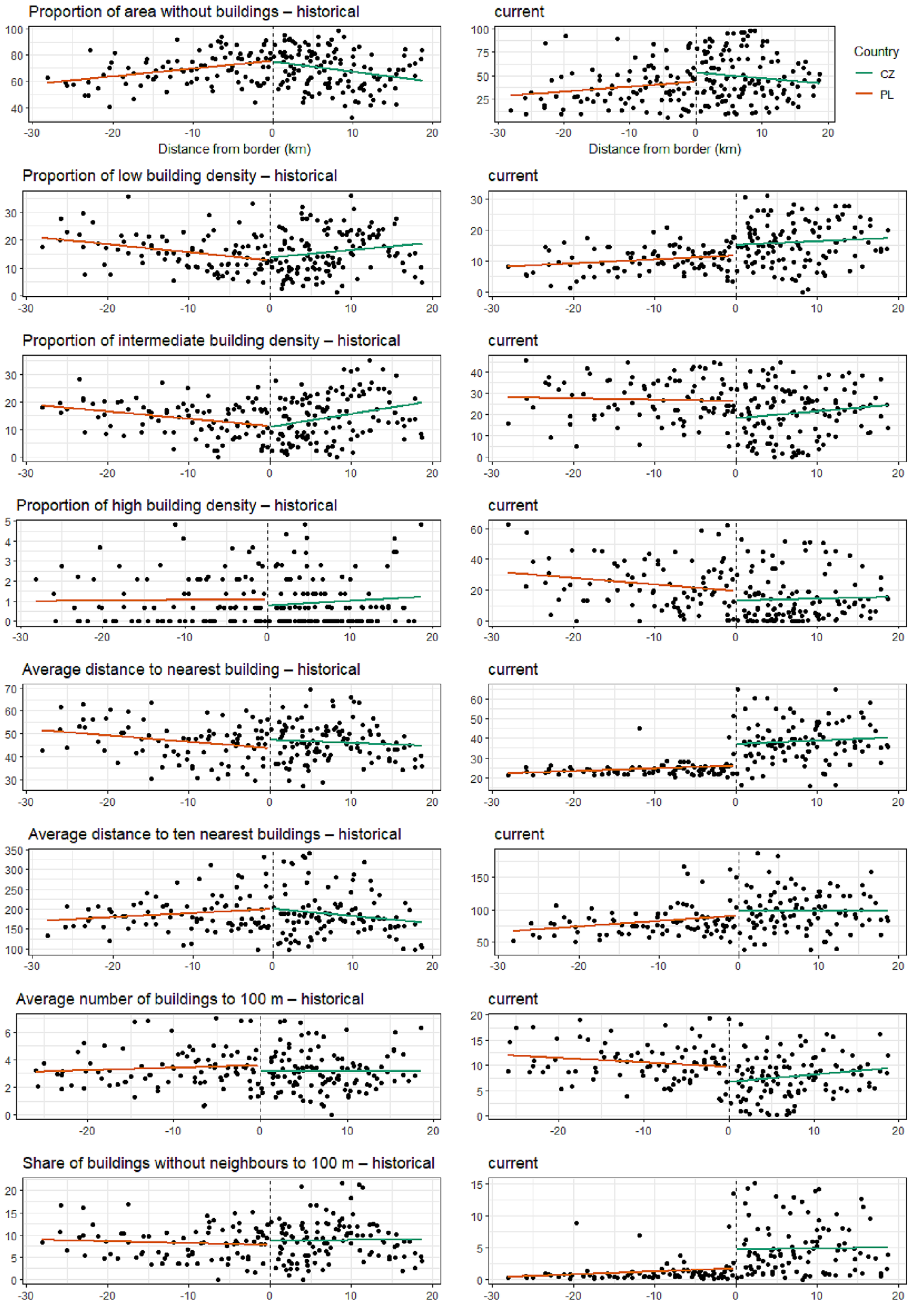

FIGURE 3 Discontinuity in the metrics.

