RESEARCH ARTICLE

The wildland-urban interface in Poland reflects legacies of historical national borders

Dominik Kaim [ORCID] · **David P. Helmers** ·
Michał Jakiel · Daniel Pavlačka ·
Volker C. Radeloff

Abstract

Context The wildland-urban interface (WUI) is an area where houses are located near wildland vegetation. As such, the WUI is a focal area of wildfire risk, human-wildlife conflicts, and other human-nature interactions. Although there is a wide consensus on the impact WUI existence might have, little is known about the WUI spatial determinants over long periods, especially in countries with long settlement history.

Objectives Our goal here was to map the WUI across Poland, and to quantify the extent to which historical legacies shape current WUI pattern, since Poland is one of the countries, which experienced substantial political changes over time, which had an impact on historical settlement development.

Methods We analysed a database of nearly 15 million building locations and a 10-m Sentinel-2-based land cover map to produce a country-wide WUI map of Poland. Then we compared the WUI pattern among parts of Poland which belonged to different political entities in 1900s and 1930s and also among different ecoregions. Lastly, we verified the effects of the historical borders or landscape units borders on WUI patterns with a discontinuity analysis.

Results We found that a substantial part of Poland is WUI, and over 60% of all buildings are in WUI. However, WUI patterns differ considerably across the country, and WUI hotspots are located around the largest metropolitan areas in central and southern part of Poland and in the Carpathians. Furthermore, WUI patterns reflect pre-1945 national borders indicating long-term legacies of past settlement patterns and urban planning approaches. Diversity among ecoregions was much less pronounced than among past political entities.

Conclusions Our work shows that current WUI pattern is to large extent shaped by former political conditions, which is likely true not only in Poland, but also in many parts of Europe and elsewhere where settlement history goes back centuries.

D. Kaim (✉) · M. Jakiel
Institute of Geography and Spatial Management, Faculty of Geography and Geology, Jagiellonian University, Gronostajowa 7, 30-387 Kraków, Poland
e-mail: dominik.kaim@uj.edu.pl

D. P. Helmers · V. C. Radeloff
SILVIS Lab, Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, 1630 Linden Drive, Madison, WI 53706, USA

D. Pavlačka
Department of Geoinformatics, Faculty of Science, Palacký University Olomouc, 17. Listopadu 50, 771 46 Olomouc, Czech Republic

Introduction

The wildland-urban interface (WUI) is where houses meet or intermingle with wildland vegetation. The WUI is the area where many wildfires start and where houses are most at risk (Radeloff et al. 2018; Bento-Gonçalves and Vieira 2020). Furthermore, the WUI is a focal area for other processes such as habitat fragmentation, disease transfer or biotic invasions (Bar-Massada et al. 2014; Jenerette et al. 2022; Schug et al. 2023). For instance in US, WUI predicts lyme disease incidents better than forest fragmentation (MacDonald et al. 2019), and is positively associated with exotic plant species abundance (Gavier-Pizarro et al. 2010a). For many wildlife species, WUI areas pose a unique trade-off between risk and reward, also providing space of relative safety for prey yet creating barriers for movement (Blecha et al. 2018). There may be more frequent conflicts among large mammals, humans, and domestic animals, especially in areas that carnivores are recolonizing (Chapron et al. 2014; Evans et al. 2017; König et al. 2020).

The WUI can grow either due to housing growth or to wildland vegetation recovery. In US, WUI was the fastest-growing land use from 1990 to 2010, largely due to housing growth (Radeloff et al. 2018). In addition to the growth of large metropolitan areas, many small and medium towns are also growing, especially if they are in the vicinity of natural areas (EEA Report 2011; Castro-Prieto et al. 2017), as do small urban areas near forests (Chai and Seto 2019). Indeed, in 2012 the number of people living within 5 km of a forest was 1.6 billion globally, with such settlement patterns being especially common in China, the United States, Indonesia, India, and Brazil (Newton et al. 2020). Furthermore, many settlements are located within natural areas, especially second homes that are only used in some periods of the year (Paris 2014; Adamiak 2016). Second homes make up 26% of the housing stock in Norway, around 5% in Switzerland, and more than 3% in US (Sheard 2019).

While the WUI is widespread in many countries (Lampin-Maillet et al. 2010; Conedera et al. 2015; Modugno et al. 2016; Badia et al. 2019; Mockrin et al. 2022), it is less clear how it originated, and to which extent historical legacies or path dependencies shape current WUI patterns (Foster et al. 2003; Munteanu et al. 2015; Rhemtulla et al. 2009). Both forests and settlements are persistent elements of

landscape, so potentially long-term legacies may play important role in WUI development over time. Additionally, both above-mentioned land uses reflects political and institutional changes over time (Main-Knorn et al. 2009; Munteanu et al. 2015; Grădinaru et al. 2020). Such legacies are more likely to be important for WUI in Europe than, for example, Australia, Canada, or the U.S., because European settlement patterns reflect a deeper history. Furthermore, in Europe, political borders have changed repeatedly in past decades and centuries (Davies 2011). For example, Poland did not exist as a country for more than a century prior to WW I, and changed its geographical extent substantially after WW II. These border changes are reflected in current land ownership pattern and cadastral history (Harvey 2013). Historical divisions of Poland are also one of the main reasons for the spatial heterogeneity of current socio-economic rural development (Rosner and Wesołowska 2020). Furthermore, there are often stark differences in land use along current borders (Noack et al. 2021; Xiao et al. 2021), suggesting that historical borders may have resulted in similarly stark differences.

So far, however, there are no WUI maps of Poland or other Central European countries, where political borders' changes took place. Therefore it was not possible to assess overall WUI spatial pattern, and to quantify to which extent WUI patterns are a result of past political and socioeconomic settings, which we hypothesized to have affected the current WUI. Additionally, in countries where WUI has not been a research focus yet, there is a need to assess a range of WUI maps, so that they can be evaluated for applications other than wildfire management. Therefore, our research questions were thus: (a) what is the current spatial pattern of the WUI in Poland?, (b) how much do WUI patterns depend on the scale of the analysis, and (c) how much are current WUI patterns the result of historical legacies, especially the borders in ca. 1900 and 1930, when the political divisions within contemporary Poland changed?

Methods

WUI mapping

To map the WUI in Poland, we employed the WUI definition of US Federal Register (USDA and USDI

2001) as operationalized by Radeloff et al. (2005), which distinguishes two kinds of WUI: *intermix*, where housing intermingle with wildland vegetation, and *interface*, where settlement abuts the wildland areas. Either WUI type requires a housing density higher than 6.17 houses/km^2 (1 house/40 acres in the US context). In intermix WUI, there has to be also > 50% wildland vegetation, while the interface WUI, has < 50% wildland vegetation but is within 2.4 km of a wildland vegetation patch larger > 5 km^2 (Fig. 1). The distance of 2.4 km reflects the distance a firebrand can fly (Radeloff et al. 2005). What is more, many processes and interactions between wildlife and humans are taking place within approximately that distance, which makes this WUI definition more inclusive. For instance, the probability of livestock damage caused by brown bears in Romania is highest

within 2.5 km of a forest edge (Pop et al. 2023), and large forest complexes provide optimal habitat for bears (Pop et al. 2018). Also, in Poland crops were the most attractive to wild boars, when located up to 2 km from the forest (Tarasiuk and Giżejewski 2021). Similar WUI definitions have been used previously to analyse disease transmission (MacDonald et al. 2019), invasive species occurrence (Gavier-Pizarro et al. 2010b) and recreation (Kil et al. 2014), which shows the broad applicability of this approach for both fire and non-fire related problems. Furthermore, by employing this definition, we were able to compare WUI in Poland to that in other countries (Argañaraz et al. 2017; Godoy et al. 2019; Carlson et al. 2022).

