



Growth of the wildland-urban interface and its spatial determinants in the Polish Carpathians

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ABSTRACT

The Wildland-Urban Interface (WUI) is the area where natural vegetation is close to housing and area of concern due to various negative consequences for humans and the environment including fire ignitions, landscape fragmentation and human-wildlife interactions. The WUI is a global phenomenon, and widespread in many countries but long-term WUI dynamics and the main factors causing WUI growth are unknown. Our goal was to assess WUI changes in the Polish Carpathians since the mid-19th century, based on high-resolution spatial data for 1860s, 1970s and 2013. We found that WUI covered already 30% of the study area in the 1860s but grew to cover nearly half by 2013, especially at lower elevations. Detailed analysis of WUI determinants confirmed the areas closer to regional administrative centres or located on steep slopes were more WUI-prone. Tourist trail density also fostered WUI occurrence. We conclude that in Central Europe, with a long history of human settlements and agricultural activities, WUI has been a persistent landscape feature for centuries, but increased in area in recent decades due to widespread abandonment of agricultural land combined with development of new residential areas.

1. Introduction

Rapid land use change in many parts of the globe has profound effects on ecosystem services (Hasan, Zhen, Miah, Ahamed, & Samie, 2020), biodiversity (Titeux et al., 2016) and carbon balance (Searchinger, Wierseni, Beringer, & Dumas, 2018). As specific land uses wax and wane, there is also change in the contact zones at the fringe of natural land cover, which may affect socio-ecological processes. One example of such a contact zone is the wildland-urban interface (WUI), the area where houses meet wildland vegetation. From 1990 to 2010 the WUI was the fastest-growing land use type in the US (Radeloff et al., 2018). Globally, the WUI covers almost 5% of the Earth's surface and is home to more than 40% of its inhabitants (Schug et al., 2023). That is concerning, because the WUI is the area where wildfires pose the greatest threat to houses (Bento-Gonçalves & Vieira, 2020; Radeloff et al., 2023), invasive species introduction are common (Gavier-Pizarro, Radeloff, Stewart, Huebner, & Keuler, 2010), wildlife competes with free-ranging pets (Bar-Massada, Radeloff, & Stewart, 2014), and some zoonotic diseases are concentrated (MacDonald, Larsen, & Plantinga,

2019). Furthermore, large carnivores may prefer WUI for relatively easily available food, in spite of human presence, which makes the WUI an area of higher rates of human-wildlife interactions (Blecha, Boone, & Alldredge, 2018). Due to all the environmental problems that are concentrated in the WUI, it is important to manage WUI areas appropriately (Jenerette et al., 2022). Often such management has focussed on wildfires either via adaptation-oriented (Edgeley, Paveglio, & Williams, 2020; Gonzalez-Mathiesen, Ruane, & March, 2021) or risk reduction-oriented measures (Sánchez, Holmes, Loomis, & González-Cabán, 2022), and a common recommendation is to limit future housing growth in WUI areas. However, WUI can grow due to either housing development or increasing wildland vegetation, and both processes reflect historical legacies (Kaim, Helmers, Jakiel, Pavlačka, & Radeloff, 2023), making WUI growth likely.

Despite the fact that the WUI is widespread in many areas with quite different environmental settings and socioeconomic history, little is known about how the WUI has evolved over time. In recent decades, WUI area grew in the conterminous US by 33%, and the number of WUI houses by 41% from 1990 to 2010 (Radeloff et al., 2018). While that

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suggests rapid recent growth, it also means two-thirds of the 2010 WUI area, and more than half of the WUI houses existed already prior to 1990. Similar rapid recent WUI growth occurred in Alaska from 2000 to 2010 (Liang, Liu, Wang, & Wang, 2022) and in central-western Patagonia between 1981 and 2016 (Godoy et al., 2019). In the city of Cape Town, South Africa, however, by contrast, the WUI decreased from 1990 to 2019 (Christ, Schwarz, & Sliuzas, 2022).