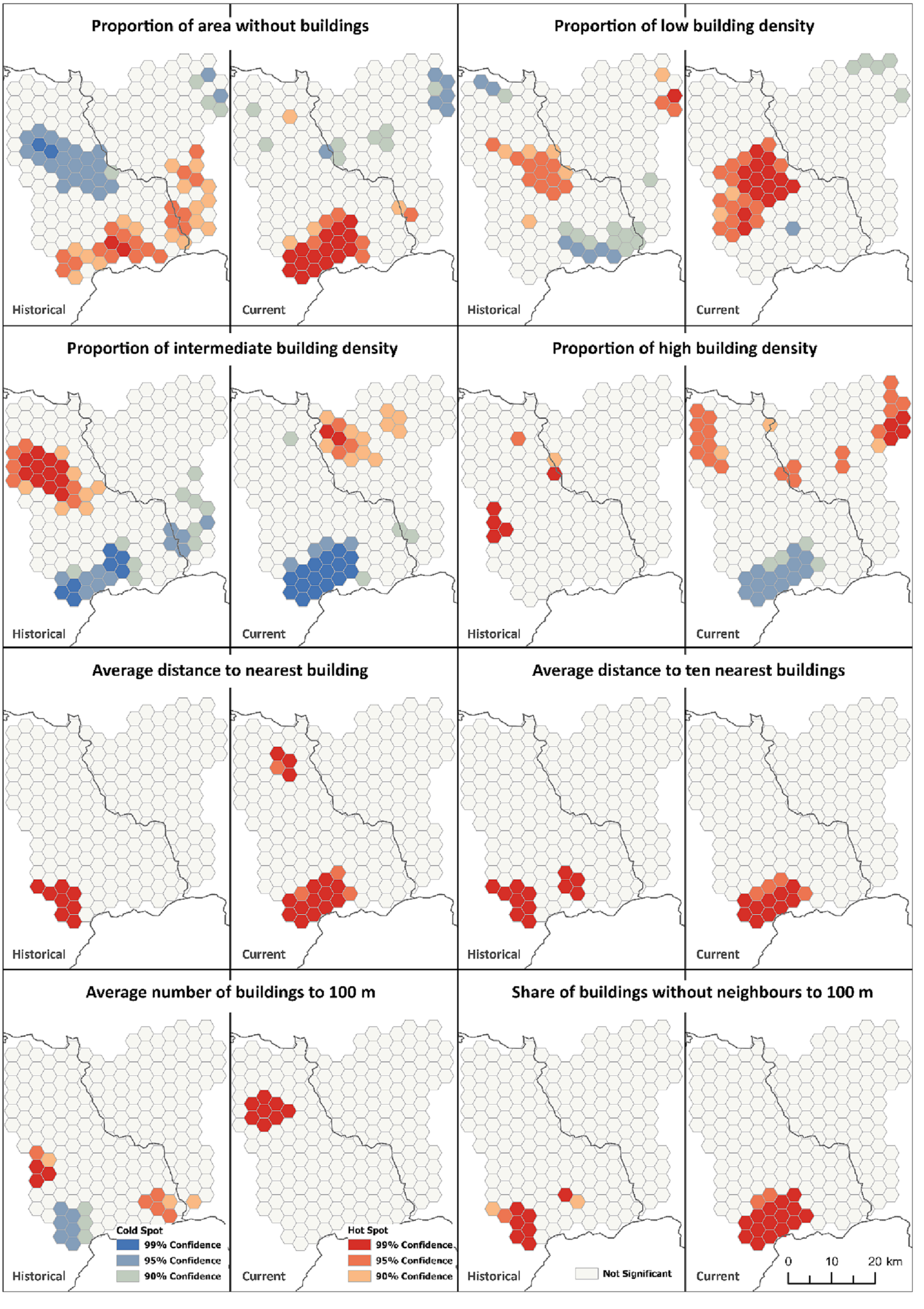

FIGURE 4 Local spatial autocorrelation (Getis-Ord Gi*).