We mapped the WUI in Poland based on exact building locations (Bar-Massada et al. 2013), and
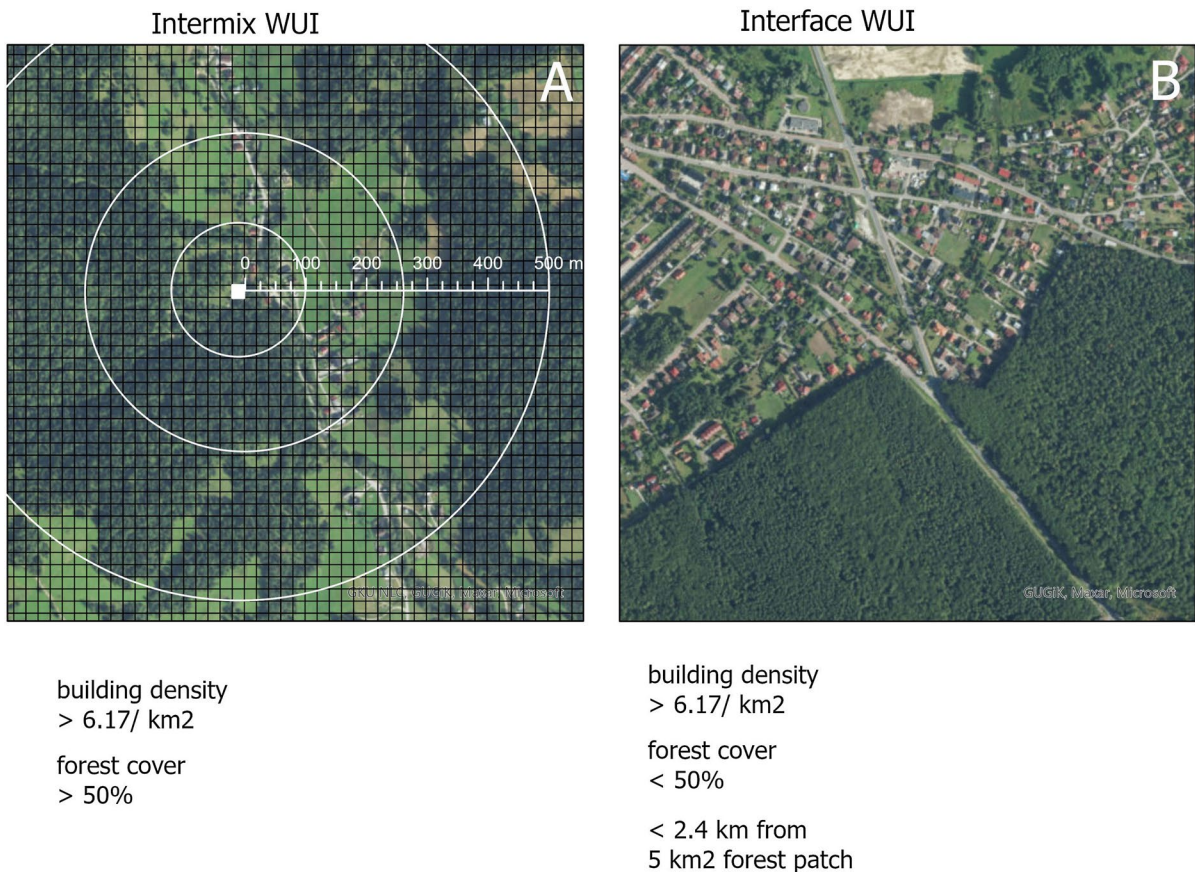

Fig. 1 Examples and schematic definition of Intermix (**A**) and Interface (**B**) WUI. On the figure A we present also the variety of radius we used to define building density and share of forest cover. The example shows only three out of six tested values: 100, 250 and 500 m. Background image source: ArcGIS PRO Basemap

detailed wildland vegetation maps. Specifically, we analysed countrywide building locations from the official Polish Topographic Objects Database (BDOT10k), where each building in Poland is mapped as a polygon (14,895,581 polygons in 2019). In terms of wildland vegetation, we focused on forest cover only, because forest is the natural, wildland climax vegetation in Poland, and there are almost no natural grasslands. We analysed the 10-m resolution Sentinel-2-based S2GLC raster product, covering the entire European Union, and freely available for scientific purposes (Malinowski et al. 2020). According to the accuracy assessment broadleaf tree cover had user and producer accuracies of 94.6%, and 95.3% respectively and coniferous tree cover 95.8% and 97% (Malinowski et al. 2020). To calculate building densities and shares of forest cover, we applied a circular moving window algorithm testing six radii: 100, 250, 500, 750, 1000 and 1500 m (Fig. 1). Smaller radii have the advantage that even small groups of buildings are mapped as WUI and focus on ecological processes that operate on short distances (e.g., noise pollution), whereas larger radii have the advantage that they focus on larger WUI areas and reflect ecological processes operating at longer distances better (e.g., habitat fragmentation for wildlife species with large territories). We map here WUI at various scales to explore variation in WUI as a function of scale and share publicly the all of the resulting datasets in order to highlight that there is considerable scale variation, and to allow users to choose the scale that is most appropriate for their application. In doing so, we hope to facilitate a wide range of WUI-related research questions (Jenerette et al. 2022).

WUI pattern

To analyse WUI spatial pattern, we delineated a set of hexagons comparable in size to the NUTS 4 administrative units (n = 398, shorter diagonal = 30 km, area ca. 780 km^2), and calculated for each WUI share (%), and the largest patch index (LPI), which indicates, how much area of the landscape (%) is occupied by the largest patch of WUI (for interface and intermix combined). We selected the LPI, because it is not sensitive to the overall number of patches which might change with different radius-based WUI maps, nor sensitive to minimal mapping unit size or map resolution (Saura and Millan 2001; Saura 2002). Those advantages of the LPI are important for potential comparison of WUI pattern among countries, because other WUI maps are based on spatial data with different resolutions. LPI offers a simple and easily understandable measure showing if WUI in particular area is forming a large patch (e.g. when LPI is > 50%), or if WUI patches are small and isolated, even if the total WUI share is relatively large.

To assess the effects of historical national borders, we attributed each hexagon according to the 1900s borders, where the contemporary territory of Poland was divided between Prussia, Russia and Austro-Hungary, and the 1930s borders, where contemporary Poland partly belonged to 1930s Poland and partly to 1930s Prussia (we excluded two hexagons located in the 1920–1939 so-called Free City of Danzig, so for 1930s only 396 hexagons were analysed; Fig. 2). When the border divided area of hexagon, we assigned it according to its centroid. Additionally, we assigned each hexagon to its major environmental division, based on the geomorphological features, which divide Poland into four main regions: (1) lowlands with post-glacial forms (characterized by hills < 350 m a.s.l. and many lakes), hereafter called lake district, (2) lowlands without obvious postglacial forms (typical lowland landscape of plains), hereafter called lowlands, (3) uplands (including also basins located between highlands and mountain foothills), and (4) mountains (the Carpathians and

Fig. 2 National borders in 1900 and 1930, and the landscape division used in the analysis
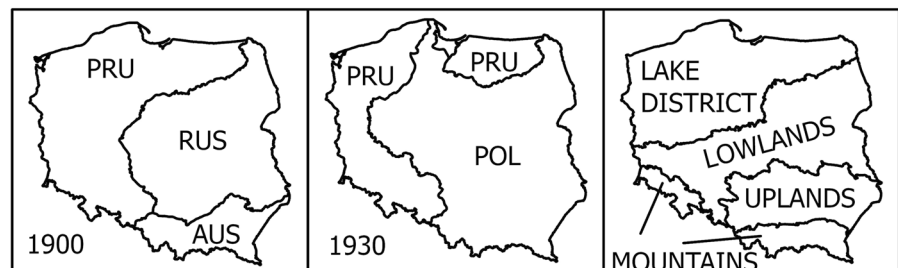
Sudetes; Fig. 2). We downloaded the historical borders from the Max Planck Institute for Demographic Research at the University of Rostock (MPIDR and CGG 2011), and the Galicia and Austrian Silesia Interactive Database (GASID Project) (Ostafin et al. 2020), and adopted the environmental division from the division proposed by Solon et al. (2018). Lastly, we conducted a hotspot analysis to see if hexagons with current high WUI proportions were clustered and depend on the historical, political divisions, by calculating the local Getis-Ord Gi* statistic, where we defined the neighbourhood as the 6 closest neighbouring hexagons, and applied a False Discovery Rate correction.

Relationship between WUI pattern, past political divisions and landscape regionalisation

To verify if past national borders affect current WUI pattern, we first tested if LPI values and WUI shares in hexagons differed among the historical political entities (three in 1900, two in 1930), or the four landscape units. First, we checked for normal distribution within the hexagons in a given strata with a Shapiro–Wilk normality test. If the hexagons within a given strata were normally distributed, we used one-way ANOVA, followed by Tukey's pairwise testing. If at least one of the strata was not normally distributed, we employed the nonparametric Kruskal–Wallis H test, followed by Dunn's test with Holm correction for p-values to test the pairs' differences. For the 1930s, where there were only two strata of hexagons, and we tested if they were significantly different with an independent sample t-test or Mann–Whitney test (for data that were not normally distributed). We conducted all the tests for three WUI radii variants: 100, 500 and 1500 m, and separately for all hexagons, and only for hexagons located > 100 km apart from each other (n = 35), which was the distance for which Morans's I indicated no spatial autocorrelation.

Lastly, we verified for the 500-m radius the effects of the historical borders or landscape units borders on WUI patterns with a discontinuity analysis. Specifically, we parameterized separate regression analyses for hexagons with centroids located within 50 km of either side of the border, where the dependent variable was the LPI value or WUI share, and the independent variable was the distance of the hexagon centroid to the border. We quantified the discontinuity

as the differences of the y-axes intercepts at the geographical border between regions. We also assessed the significance of the relationship between LPI value or WUI share versus distance from the border. Based on this, we determined whether or not there was a statistically significant difference between neighbouring regions, and if so, whether it manifested itself via a difference in intercepts (indicating a sharp jump in values right at the boundary) or in slopes (a gradual change in direction from the boundary) or a combination of both.