The determinants of WUI growth vary considerably among regions. In southern Europe urbanization and population growth in forested areas at the beginning of 21st century, combined with poor land use planning in WUI were the important factors (Ganteaume, Barbero, Jappiot, & Maillé, 2021). In the conterminous US, housing growth was by far the dominant determinant from 1990 to 2010 (Radeloff et al., 2018). However, which determinants are most important may differ quite strikingly even among areas that are fairly close. In a comparison of WUI dynamics between 1860s and 2013 in two small districts in the Polish Carpathians, forest cover increase was the main determinant in one district but housing growth in the other (Kaim, Radeloff, Szwagrzyk, Dobosz, & Ostafin, 2018). That suggest that more in-depth analysis of long-term WUI growth patterns and determinants are necessary in general and that the Carpathians are an especially interesting place to do so because causes of WUI growth vary there.

Our goal here was to: a) analyze WUI change and persistence for three time steps spanning over 150 years to define WUI trajectories in the Polish Carpathians, b) compare the role of housing growth and forest cover change as main triggers of WUI growth, c) assess the role of other spatial determinants of WUI occurrence.

2. Methods

2.1. Study area

We conducted our analyses for three time periods (1860s, 1970s, 2013) in the Polish part of the Carpathian Mountains (Fig. 1), with the boundaries defined by the current political boundaries in the south, west and east, and the ecoregion boundary in the north (ca. 20,000 km² in total) for 1970s and 2013, and administrative boundaries of the Austrian Empire for the 1860s resulting in a 2.5% smaller area than in 1970s and 2013, due to the more limited availability of historical data (see section WUI mapping). Analyses based on commune-level socioeconomic data were conducted for the communes located completely within the ecoregion boundaries (n = 194), with a total area of 18,200 km², again due to data availability.

The Carpathian landscape is a mosaic of forest and agriculture. Due to long-term human colonisation and agricultural expansion, forest cover reached a minimum extent (27%) around the mid-19th century but has been increasing since reaching 47% currently (Kaim et al., 2016; Troll & Ostafin, 2016). Concomitantly, population almost doubled in the

region, increasing from 1869 to 1998 from 1.3 million to 2.4 million (Soja, 2012), which included a substantial transformation of the settlement network.

2.2. WUI mapping

We based our WUI analyses on the definition in the US Federal Register (USDA and USDI, 2001) and further developed by Radeloff et al. (2005), which identifies two main types of WUI: intermix and interface. Intermix WUI is an area with a housing density higher than 6.17 houses/km² (1 house/40 acres) and more than 50% of wildland vegetation. Interface WUI is an area with housing density higher than 6.17 houses/km², less than 50% of wildland vegetation, and within 2.4 km of a wildland vegetation patch (contiguous region with more than 75% wildland vegetation) larger than 5 km². Given the ecological context of the Polish Carpathians, we defined wildland vegetation as forests, because forests are the climax vegetation type below the tree-line. To assess settlements, we analysed all buildings (residential and non-residential), because all buildings reflect human activities.

To map WUI we used a range of sources for three periods: 1860s, 1970s and 2013. For the 1860s a detailed forest delineation was available from the Austrian second military survey maps (1:28,800) vectorisation (Kaim et al., 2016). We also obtained information on historical building locations (vector point file) from the military survey maps, which provide high-quality building data (OA > 95%) (Kaim, Szwagrzyk, Dobosz, Troll, & Ostafin, 2021). For 1970s, our forest cover dataset stemmed from the semi-automatic processing of 1:25,000 topographic maps (Ostafin et al., 2017). Building locations were obtained from 630 map sheets of the 1:10,000 topographic maps, analysed with a deep learning algorithm Mask R-CNN model implemented in ArcGIS Pro software (He, Gkioxari, Dollár, & Girshick, 2020) to extract building locations. The model was trained using sample of 6000 building footprints and after creating a complete coverage, visually inspected in order to add omitted, and remove falsely detected buildings (Szubert et al., in preparation). For 2013, we used digital forest data created by Dobosz, Kozak, and Kolečka (2019), where forest is presented based on land use, matching the topographic maps for the prior times periods, which makes the data comparable. The building locations were obtained from the Polish Topographic Database at 1:10,000 scale (BDOT10k, 2013).

The buildings layers were stored in the point vector format, while the forest cover data were converted to raster format with 10-m resolution. We used WUI definitions explained above to compute forest cover and building densities, and forest cover patch sizes. Densities were calculated for a moving window with a 500-m radius, which is the optimal radius to map forest patches and settlements pattern in e.g. the US, Argentina, and Poland (Carlson, Helmers, Hawbaker, Mockrin, & Radeloff, 2022; Godoy et al., 2019; Kaim et al., 2023). Outputs were overlaid to receive the WUI maps for all periods (1860s, 1970s, 2013).