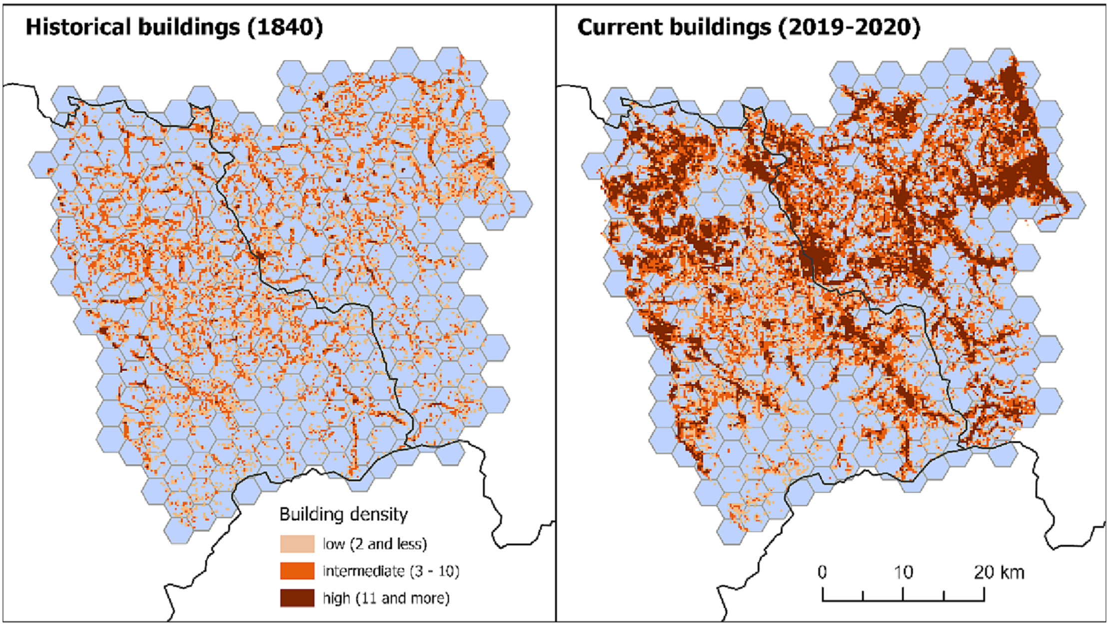

FIGURE 5 Number of buildings in 250 × 250 m regular grid for the historical data (left) and the current data (right)

hexagons with the current values fall either into the interval with the lowest or highest value (accordingly, the areas which logically fall where the number of buildings has increased significantly). Despite this, it is easy to identify an area in the Beskidy Mountains where many buildings have been lost on the Czech side. Statistically significant clusters identified and described in the previous subsection are also evident in the choropleth maps (Figure 6) and index of change maps (Figure 7).

Almost the entire study area has seen a decrease in areas with no buildings, except for the southwestern Beskidy region, where only large clusters of hexagons appear with almost no change (light yellow) and the mining area between the towns of Ostrava, Karviná and Havířov. The most substantial decrease has occurred in the study area's northern part and the valley which separates the Polish and Czech parts of the Beskidy Mountains.

The change in the proportion of low building density is the most scattered. The south shows rather an increase mixed with almost no change. The largest clusters of areas where declines have occurred are in the northern part from the city of Ostrava to Havířov, from Karviná on the Czech side to the Polish part of Těšín, and the largest around the Polish towns of Bielsko-Biala and Skoczów.

In most of the area, most notably on the Polish side and in the valley to the south, the proportion of intermediate building density has increased. On the Czech side, two clusters appear in areas with a decrease, the first in the Beskydy Mountains and the second combined with almost no change around Havířov (including the city).

The entire study area shows a large increase in the proportion of high building density, excluding the Beskidy Mountains on the Czech side, which is the only large cluster in the grey category of zero values in both the current and historical data, indicating no change. Hexagons with zero values in the historical data (dark grey) are numerous for this metric on both the Czech and Polish sides. These are hexagons where no 250 × 250 m cell contains more than 11 buildings. The mining area on the Czech side is visible as light-grey hexagons.