Results

WUI extent

Our results showed that a substantial part of Poland is located in WUI. Depending on the radius of the circular moving window, the percentage ranges from 11.4 to 55.4% (35.1% with 500-m radius) of the country (Figs. 3, 4). Regardless the radius defined, most of the buildings in the country (61.4–63.7%; the highest number with 100-m radius, while the lowest number with 250-m) were located in WUI with the majority in the interface (Figs. 3, 4). Among all the radii that we tested, 10.8% of Poland was always mapped as WUI, while 42.3% was never mapped as WUI. WUI was especially common in the southern part of country, while in the west and north, the share of WUI was comparatively rather low. The lowest WUI share occurred in the traditional agricultural areas with large fields such as the Silesian Lowlands, the alluvial delta of Vistula, and the central part of the Polish lowlands (Fig. 3).

Effects of WUI radius size

We found that the WUI included the majority of the buildings in Poland, irrespective of the radius that we applied to map the WUI (Fig. 4). However, WUI area was more sensitive to the radius, and especially in areas close to large forests, increasing radius size enlarged substantially the area of the forest mapped as WUI (Fig. 5A), while the area of settlements in WUI remained similar. In areas with relatively small forest patches and dense settlements (i.e., suburban areas), smaller radii (100 or 250 m) identified many small

Fig. 3 WUI extent in Poland depending on the moving window radius used to calculate building and vegetation thresholds

Intermix WUI
Interface WUI
No WUI

km
0   500
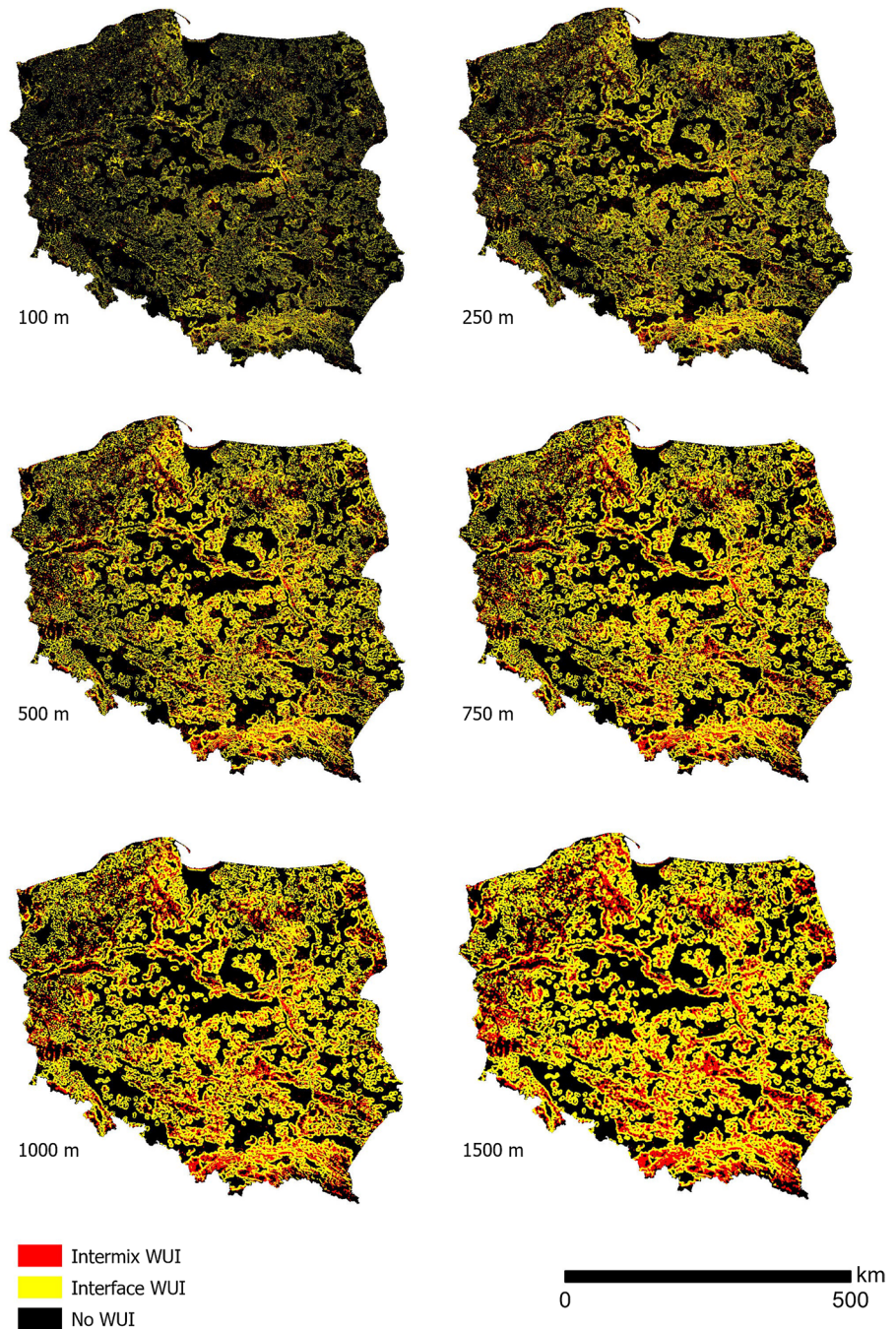
intermix patches, which disappeared with larger radii (Fig. 5B).

When we compared the different WUI maps, we found that the 500-m radius represented a good compromise providing high spatial detail, but not mapping small number of building as WUI (only one house is sufficient to meet the density threshold at

the 100-m radius), and the 500-m radius is also the recommended in the U.S. (Carlson et al. 2022) and in Argentina (Argañaraz et al. 2017), where smaller neighbourhoods were associated with potentially higher error rates, while larger neighbourhoods offered lower precision around buildings. That is why, for general purposes, 500-m neighbourhood was

Fig. 4 Percentage of all buildings located in WUI (line) and total WUI share (bars) in Poland, depending six different circular neighborhood sizes, indicated by the radius distance
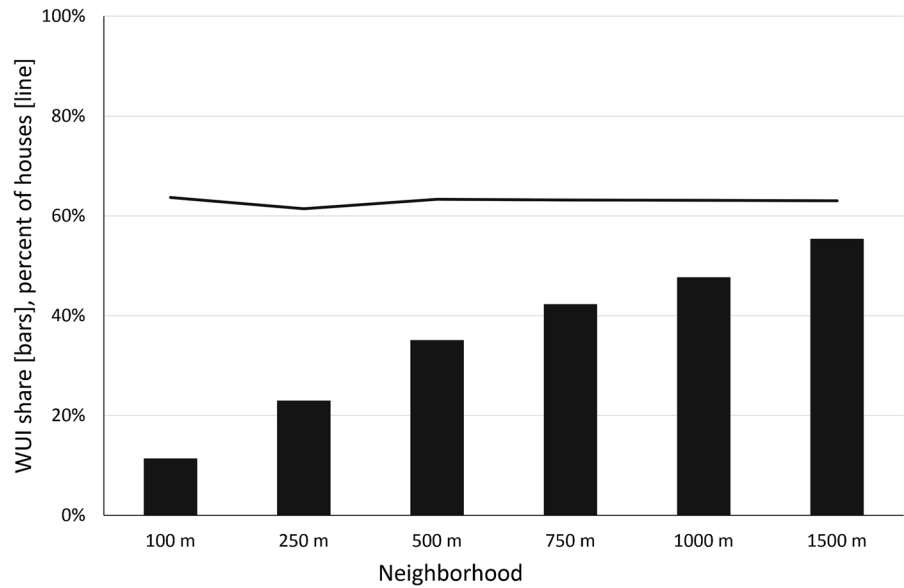
recommended, unless a specific application requires a different radius. In the following, we present all results for 100, 500, and 1500 m radii though, to highlight differences due to scaling effects, and we provide all the 6 variants of maps derived from different radii in the supplementary material.

Our hotspot analysis of the 398 hexagons showed that WUI share and LPI had similar spatial pattern, with several statistically significant hotspots, but only few statistically significant coldspots. The WUI hotspots were mainly in the southern part of Poland around Kraków, in Silesia, and in the surroundings of Warszawa and Łodź. More specifically, the WUI hotspot in the south covered almost all of Małopolska province plus western Podkarpackie province, and the west part of Silesia urban area together with Silesian Beskidy Mts, which is a part of the Carpathians. However, there were no hotspots surrounding the metropolitan areas in the western part of Poland. The coldspots of WUI share were located in the northwest and in south-west of Poland, while coldspot of LPI occurred in the north-west of Poland, or central Poland (1500-m radius WUI map; Fig. 6). Although the overall pattern among the different radii maps was similar, the statistical significance of the hotspots was highest for the 100-m radius map, and lowest for the 1500-m-radius map (Fig. 6). Additionally, in the 1500-m radius maps, coldspots of moderate siginificance were more widespread than for the other radii (Fig. 6).