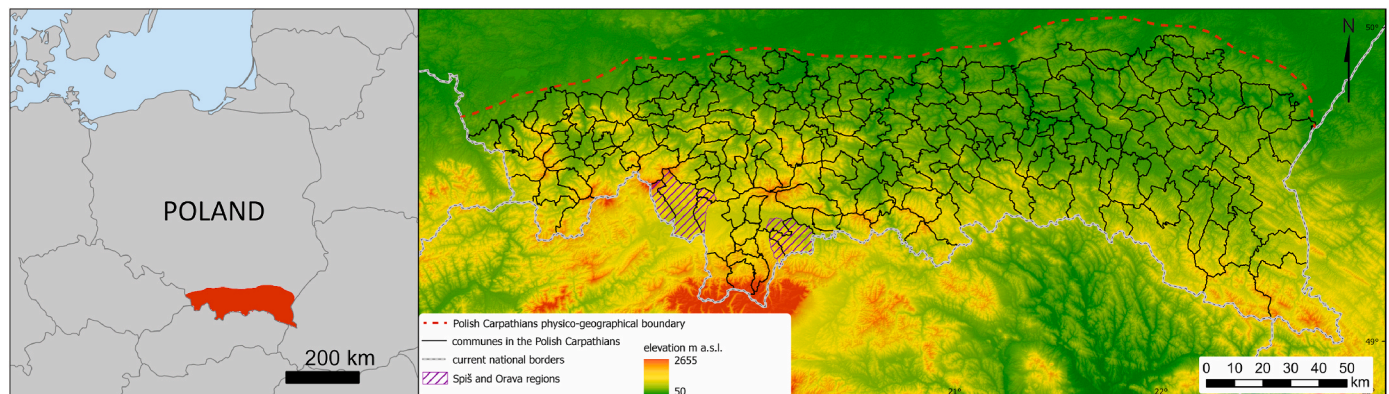


Fig. 1. Study area.

with a spatial resolution of 10 m.

In addition, we stratified interface and intermix WUI, and non-WUI areas into very low, low, medium and high building density level classes (by definition, the very low-density class can occur only in non-WUI areas, Table 1) to assess changes in building densities in WUI and non-WUI areas. The building density threshold values for WUI classes followed precedent (Radeloff et al., 2005; Syphard et al., 2007; Zheng, Heath, & Ducey, 2012). We also added information on which land cover dominated in the different non-WUI classes, to characterize them.

2.3. WUI changes over time

We compared the spatial extent of WUI areas in three periods and changes over time. Thereafter, we analysed transitions between level 3 density-related WUI classes over time in a post-classification comparison (Table 1). Additionally, we computed the percentages of all buildings in respective WUI categories and how they changed among time periods.

2.4. WUI spatial determinants

For the other approach, to explain commune-level occurrence of WUI we applied stepwise OLS regressions (Tables A1–A3 in the Appendix). We tested several models with up to five variables, with a threshold for collinearity ($VIF < 7.5$). In total, we tested 1585 models for the 1860s, 6884 for the 1970s and 21,699 for 2013, because the number of models tested depended on the number of variables available for a given time point. Then we checked how many times each variable was statistically significant, and how often its effect was positive or negative (Table 2). For the best performing models (5 best variables, highest adjusted r-Square, lowest AIC), we accounted for the spatiotemporal character of the relation between the WUI and other determinants by using a spatial lag regression model (Anselin, 2005). Finally, we assessed legacy effects for the 1970s and 2013 WUI by including the area of WUI from the previous time period as an additional variable.

Table 1

Building density classes for WUI and non-WUI areas (with dominating land cover).