On almost the entire Polish side, a decrease in the average distance to the nearest building is evident, the most prominent being around Bielsko-Biała and at the border around the town of Těšín. The Czech side appears more

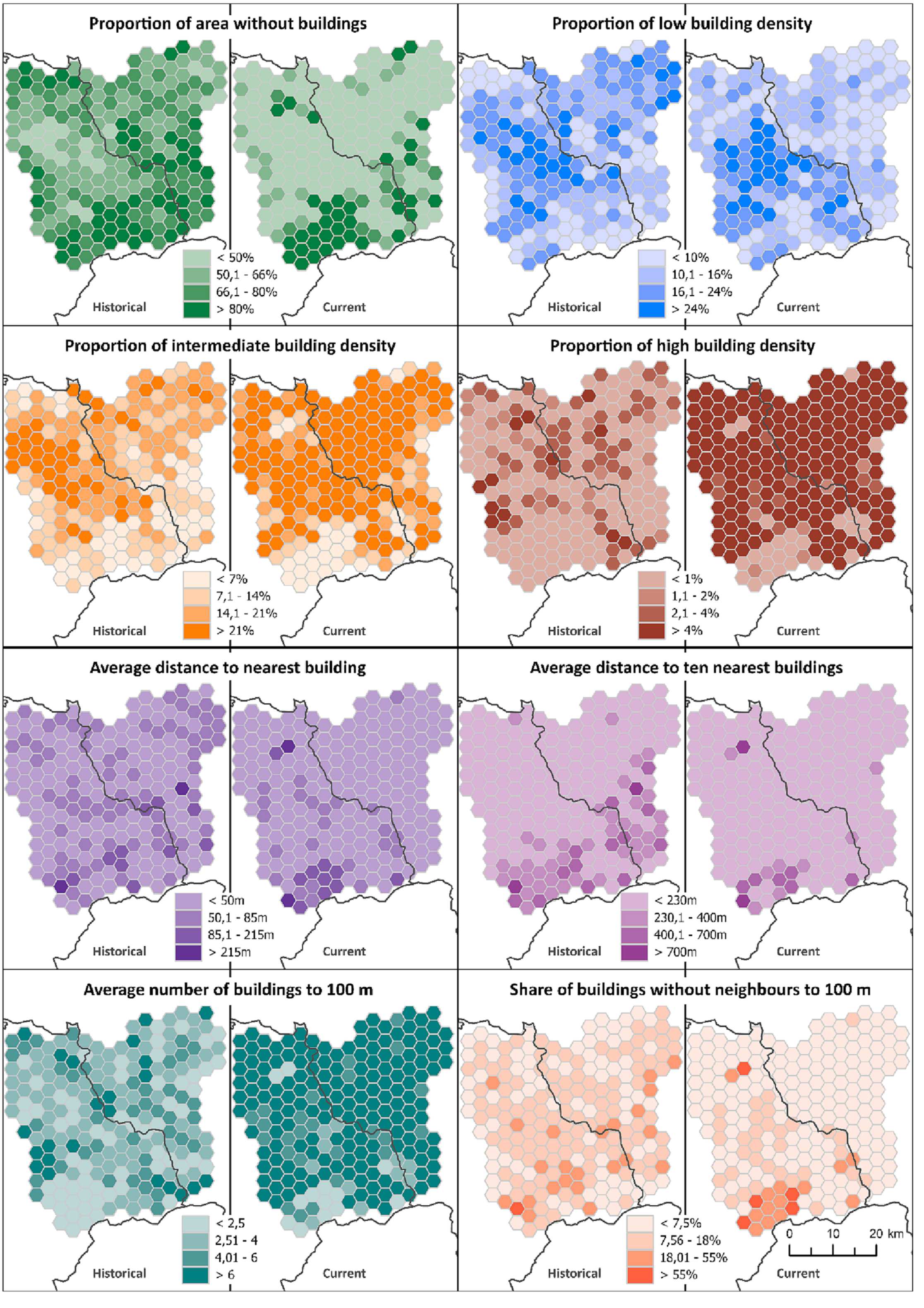

FIGURE 6 Visualisation of the metrics.