WUI pattern

Analysis of WUI pattern in relation to historical borders of Poland showed substantially more WUI areas in the southern part of the country, which belonged to the Austro-Hungarian Empire before 1918, and in the central part, which belonged to Russian Empire at that time, than in the formerly Prussian part. In some cases, neighbouring hexagons located along the state border between Poland and Prussia in 1930s had substantial differences in WUI share. Differences in WUI among the ecoregions were minor, but the highest WUI shares occurred in the Carpathians (Fig. 7; for maps based on 100 and 1500-m radii see the supplementary material figures S1 and S2).

WUI pattern analysis based on LPI matched that of the WUI share pattern, in that the largest WUI patches were located in the south, which belonged to the Habsburg Empire before 1918. Differences in the size of the largest WUI patches along the historical Polish-Prussian border from 1930 were again stark. Among the ecoregions, the largest WUI patches were in the Carpathians, but sporadically also in the Lowlands and the Uplands (Fig. 7; and supplementary material S1 and S2).

We found that there was a statistically significant difference among the strata in each case of WUI share and LPI for WUI maps of any radius when we analyzed the differences based on the political divisions of 1900 and on landscape units (please see the
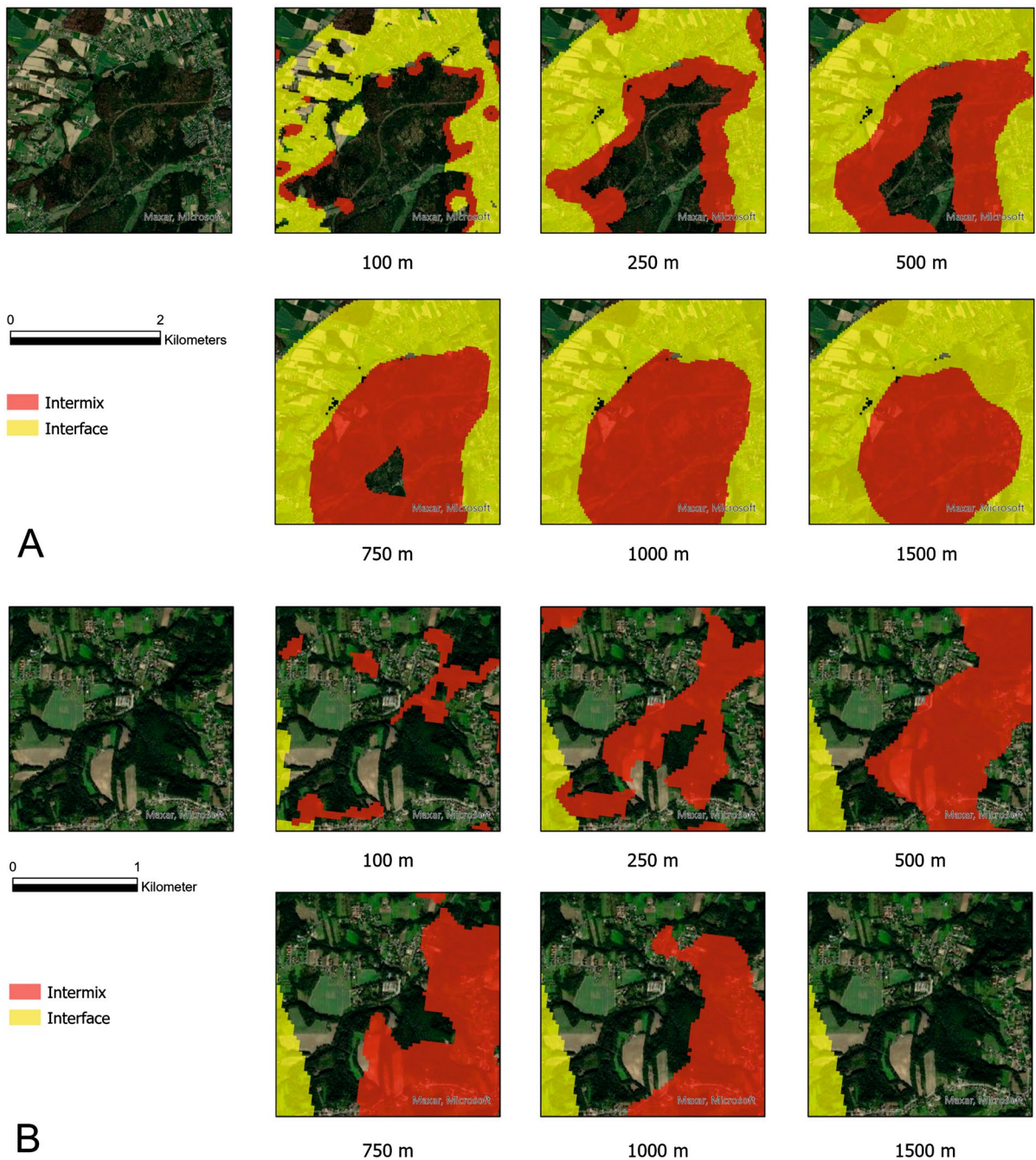
Fig. 5 The effect of the moving window radius on WUI patterns in areas located close to large forests (**A**), or dominated by small forest patches (**B**)

supplementary material for details, Table S2). The pairwise testing showed that for the political division of 1900, the most significant differences, both in terms of WUI share and LPI, occurred when comparing Prussia with other countries, and they were strongest for the 100-m radius map in the case of WUI share, and 500-m radius map for LPI (Table S3).

Fig. 6 Hotspots and coldspots of WUI share (left column) and LPI (Right column) for WUI maps based on 100, 500, and 1500-m radii in Poland
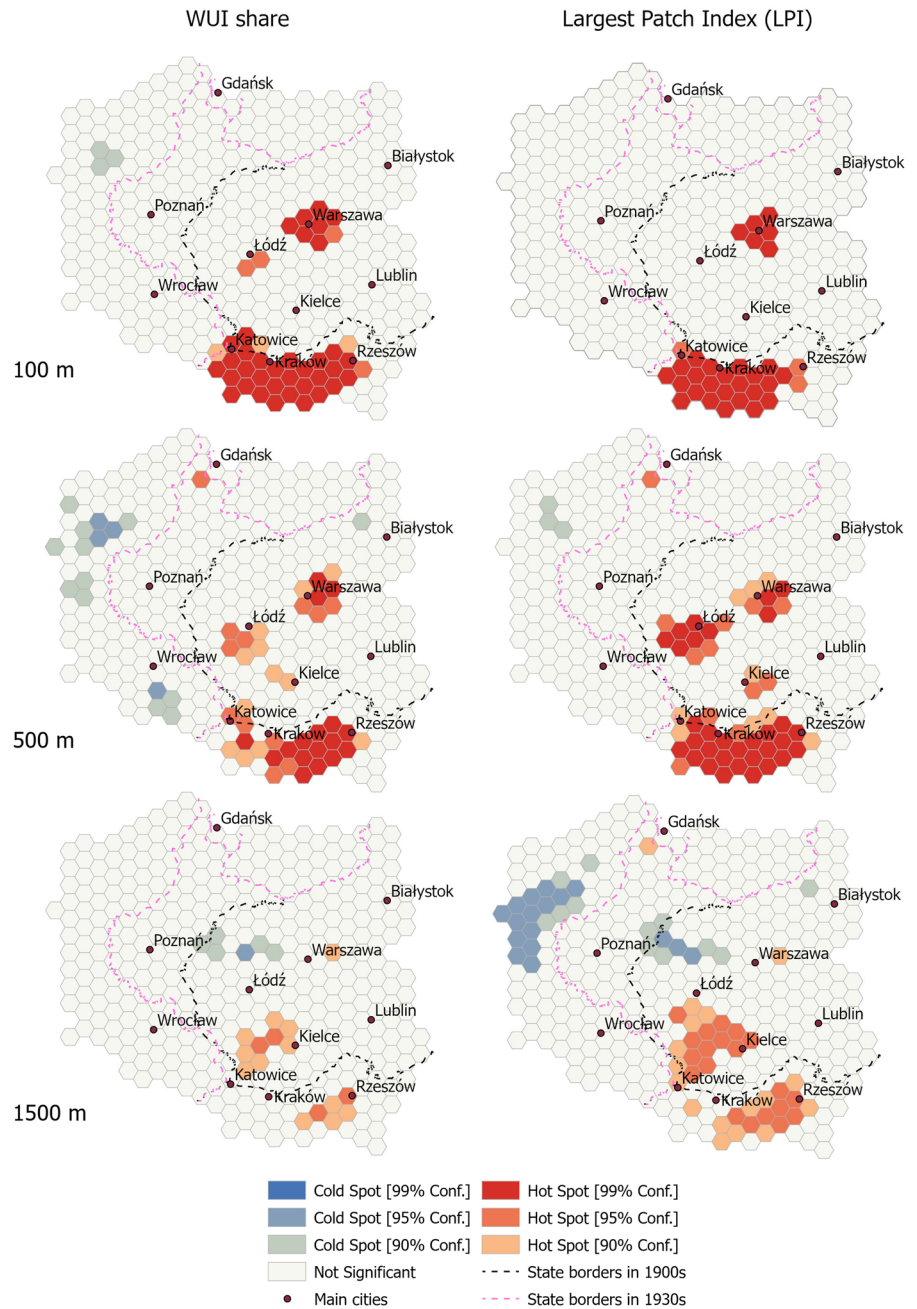
The pairwise differences among the landscape units in WUI share were in most cases statistically significant for 100-m radius, except for the comparison of uplands versus mountains. However, for larger radii, they were only significant for the comparison of the lake district versus the other landscape units. For LPI all the differences in pairs were significant, except for uplands versus mountain (regardless of

radius), and for lake district versus lowlands for the 100-m radius (Table S3).