Level 1	Level 2	Level 3	Building density [building units/km ²]
WUI areas	Intermix WUI	Medium building density Intermix WUI	49.42–741.31
		Low building density Intermix WUI	6.17–49.42
		High building density Interface WUI	>741.31
	Interface WUI	Medium building density Interface WUI	49.42–741.31
		Low building density Interface WUI	6.17–49.42
		Very low building density non-WUI	<6.17
Non-WUI areas	Dominant land cover		
	Dense urban areas	High building density non-WUI	>741.31
	Other urban areas and highly developed rural areas	Medium building density non-WUI	49.42–741.31
	Areas with more agriculture than forest	Low building density non-WUI	6.17–49.42
	Areas with more forest than agriculture	Very low building density non-WUI	<6.17

Table 2

Variable significance (the percentage of our regression models in which a given variable was a candidate variable and significant), and the direction of its effect in regression models (only variables significant in at least 50% of the models are shown).

variable	% significant	% negative	% positive
1860 (n = 1585)			
Average nearest neighbor among buildings	100	0	100
Distance to railways	100	100	0
Forest cover	98.40	0	100
Mean slope	84.70	0	100
Distance to rivers	52.49	100	0
Building density	51.96	14.77	85.23
Elevation range	50.18	44.13	55.87
Forest largest patch index	50.00	31.32	68.68
1970 (n = 6884)			
WUI in 1860	100	0	100
Average nearest neighbor among buildings	100	100	0
Tourist trail density	83.72	0	100
Mean slope	81.14	2.06	97.94
Distance to regional center 1975	56.11	93.56	6.44
Forest largest patch index	55.69	70.84	29.16
Forest cover	52.50	19.53	80.47
2013 (n = 21,699)			
WUI in 1970	100	0	100
WUI in 1860	98.55	0	100
Orthodox church in municipality in 1857	84.53	100	0
Distance to main regional center 2013	81.35	100	0
Average farm size	78.87	93.43	6.57
Mean slope	63.22	30.22	69.78
Tourist trail density	61.34	17.24	82.76
Elevation range	58.44	91.38	8.62
Forest largest index patch	54.35	73.73	26.27
Forest cover	50.18	41.14	58.86

3. Results

3.1. WUI changes over time and transitions among WUI and non-WUI classes

The WUI grew in the Polish Carpathians from 30.4% in the 1860s (Interface: 26.2%, Intermix: 4.2%) to 40.7% in the 1970s (Interface: 31.6%, Intermix: 9.1%) and 48.9% in 2013 (Interface: 35.1%, Intermix: 13.8%). The share of buildings in WUI increased from 55.9% in the 1860s to 57.2% in the 1970s and 68.4% in 2013. Building density in WUI also increased over time. In the Interface WUI, low building density dominated in the 1860s (21.6%), but medium building density became dominant in the 1970s (17.9%) and remained dominant in 2013 (26%; Fig. 2). In the Intermix WUI, low building density was always more widespread than medium building density, but both density classes increased in area over time (Fig. 3). Non-WUI areas decreased in area from the 1860s to 2013, even though building density in non-WUI areas increased (Fig. 3). For example, medium density of buildings covered 4% of non-WUI areas in the 1860s, nearly 15% in the 1970s and 11.3% in 2013, being partly transformed into Interface WUI, while share of low-density areas decreased from 15.4% the 1860s to 2.9% in 2013 (Fig. 3).

In general, WUI was more widespread at all time periods in the western and central parts of the Polish Carpathians compared to the eastern part. However, while the western part experienced a substantial increase in WUI area and intensity from the 1860s to the 1970s, in the eastern part, large portions of WUI disappeared, while the intensity in the areas of persistent WUI increased, similar to the western part. The main pattern of change from the 1970s to 2013 was a further increase of WUI intensity, but not much WUI area growth in the southern, mountainous part of the study area, with a substantial increase in WUI area in