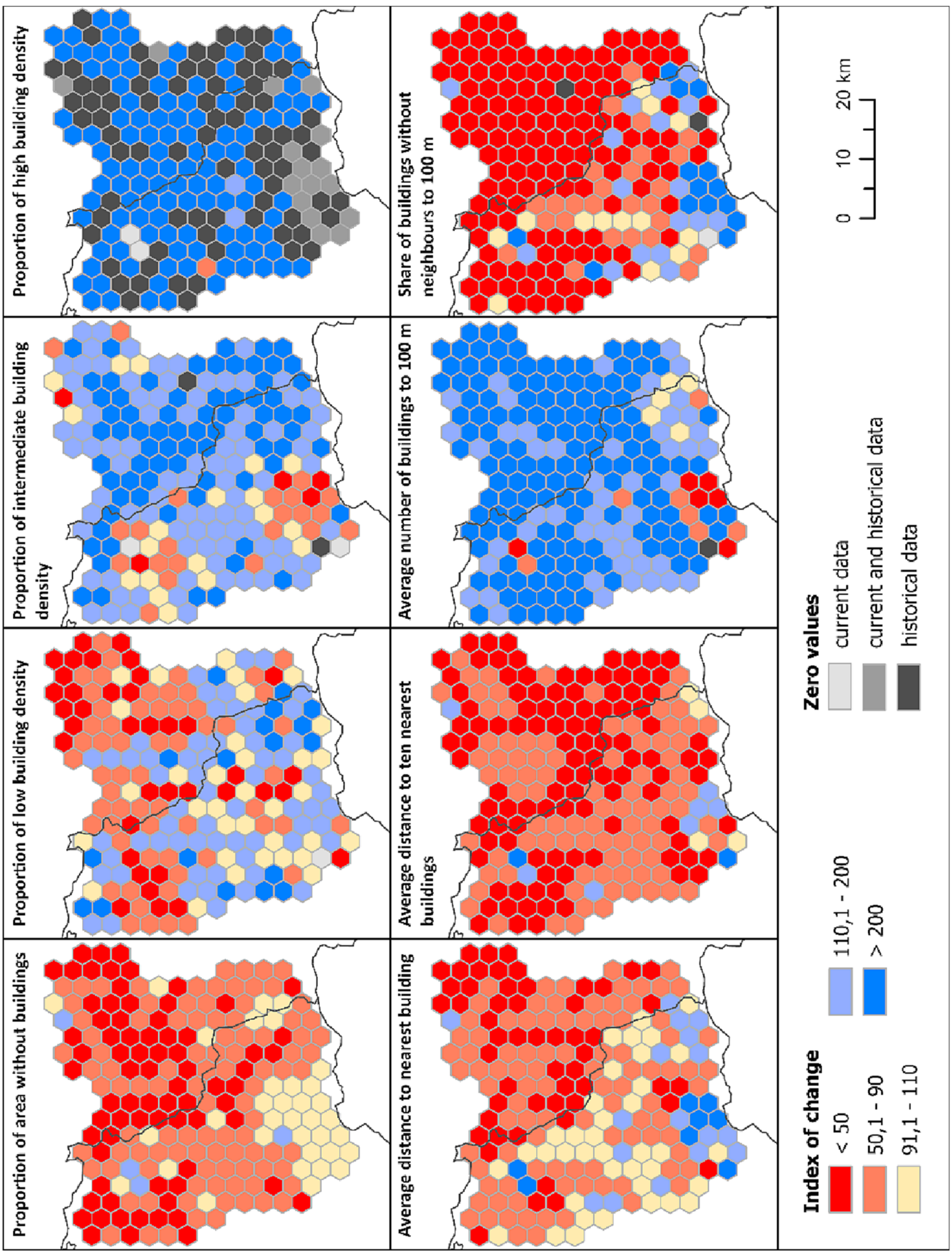

FIGURE 7 Index of change.

scattered, with an increase in the Beskidy Mountains and a decrease around Ostrava, Havířov and Karviná. A cluster of hexagons with almost no change also appears to the east of Havířov and Frýdek.

The average distance to the nearest 10 buildings indicated a decrease across almost the entire study area. The main exception is the part of Beskidy on the Czech side, combined with a few hexagons with an increase and a few hexagons with almost no change.