The political division of 1930 split the hexagons directly into two strata, so we employed only the pairwise testing, which showed that for all mapping radii, the difference between Poland and Prussia was always statistically significant for both WUI share and for LPI (Table S4). For the hexagons located
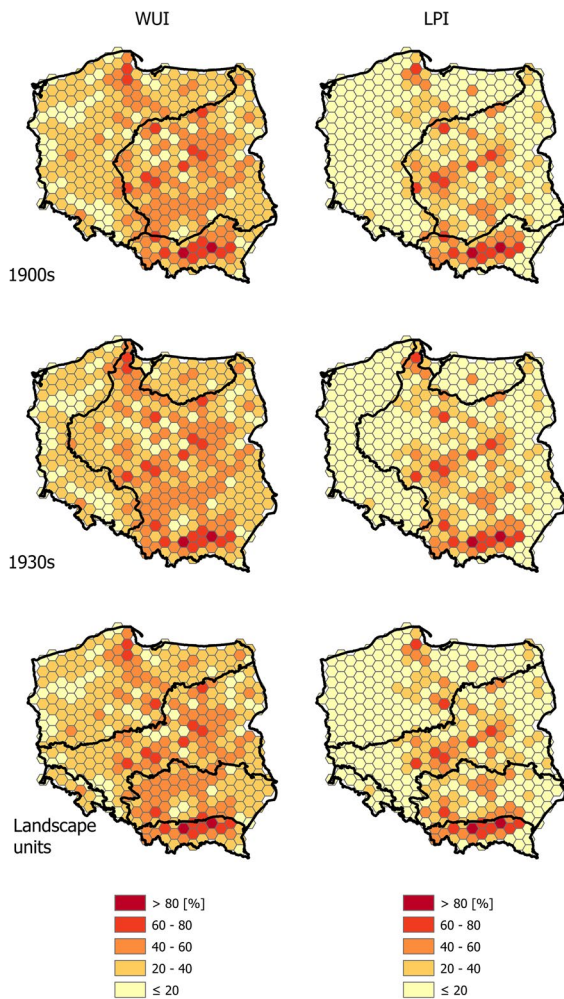
Fig. 7 WUI and LPI (based on 500-m radius) in relation to historical borders and landscape features. Similarly figures for 100 and 1500-m radius maps are available in the supplementary material (Figs. S1, S2)

more than 100 km apart, the only significant differences occurred for the strata reflecting the borders in 1930s for the 100-m radius map for WUI share and the 500-m radius map for LPI (Table S4).

Results from our 500-m radius-based discontinuity analysis, which tested if the proximity to borders affected WUI patterns, found the highest statistically significant effect on WUI share in Prussia along Prussian-Polish border in 1930, and in the lowlands along the border between lowlands and mountains (Table 1). LPI values were in most cases not affected by the distance to border, either national borders, or borders based on landscape units. The place where distance

to border was significant, was in former Russia along the border between former Russia and Austro-Hungary in 1900 (Table 1). However, while distance to border was largely not a significant determinant of WUI share or LPI values, graphical representations of the regression lines showed that differences among countries were nevertheless stark as indicated by the differences in intercepts and slopes in the regression lines right at the borders (Table 1, Fig. 8). Differences in intercepts were the highest along the border of former Austro-Hungary or between uplands and mountains (Table 1). In other words, it was not the distance to the border that mattered, but rather the political unit a given hexagon occurred in.

Discussion

Our results showed that large parts of Poland are located in WUI, with more than 60% of the houses. However, the spatial pattern of WUI is quite heterogeneous raising the question why. In the twentieth century Poland regained independence and witnessed substantial border changes, which are strongly reflected in current WUI pattern. We found that strong differences in WUI share in both, rural areas with different political history, and in urban agglomerations, indicating less WUI in former Prussian lands than elsewhere.

We conducted a structure-based WUI analysis (Bar-Massada et al. 2013), because we had access to exact building locations across the country. When mapping WUI based on structure locations, the radius within which structure density and wildland vegetation proportions are calculated, affects the resulting WUI patterns (Argañaraz et al. 2017; Kaim et al. 2018). We tested a large range of radii and found that 500-m performed especially well for Poland, as is the case for the U.S. (Carlson et al. 2022) and Argentina (Godoy et al. 2019), where that scale was recommended because it provides a good trade-off between high precision around buildings and low error rates. In our case, however, 100 and 1500-m provided broadly similar results to the 500-m radius. Interestingly, this 500-m radius to map the WUI is similar to the recommended radius of the disturbance zone (Theobald et al. 1997; Hawbaker et al. 2006), which is not focused on mapping which settlements are adjacent to wildland areas, but rather which wildland

Table 1 Discontinuity analysis indicating statistical sigfnificance of distance to border on the WUI share and LPI values for hexagons with the centroids within 50 km of the border

WUI share					
	SLOPE 1	SLOPE 2	Differences in intercepts	RMSE 1	RMSE 2
1900					
AUS-PRU[a]	1.541*	− 0.257	92.891	1.987	10.736
RUS-PRU	0.00417	0.0162	2.811	14.124	9.673
RUS-AUS	− 0.523**	0.234	20.509	12.195	18.513
1930					
PRU-POL	0.225***	− 0.0656	5.543	7.909	12.277
Landscape units					
LAKE-LOW	− 0.0556	0.00267	1.183	11.381	12.326
LOW-UP	0.0579	0.0716	2.776	12.576	12.445
LOW-MOUNT	− 0.323***	0.125	9.456	6.360	12.155
MOUNT-UP	0.349	− 0.0766	24.470	16.393	16.076
LPI					
1900					
AUS-PRU	1.541*	− 0.257	92.891	1.987	10.736
RUS-PRU	0.00609	− 0.109	7.553	16.227	10.569
RUS-AUS	− 0.561**	0.514	18.266	13.542	23.838
1930					
PRU-POL	0.0940*	0.0905	10.161	5.331	15.129
Landscape units					
LAKE-LOW	− 0.838	0.0915	0.0389	13.902	13.546
LOW-UP	− 0.143	0.0777	0.967	15.720	13.597
LOW-MOUNT	− 0.0434	0.116	4.205	3.270	8.745
UP-MOUNT	0.449	− 0.491*	20.430	21.660	17.484

1 refers to the first country (landscape unit) in the pair in column 1 and 2 refers to the second country (landscape unit) in the pair in column 1; please note that in the pair UP-MOUNT of the landscape units, in unit UP due to the distance threshold of 50 km, also objects from the unit LOW were also included

AUS Austro-Hungary, *PRU* Prussia, *RUS* Russia, *POL* Poland, *LAKE* lake district, *LOW* lowland, *UP* uplands, *MOUNT* mountains

[a]On the Austro-Hungarian side there were only three observations due to short border section

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

areas are near settlements, and hence most affected by people (Druga and Minár 2018; Xi et al. 2021). The 500-m radius was also advantageous in our study in that it detected WUI in suburban areas well, where both clusters of buildings and wildland vegetation patches are relatively small and were missed by larger radii. However, WUI maps based on the other radii may be of value for specific purposes. For example, smaller radii ensures that all the homes that may be prone to wildfires are mapped. While wildfires are currently not as problematic in Poland as in the United States or Mediterranean Europe, but this may change due to climate change (Fernandez-Anez et al. 2021). On the other hand, larger radii may be helpful for regional, strategic planning, such as conservation planning, which often focuses on large areas with minimal human impact. However, further analyses of the effects scale variation for specific applications (such as human-wildlife interactions, disease transmission, competition between domestic animals and

wildlife) would be very interesting. Lastly, we were surprised to see that while different radii resulted in substantial differences in the total areas mapped as WUI, the number of buildings located in WUI was relatively stable (61.4–63.7%). That gives confidence that slightly more than 60% of buildings in Poland are located in WUI, which is high. Given that urban centers are usually not included in the WUI, it shows that most Polish rural settlements are located relatively close to forests. We suggest that our results thus highlight the need for more strategic spatial planning for future, given that WUI patterns have so far not been taken into account in any local, regional or national planning in Poland.

The value of WUI share for the 500-m radius, which we focused on in our analyses, was also quite high (35.1%). In comparison to the US, when mapping the WUI with the same approach, Poland has a higher share of WUI on average (US average is 15.4%), but similar values to those for Georgia
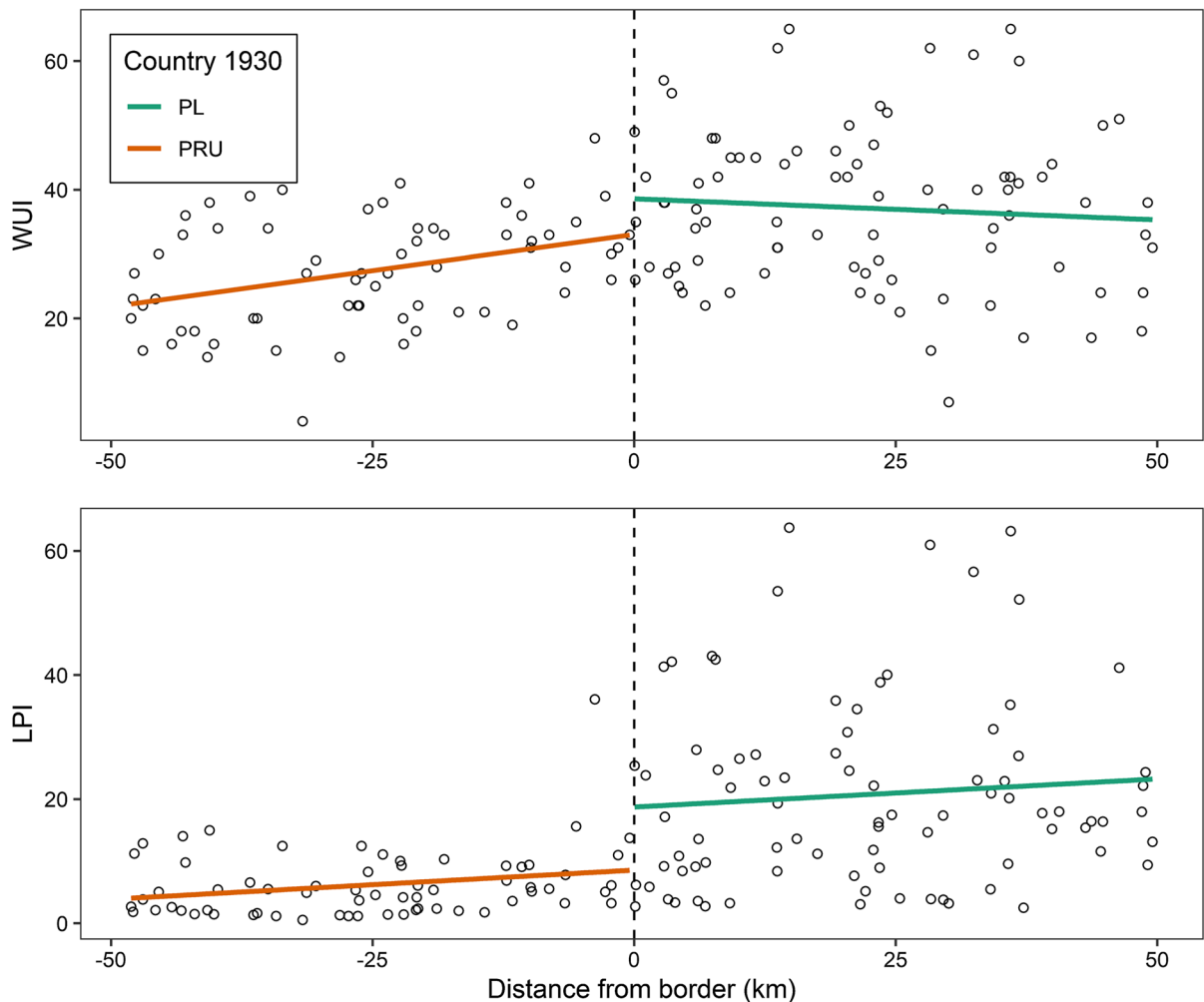
Fig. 8 Discountinuity in WUI share [%] and LPI values within 50 km along the Polish-Prussian border in the 1930s

(36.1%) and New York (34.3%) in 2015, which were respectively the 14th and 15th highest WUI share out of 48 states in the conterminous U.S. (Carlson et al. 2022). However, eastern part of the U.S. with high proportion of WUI areas is partly due to mountainous landscape of Appalachians with high forest proportions due to constraints on farming, coupled with relatively high population density due to a long history of European settlement. However, given that Poland is mainly a lowland country, with less pronounced constraints on agriculture, the WUI is surprisingly widespread in Poland.

When we analyzed the spatial patterns of the WUI across Poland, we found strong evidence that historical national borders, and their legacies, had stronger

effects than ecoregions. To assess the WUI pattern, we compared WUI share and LPI across Poland. We used LPI as an indicator because it is not sensitive to the number of patches, which changes with different radii (Saura 2002). Additionally, LPI is not sensitive to the minimum mapping unit or map resolution, which enables to compare the WUI in different countries. The LPI capture well if WUI occurs in a single large patch, or is fragmented, and occurs in many isolated patches, even when the WUI share is equal. The variation in LPI that we observed highlights the need for future research into the effects of WUI patterns on various ecological processes. Specifically, the part of Poland belonging to Prussia until WW II, was significantly different from the other parts, according to

both the 1900 and the 1930 borders. One reason why those legacies are so strong may be that although the political divisions of the western and northern part of Poland were different in 1900s and 1930s, substantial part of the region belonged to Prussia for long time before, regardless the 1930s border changes. It means, land use evolved under similar institutional conditions for longer periods there than in the other regions, which belonged to Austro-Hungary or Russia in 1900s and became part of Poland in 1918. In general, the persistence of the cultural landscape in Europe is well explained by the frequency of political changes in a given area (Lieskovský and Bürgi 2018). The differences in WUI pattern among ecoregions were also statistically significant, albeit less strongly, with the biggest differences were between the lake district and other ecoregions. This may be an artefact though because > 50% of the hexagons located in lake district belonged to former Prussia in 1930 and almost 90% belonged to Prussia in 1900. So, we cannot rule out that the minor differences among the ecoregions were also at least partly due to political history. This is in line with the difference among the Sudetes and the Carpathians, two mountain areas, that in the past belonged to the different political entities and are only both part of the same country since 1945. In Sudetes, only one hexagon had a WUI share of over 40%, based on 500-m radius map, while in the Carpathians, there were several hexagons with > 75% and some even approaching 90%.

The differences of WUI share among the regions of Poland with different political history may be due to various reasons. Because WUI pattern depends on both settlement and forest pattern, differences in land use planning over long periods may exert strong legacies on current conditions. Additionally, the former Prussian territory witnessed massive out- and in-migration after 1945 (Iglicka 2019), which also affected land use (Latocha et al. 2016). Furthermore, the rural settlement pattern of contemporary Poland still reflects the original processes of village formation taking place centuries ago, and differences between the size and pattern of traditional rural settlement types of western and eastern part of contemporary Poland are stark (Szulc 1995). After WW II, much of the agricultural areas located in the former Prussia were collectivised after German population displacement (Bański 2014), which shaped regional and local land use patterns. Our discontinuity analysis conducted along the former political and landscape borders confirmed that there are strong differences between the regions with different landscape history, and that it is the difference among regions, not the distance to the border than determines those differences. In other words, what matters is past land use history reflecting political divisions, rather than the presence of the borders themselves.

Recent Polish history reinforced historical processes and hence WUI patterns. After the political system changed in 1989, state-owned farms operating on the collectivised lands collapsed, and lands were either sold or leased out by the national Agricultural Property Agency (Bański 2014). Both collectivisation and post-1989 land transactions limited new settlements on agricultural lands strongly in the central and western parts of Poland, but less so in the small-scale privately-owned farmland typical for eastern and southern Poland. Although currently the western and north-western part of Poland is among the most forested areas in the country (Kolecka 2021), which would potentially support WUI existence, its settlement pattern limited WUI there. This is contrary to e.g. the Polish Carpathians, where both high forest cover share and scattered settlements supports WUI existence (Kaim et al. 2018). This suggest, that contrary to U.S., where most of the WUI is due to settlement development (Radeloff et al. 2018), in Poland both forest increase or settlement extent may be important drivers of WUI growth (Kaim et al. 2018).