The average number of buildings within 100 m increased across almost the entire Polish side, mostly greater than 100%. Along the border in the south is a small area with almost no change. Most of the Czech part also showed an increase, with the small exception of the Beskidy Mountains.

The proportion of buildings with no neighbours within 100 m decreased substantially across almost the entire Polish side. The Czech side is more scattered. The largest cluster with a major decrease on the Czech side is around Ostrava, Havířov and Karviná. An increase on the Czech side is also evident in the Beskidy Mountains and the south of the study area near the border.

Comparing all the metrics, the Czech side is generally more scattered in terms of development of the settlement patterns. On the Polish side, the settlement pattern has become more compact and denser in space relatively evenly. On the Czech side, the settlement pattern shows a large difference between the more densely populated northern part of the study area in the cities of Ostrava, Karviná and Havířov compared to the very specific mining area between these towns and the sparsely populated Beskidy Mountain area.

5 | DISCUSSION

We calculated and described eight metrics to measure spatial settlement patterns and applied six different statistical and cartographic methods to analyse and visualise the data.

One of the key findings of this work is the significantly greater difference in the current data compared to historical data between the Czech and Polish sides, indicating that different developments have occurred within a relatively small region with very similar environmental conditions.

Another important finding is the far greater increase in building density in Silesian Beskidy on the Polish side than the Moravian-Silesia Beskidy in the Czech part of the study area. These are mountainous areas which were very sparsely developed historically, and which, according to our analyses, have changed substantially only on the Polish side despite having similar conditions. On the Polish side, this is potentially a result of the relatively close proximity of the large urban conurbation of Polish Silesia (Katowice, Zabrze, Chorzów, etc.), which became well connected with road and railway for the tourist centres in Wisła (winter sports centre) and Ustroń (spa) located in the mountains, also being a trigger for second home development in these mountainous areas (Mika, 2004).

As a result of the differences in collectivisation, we assumed a more compact and less-fragmented settlement pattern on the Czech side of the study area, as shown, e.g., in the greater Carpathian area (Kaim et al., 2022). While in Czechoslovakia, whole-scale rural collectivisation was accomplished in the 1950s, in Poland, due to fierce resistance from peasants, whole-scale collectivisation was abandoned in the early 1950s (Bideleux & Jeffries, 2007) and was never reintroduced, leaving the petty bourgeoisie in the countryside (Crampton, 2002). Our analyses produced opposite findings, with a more compact settlement pattern on the Polish side. The settlement pattern has also developed more evenly on the Polish side in terms of compactness and building density than the Czech side, with a major difference between the mountain area in the south and the urbanised area in the north. This is also expressed by the values between hexagons varying more in current data, especially on the Czech side. These findings might be, however, partly explained by the economic transformation of the region during the period we analysed, which is not typical for larger mountainous areas. At the beginning of the studied period, Těšín was the most important urban centre, located centrally, and an important urban centre of the eastern part of the province in the Habsburg Empire, while

Bielsko and Ostrava were less important and located on the outskirts (Ostafin, Kaim, Siwek, & Miklar, 2020). In the 21st century, their trajectories are already very different. Těšín was divided by the national border in 1918, which immediately reduced its rank in the settlement network (Gwosdz & Domański, 2015). At the same time, Bielsko became a large industrial centre, further developing after World War II (WWII), when it was formally joined to neighbouring Biała, creating Bielsko-Biała. In the 1970s, the town became the centre for a new administrative unit created in Poland, while fast development in the automotive industry under a Polish-Italian cooperation boosted the economy and further demographic increase (Gwosdz & Domański, 2015). Ostrava also experienced rapid development over 20th century, mainly due to mining and the metallurgy industry (Krejčí et al., 2011). Similar processes impacted the quick development of other towns on the Czech side of the border (e.g., Karviná, Havířov). The mining industry was also responsible for an adverse impact on the former rural areas through the location of mining waste dumps, post-mining heaps and other brownfields (specifically the mining area between the towns of Ostrava, Karviná and Havířov). These areas were only partially used in future settlement developments, and only with careful spatial planning requirements (Vojvodíková, 2005). These processes indicate that the relatively homogeneous settlement pattern, as observed in the mid-19th century, was then deeply transformed not only by the national border dividing the area into two but also by very different development trajectories in the main urban centres of the region, both on the Polish and Czech sides. The development paths of cities are very important drivers of regional development, especially in former industrial regions (Gwosdz et al., 2020).

The appearance of the border dividing the region between two newly established states after WWI, Czechoslovakia and Poland, had a substantial impact on the legislative procedures influencing spatial planning policies in two separated, instead of one country. However, what seemed to have a larger impact was the role of the region divided by the boundary in relation to the heavy industry economy of the states after WWII (Regulska, 1987). Yet, on the Czech side, we observed a decrease in housing density in the northern part due to the development of mining and mining-related waste disposals, which is different from what happened in similar conditions on the Polish side. The Polish part of the mountains in the south experienced, by contrast, contrary to the Czech side, an increase in tourist and recreational settlements, as a result of a rapid road connection to another mining region – Upper Silesia, located in Poland. What connects these two, somehow contradictory processes of settlement transformation, is the importance of heavy industry in the socialist economy as a trigger of spatial processes in a regional scale (Domański, 2011). The appearance of the national border shaped the way where exactly the manifestations of this policy happened and how it impacted the space in the new political conditions.

The peripheral character of the area directly on the border is somewhat surprising in the historical data. Historically, borders were more of a barrier, and borderlands were peripheries. Still, no border existed in the historical period we studied, and the area belonged to one state. Later, the border was rather closed and impermeable with very limited cross-border interaction. With the collapse of communism, the border finally began to open, which brought better conditions for cross-border cooperation and integration. The accession of the Czech Republic and Poland to the EU and the associated establishment of the Schengen area have brought significant openness and permeability to the border, allowing organisations, individuals and companies to benefit from the advantages of being located at the border. Reducing legal and administrative barriers is expected to enhance trade flows, increase productivity, avoid duplication of public infrastructure across borders and facilitate economic interactions (Caragliu, 2022). Recently, in addition to the usual advantages such as the possibility to work in a nearby neighbouring foreign country, tourism, entertainment, a great advantage of Czech border residents is the possibility to shop abroad, especially in Poland.

As in the study by Pászto et al. (2019), we have demonstrated that spatial cross-border continuity is observable in the given data. We also compared the discontinuities over two time periods; however, we applied largely different methods inspired by the well-established GRDD methodology. Unlike typical GRDD (e.g., Ehrlich & Seidel, 2018), our goal was not to quantify the outcome of any particular treatment.

5.1 | Limitations

The unavailability of a larger historical data set was the study's main limitation. Events with major impacts on the study area (and the whole of Czechia and Poland), e.g., WWI, WWII, communist collectivisation and rapid industrialisation, occurred between the periods we studied and whose consequences could be analysed if corresponding data from other periods were also available.

The change in the delimitation of administrative boundaries at the municipal level between the studied periods removed the possibility of using other socio-economic and demographic data, such as population density, unemployment or economic activity, since these types of data are related to existing statistical, administrative units and would not be comparable.

Indicators of urban sprawl are considered a way of assessing settlement pattern. However, these consist of multiple attributes (built-up areas, new buildings, accessibility, population density, etc.) that cannot be obtained for the historical period we assessed; therefore we had to focus on what could be done with the available historical data and replicate it for the current data to allow a comparison. The metrics presented in this paper are not intended to have a general application in the classification or quantification of settlement pattern. It was a method of investigating only a layer of point-located buildings. In general, more accurate multicriteria approaches are available in combining different types of data.

An issue discussed in the assessment of spatial discontinuity is defining the distance from a boundary. In applying socio-economic indicators, it is appropriate to consider accessibility of the road network, even in GRDD (e.g., Lalive, 2008), when distances from the border or the borderlands themselves are defined (e.g., Halás, 2002). In our case, it was impossible, because the only data required for network analysis in the historical period are the data for main roads (Kaim et al., 2020). In this case, however, it would also be methodologically challenging to define and determine transport accessibility for the year 1840.