We found current WUI hotspots mainly around the largest metropolitan areas of central and southern Poland and in the Carpathians. This suggests that suburban regions around largest Polish cities there, are greatly affected by the ecological processes that are concentrated in the WUI. However, this is not the case for suburban areas in the west. This also confirms the importance of the past land use structure of former Prussia, even in the patterns of current metropolitan areas. In general, WUI in suburban areas is a result of two processes. On the one hand, farmland abandonment can lead to more forest there (Krysiak et al. 2020), while on the other hand new settlements at the fringes of cities and along major transportation corridors brings new houses close to existing forests (Bański and Wesołowska 2010; OECD 2018). Rapid land changes around large cities has been common in post-socialists countries including Romania (Grădinaru et al. 2015), Hungary (Cegielska

et al. 2018), and both Czechia and Slovakia (Wnęk et al. 2021). The decline of agriculture and high prices for land that is settled, both enlarge the WUI areas. In the areas, where such settlement arrangements meet or intermingle with wildland vegetation, WUI increase may be much more rapid than in rural areas. Rates of suburbanisation appears to be higher in Poland than, for example, in Slovakia or Czechia, as showed the analysis of more than 50 Functional Urban Areas (Wnęk et al. 2021). This is a result of weak spatial planning (Niedziałkowski and Beunen 2019; Śleszyński et al. 2020), which manifests itself in spontaneous and chaotic settlement development, and supports WUI creation. It is important to add that many of the most rapid land use changes occurred after the political and economic transformations after 1989. The legislation implemented during the 1990s strengthened the rights of private property owners greatly, and weakened local spatial planning. Public interests became less important than private ones (Niedziałkowski and Beunen 2019), and private actors imposed pressures on the planning system to develop more areas. A great example is what happened in the Polish Carpathians, where small-scale privately owned agricultural lands have been abandoned, leading to forest cover increase (Kaim 2017), while weak spatial planning procedures supported the sprawl of settlements (Ćwik and Hrehorowicz-Gaber 2021). Land abandonment in the Carpathians is due to better employment opportunities outside of the agricultural sector (Kolecka et al. 2017), especially in the parts that are easily accessible from the regional urban centres (Kolecka and Kozak 2019). Similar processes may have supported new WUI creation not only in remote mountain areas, but also in around Polish cities. Furthermore, similar institutional changes of spatial planning system occurred in other post-communist countries (Munteanu and Servillo 2014; Varró and Faragó 2015; Grădinaru et al. 2020).

In summary, we present here the first country-wide WUI map of Poland, or for any Central-European country for that matter. Understanding WUI patterns is important for both many research challenges and land management questions in Poland. For instance, the contact zone of forest and settlements are of great importance for indicating human-wildlife interactions, and so the WUI can be used e.g. to better detect the hotspots of the African Swine Fever (Woźniakowski et al. 2021), areas of predation of wildlife by domestic species (Wierzbowska et al. 2016; Krauze-Gryz et al. 2018), animal-vehicle collisions (Basak et al. 2022) or illegal shooting or poaching (Nowak et al. 2021). It could also better define the areas of trade-offs between tourist-related pressures, suburbanisation and environmental protection (Jakiel et al. 2018; Zawilińska 2020). Finally, while wildfires are currently not a major problem in Poland, this may change in the future, and based on stand composition about 83% of all Polish forests are subjected to fire risk (Fernandez-Anez et al. 2021). Should wildfires become more prevalent, then the WUI being so widespread will be a major concern, because of both higher rates of ignitions and higher risk to homes and lives there.

Conclusions

We developed structure-based, spatially detailed WUI maps for all of Poland, and found that the WUI covers substantial parts of Poland. Interestingly though, its current spatial pattern is strongly related to past political divisions and more so than to biophysical differences. So far, the WUI has not been considered in spatial planning in Poland, which is unfortunate given its regarding fire risk, human-animal coexistence, or spatial planning. Our analysis introduces the WUI concept for Poland, and for Eastern Europe, which will open new opportunities to test its applicability in many disciplines. Additionally, the results may provide a basis for formulating recommendations to improve land use planning and protection of agricultural and forest lands and their effective management.

Author contributions DK and MJ and VR designed the study. DK and DH prepared the data. DK and DP conducted the analysis. DK wrote the main manuscript text and prepared Figs. 1–7. DP prepared Fig. 8. VR corrected the language. All authors reviewed the manuscript.

Internal Grant Agency of the Palacký University Olomouc (IGA_PrF_2023_017).

Declarations

References

Adamiak C (2016) Cottage sprawl: spatial development of second homes in Bory Tucholskie, Poland. Landsc Urban Plan 147:96–106.

Argañaraz JP, Radeloff VC, Bar-Massada A et al (2017) Assessing wildfire exposure in the Wildland-Urban Interface area of the mountains of central Argentina. J Environ Manag 196:499–510.

Badia A, Pallares-Barbera M, Valldeperas N, Gisbert M (2019) Wildfires in the wildland-urban interface in Catalonia: vulnerability analysis based on land use and land cover change. Sci Total Environ 673:184–196.

Bański J (2014) Structure and ownership of agricultural land in Poland in the first years of new millennium. J Agric Sci Technol B 4

Bański J, Wesołowska M (2010) Transformations in housing construction in rural areas of Poland's Lublin region—influence on the spatial settlement structure and landscape aesthetics. Landsc Urban Plan 94:116–126.

Bar-Massada A, Stewart SI, Hammer RB et al (2013) Using structure locations as a basis for mapping the wildland urban interface. J Environ Manag 128:540–547.

Bar-Massada A, Radeloff VC, Stewart SI (2014) Biotic and abiotic effects of human settlements in the wildland-urban interface. Bioscience 64:429–437.

Basak SM, O'Mahony DT, Lesiak M et al (2022) Animal-vehicle collisions during the COVID-19 lockdown in early 2020 in the Krakow metropolitan region. Poland Sci Rep 121(12):1–14.

Bento-Gonçalves A, Vieira A (2020) Wildfires in the wildland-urban interface: key concepts and evaluation methodologies. Sci Total Environ 707:135592.

Blecha KA, Boone RB, Alldredge MW (2018) Hunger mediates apex predator's risk avoidance response in wildland-urban interface. J Anim Ecol 87:609–622.

Carlson AR, Helmers DP, Hawbaker TJ et al (2022) The wildland-urban interface in the United States based on 125 million building locations. Ecol Appl 32:e2597.

Castro-Prieto J, Martinuzzi S, Radeloff VC et al (2017) Declining human population but increasing residential development around protected areas in Puerto Rico. Biol Conserv 209:473–481.

Cegielska K, Noszczyk T, Kukulska A et al (2018) Land use and land cover changes in post-socialist countries: some observations from Hungary and Poland. Land Use Policy 78:1–18.

Chai B, Seto KC (2019) Conceptualizing and characterizing micro-urbanization: a new perspective applied to Africa. Landsc Urban Plan 190:103595.

Chapron G, Kaczensky P, Linnell JDC et al (2014) Recovery of large carnivores in Europe's modern human-dominated landscapes. Science (80-) 346:1517–1519.

Conedera M, Tonini M, Oleggini L et al (2015) Geospatial approach for defining the wildland-urban interface in the Alpine environment. Comput Environ Urban Syst 52:10–20.

Ćwik A, Hrehorowicz-Gaber H (2021) Causes and effects of spatial Chaos in the Polish Carpathians—a difficult way to sustainable development. Eur Countrys 13:153–174

Davies N (2011) Vanished kingdoms: the history of half-forgotten Europe. Penguin UK

Druga M, Minár J (2018) Exposure to human influence—a geographical field approximating intensity of human influence on landscape structure. J Maps 14:486–493.

EEA Report (2011) Landscape fragmentation in Europe

Evans MJ, Rittenhouse TAG, Hawley JE, Rego PW (2017) Black bear recolonization patterns in a human-dominated landscape vary based on housing: new insights from spatially explicit density models. Landsc Urban Plan 162:13–24.

Fernandez-Anez N, Krasovskiy A, Müller M et al (2021) Current wildland fire patterns and challenges in europe: a synthesis of national perspectives. Air Soil Water Res 14:11786221211028185.

Foster D, Swanson F, Aber J et al (2003) The importance of land-use legacies to ecology and conservation. Bioscience 53:77–88.

Gavier-Pizarro GI, Radeloff VC, Stewart SI et al (2010a) Housing is positively associated with invasive exotic plant species richness in New England, USA. Ecol Appl 20:1913–1925.

Gavier-Pizarro GI, Radeloff VC, Stewart SI et al (2010b) Rural housing is related to plant invasions in forests of southern Wisconsin, USA. Landsc Ecol 25:1505–1518.

Godoy MM, Martinuzzi S, Kramer HA et al (2019) Rapid WUI growth in a natural amenity-rich region in central-western Patagonia, Argentina. Int J Wildl Fire 28:473–484.

Grădinaru S, Iojă CI, Onose DA et al (2015) Land abandonment as a precursor of built-up development at the sprawling periphery of former socialist cities. Ecol Indic 57:305–313.

Grădinaru S, Fan P, Iojă CI et al (2020) Impact of national policies on patterns of built-up development: an assessment over three decades. Land Use Policy 94:104510.

Harvey F (2013) The power of mapping: considering discrepancies of Polish cadastral mapping. Ann Assoc Am Geogr 103:824–843.

Hawbaker TJ, Radeloff VC, Clayton MK et al (2006) Road development, housing growth, and landscape fragmentation in Northern Wisconsin: 1937–1999. Ecol Appl 16:1222–1237.