It was not only the unavailability of historical data in terms of quantity that was limiting. If data for a larger area were available, the analysis could be extended to the entire Czech-Polish border area, or a comparison could be made with the Czech-Slovak or Slovak-Polish border area.

More methods are available for assessing discontinuity size through linear regression. Differentiating between states using negative values of distance from the border for one state (or another areal unit) is typical in RDD. Visual analysis of the choropleth map can also be applied to identify local cross-border (dis)continuity (Pászto et al., 2019). However, we preferred to use local spatial autocorrelation results, and thus, it is certain that the identified (dis)continuities are statistically significant; however, only (dis)continuous clusters of significantly high or low values are detectable.

It is recommended to use a smooth, simple function in regression discontinuity analysis (Gelman & Imbens, 2017). We applied simple linear regression for the sake of simplicity in interpretation. A simple model is generally preferred when the goal of modelling is inference because the aim is understanding the associations between the data (Hastie et al., 2021), not modelling for the most accurate prediction.

6 | CONCLUSION

In this paper, we examined the settlement pattern in the Czech-Polish cross-border area, using the Těšín Silesia historical region as an example. For this purpose, limited by the available data from two time periods only, we created eight metrics to allow us to capture the spatial variability and pattern in these settlements. The analyses explored the differences between the Czech and Polish sides, the cross-border discontinuity of these metrics and their spatial pattern, which has been developing for over 150 years. We used a combination of spatial and statistical analyses and cartography visualisations. In all analyses, we compared the historical period (1840) and the current situation (2020).

Statistical tests revealed that in 1840, no statistically significant differences existed between the Czech and Polish sides, but today, differences are evident in all the metrics we examined. In the same direction, the discontinuity analysis showed us a significant increase in spatial discontinuity in all the selected metrics. The index of change indicated a large difference in changes in the settlement pattern on the Czech and Polish sides. On the Polish side, the change was spatially quite uniform, whereas on the Czech side, it was much more scattered. These results support the main hypothesis of this research that the demarcation of the Czech-Polish boundary is the cause of changes in the settlement pattern in this area. The existence of a border launched different regional development trajectories which caused these differences and the changes we described in the discussion.

Institutional cross-border cooperation and development is an important topic for researchers in various study fields and also for institutions at different levels of spatial hierarchy, from international organisations to governments to local authorities. Research on spatial cross-border discontinuity is beneficial in this field because it can partially capture both the overall state and the difference between the countries (or other territories) under study, in addition to the influence of the border and borderlands in terms of peripherals causing an increase or decrease in the intensity of phenomena towards the border. From the perspective of geoinformatics, the advantage of discontinuity analysis is simplification of the presented information by transferring it from a map to a graph while preserving the basic spatial information to allow a more general point of view which can be combined with commonly used methods (e.g., choropleth maps or local spatial autocorrelation) to assess local differences.

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SUPPORTING INFORMATION

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Resumen. El artículo presenta un análisis basado en la discontinuidad de los cambios en el patrón de asentamiento en la región histórica transfronteriza checo-polaca de Těšín Silesia. Para medir la discontinuidad espacial se aplicó un enfoque basado en un método conocido y popular (diseño de regresión en discontinuidad). Para describir los cambios espaciotemporales se utilizó una combinación de métodos espaciales, estadísticos y cartográficos. Las diferencias observadas se han ido desarrollando durante más de 150 años; al principio, esta zona pertenecía al territorio de un Estado, y más tarde quedó dividida por una frontera nacional. La división de la región dio lugar a zonas que siguieron trayectorias de desarrollo diferentes.

抄録: 本稿では、チェコとポーランドの国境を跨ぐ歴史的地域であるチェシン・シレジアにおける定住パターンの変化の不連続ベースの分析について述べる。空間不連続性を測定するために、よく知られた一般的な方法(回帰不連続デザイン)に基づくアプローチを適用した。時空間的変化を説明するために、空間的、統計的、地図学的方法を組み合わせた。観測された差異は150年以上にわたって生じてきたものである。すなわち、この地域は当初は1つの州の領土であったが、後に国境により分断された。その分断により、この地域は場所によって異なる発展の軌跡をたどることとなった。