Iglicka K (2019) Poland's post-war dynamic of migration. Routledge

Jakiel M, Bernatek-Jakiel A, Gajda A et al (2018) Spatial and temporal distribution of illegal dumping sites in the nature protected area: the Ojców National Park, Poland. J Environ Plan Manag 62:286–305.

Jenerette GD, Anderson KE, Cadenasso ML et al (2022) An expanded framework for wildland–urban interfaces and their management. Front Ecol Environ 9:516–523

Kaim D (2017) Land cover changes in the Polish Carpathians based on repeat photography. Carpathian J Earth Environ Sci 12:485–498

Kaim D, Radeloff VC, Szwagrzyk M et al (2018) Long-term changes of the wildland–urban interface in the Polish Carpathians. ISPRS Int J Geo-Inf 7:137.

Kil N, Stein TV, Holland SM (2014) Influences of wildland-urban interface and wildland hiking areas on experiential recreation outcomes and environmental setting preferences. Landsc Urban Plan 127:1–12.

Kolecka N (2021) Greening trends and their relationship with agricultural land abandonment across Poland. Remote Sens Environ 257:112340.

Kolecka N, Kozak J (2019) Wall-to-wall parcel-level mapping of agricultural land abandonment in the Polish Carpathians. Land 8:129.

Kolecka N, Kozak J, Kaim D et al (2017) Understanding farmland abandonment in the Polish Carpathians. Appl Geogr 88:62–72.

König HJ, Kiffner C, Kramer-Schadt S et al (2020) Human–wildlife coexistence in a changing world. Conserv Biol 34:786–794.

Krauze-Gryz D, Gryz J, Żmihorski M (2018) Cats kill millions of vertebrates in Polish farmland annually. Glob Ecol Conserv 17:e00516.

Krysiak S, Papińska E, Majchrowska A et al (2020) Detecting land abandonment in Łódź Voivodeship using convolutional neural networks. Land 9:82.

Lampin-Maillet C, Jappiot M, Long M et al (2010) Mapping wildland-urban interfaces at large scales integrating housing density and vegetation aggregation for fire prevention in the South of France. J Environ Manag 91:732–741.

Latocha A, Szymanowski M, Jeziorska J et al (2016) Effects of land abandonment and climate change on soil erosion—an example from depopulated agricultural lands in the Sudetes Mts. SW Poland CATENA 145:128–141.

Lieskovský J, Bürgi M (2018) Persistence in cultural landscapes: a pan-European analysis. Reg Environ Chang 18:175–187.

MacDonald AJ, Larsen AE, Plantinga AJ (2019) Missing the people for the trees: Identifying coupled natural–human system feedbacks driving the ecology of Lyme disease. J Appl Ecol 56:354–364.

Main-Knorn M, Hostert P, Kozak J, Kuemmerle T (2009) How pollution legacies and land use histories shape post-communist forest cover trends in the Western Carpathians. For Ecol Manag 258:60–70.

Malinowski R, Lewiński S, Rybicki M et al (2020) Automated production of a land cover, use map of Europe based on Sentinel-2 imagery. Remote Sens 12:3523.

Mockrin MH, Helmers D, Martinuzzi S et al (2022) Growth of the wildland-urban interface within and around US National Forests and Grasslands, 1990–2010. Landsc Urban Plan 218:104283.

Modugno S, Balzter H, Cole B, Borrelli P (2016) Mapping regional patterns of large forest fires in wildland-urban interface areas in Europe. J Environ Manag 172:112–126.

MPIDR [Max Planck Institute for Demographic Research] and CGG [Chair for Geodesy and Geoinformatics U of R (2011) MPIDR Population History GIS Collection (partly based on Hubatsch and Klein 1975 ff.)—Rostock. Hubatsch W, Klein T (eds) 1975 ff. Grundriß der deutschen Verwaltungsgeschichte, Marburg

Munteanu M, Servillo L (2014) Romanian spatial planning system: post-communist dynamics of change and europeanization processes. Eur Plan Stud 22:2248–2267.

Munteanu C, Kuemmerle T, Keuler NS et al (2015) Legacies of 19th century land use shape contemporary forest cover. Glob Environ Chang 34:83–94.

Newton P, Kinzer AT, Miller DC et al (2020) The number and spatial distribution of forest-proximate people globally. One Earth 3:363–370.

Niedziałkowski K, Beunen R (2019) The risky business of planning reform—the evolution of local spatial planning in Poland. Land Use Policy 85:11–20.

Noack F, Larsen A, Kamp J, Levers C (2021) A bird's eye view of farm size and biodiversity: the ecological legacy of the iron curtain. Am J Agric Econ 4:1460–1484.

Nowak S, Żmihorski M, Figura M et al (2021) The illegal shooting and snaring of legally protected wolves in Poland. Biol Conserv 264:109367.

OECD (2018) Rethinking urban sprawl. OECD Publishing, Paris

Ostafin K, Kaim D, Troll M, Maciejowski W (2020) The authorship of the Second Military Survey of Galicia and Austrian Silesia at the scale 1:28,800 and the consistency of sheet content based on selected examples. Polish Cartogr Rev 52:141–151.

Paris C (2014) Critical commentary: second homes. Ann Leis Res 17:4–9.

Pop MI, Iosif R, Miu IV et al (2018) Combining resource selection functions and home-range data to identify habitat conservation priorities for brown bears. Anim Conserv 21:352–362.

Pop MI, Dyck MA, Chiriac S et al (2023) Predictors of brown bear predation events on livestock in the Romanian Carpathians. Conserv Sci Pract 5:e12884.

Radeloff VC, Hammer RB, Stewart SI et al (2005) The wildland-urban interface in the United States. Ecol Appl 15:799–805.

Radeloff VC, Helmers DP, Kramer HA et al (2018) Rapid growth of the US wildland-urban interface raises wildfire risk. Proc Natl Acad Sci USA 115:3314–3319.

Rhemtulla JM, Mladenoff DJ, Clayton MK (2009) Legacies of historical land use on regional forest composition and structure in Wisconsin, USA (mid-1800s–1930s–2000s). Ecol Appl 19:1061–1078.

Rosner A, Wesołowska M (2020) Deagrarianisation of the economic structure and the evolution of rural settlement patterns in Poland. Land 9:523.

Saura S (2002) Effects of minimum mapping unit on land cover data spatial configuration and composition. Int J Remote Sens 23:4853–4880.

Saura S, Millan M (2001) Sensitivity of landscape pattern metrics to map spatial exte. Photogramm Eng Remote Sen 67:1027–1036

Schug F, Bar-Massada A, Carlson AR, et al (2023) The global wildland-urban interface. Nature

Sheard N (2019) Vacation homes and regional economic development. Reg Stud 53:1696–1709.

Śleszyński P, Kowalewski A, Markowski T et al (2020) The contemporary economic costs of spatial Chaos: evidence from Poland. Land 9:214.

Solon J, Borzyszkowski J, Bidłasik M et al (2018) Physico-geographical mesoregions of Poland: verification and adjustment of boundaries on the basis of contemporary spatial data. Geogr Pol 91:143–170.

Szulc HZ (1995) Morfogeneza osiedli wiejskich w Polsce. IGiPZ PAN

Tarasiuk K, Giżejewski Z (2021) Behawior dzików w aspekcie znaczenia tego gatunku zwierząt jako głównego rezerwuaru wirusa ASF. Med Weter 77:6501–2021.

Theobald DM, Miller JR, Hobbs NT (1997) Estimating the cumulative effects of development on wildlife habitat. Landsc Urban Plan 39:25–36.

USDA and USDI (2001) Urban wildland interface communities within vicinity of Federal lands that are at high risk from wildfire. Federal Register 66

Varró K, Faragó L (2015) The politics of spatial policy and governance in post-1990 Hungary: the interplay between European and national discourses of space. Eur Plan Stud 24:39–60.

Wierzbowska IA, Hędrzak M, Popczyk B et al (2016) Predation of wildlife by free-ranging domestic dogs in Polish hunting grounds and potential competition with the grey wolf. Biol Conserv 201:1–9.

Wnęk A, Kudas D, Stych P (2021) National Level Land-Use Changes in Functional Urban Areas in Poland, Slovakia, and Czechia. Land 10:39.

Woźniakowski G, Pejsak Z, Jabłoński A (2021) Emergence of African Swine Fever in Poland (2014–2021). Successes and failures in disease eradication. Agric 11:738.

Xi C, Wu Z, Qian T et al (2021) A Bayesian model for estimating the effects of human disturbance on wildlife habitats based on nighttime light data and INLA-SPDE. Appl Spat Anal Policy 15:573–594.

Xiao C, Li P, Feng Z, Zheng F (2021) Global border watch: From land use change to joint action. Int J Appl Earth Obs Geoinf 103:102494.

Zawilińska B (2020) Residents' attitudes towards a national park under conditions of suburbanisation and tourism pressure: a case study of Ojców National Park (Poland). Eur Countrys 12:119–137.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.