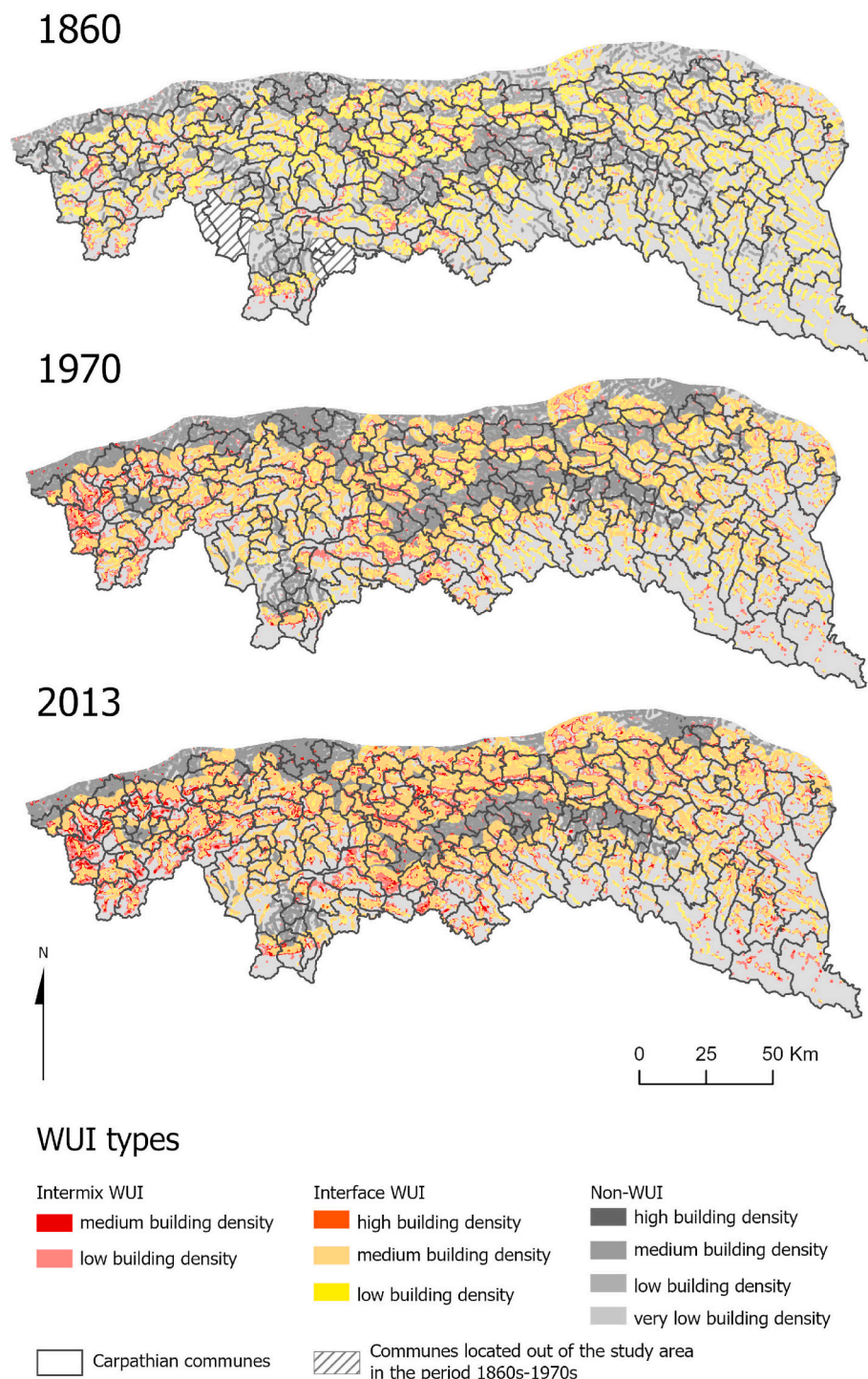


Fig. 2. WUI in the Polish Carpathians in the 1860s, 1970s and 2013.

the north, foothills part (Fig. 2).

3.2. WUI persistence

WUI persistence over time was spatially quite heterogeneous in the Carpathians. While in some communes in the northern and central part of the study area more than 60% of the 2013 WUI areas were WUI already in the 1860s, the persistence of WUI in the southern, and especially in the south-eastern part of the Carpathians was less than 15%. On average, 31% of the current WUI was already WUI the 1860s and 45% of the current WUI was already WUI in the 1970s (Fig. 4).

When taking the 1970s as the starting point, in nearly 30% of communes, located mainly in western and central part of the Carpathians, at least 60% of the 2013 WUI was already WUI in 1970s (Fig. 4).

3.3. WUI spatial determinants

The comparison of factual and counterfactual scenarios for the WUI changes from the 1860s to the 1970s indicated that the Jaccard index-based similarity of the actual 1970s WUI map was higher for the scenario based on 1860s forests and 1970s settlements than that for 1860s buildings and 1970s forests (76%; Fig. 5). In contrast, for the WUI

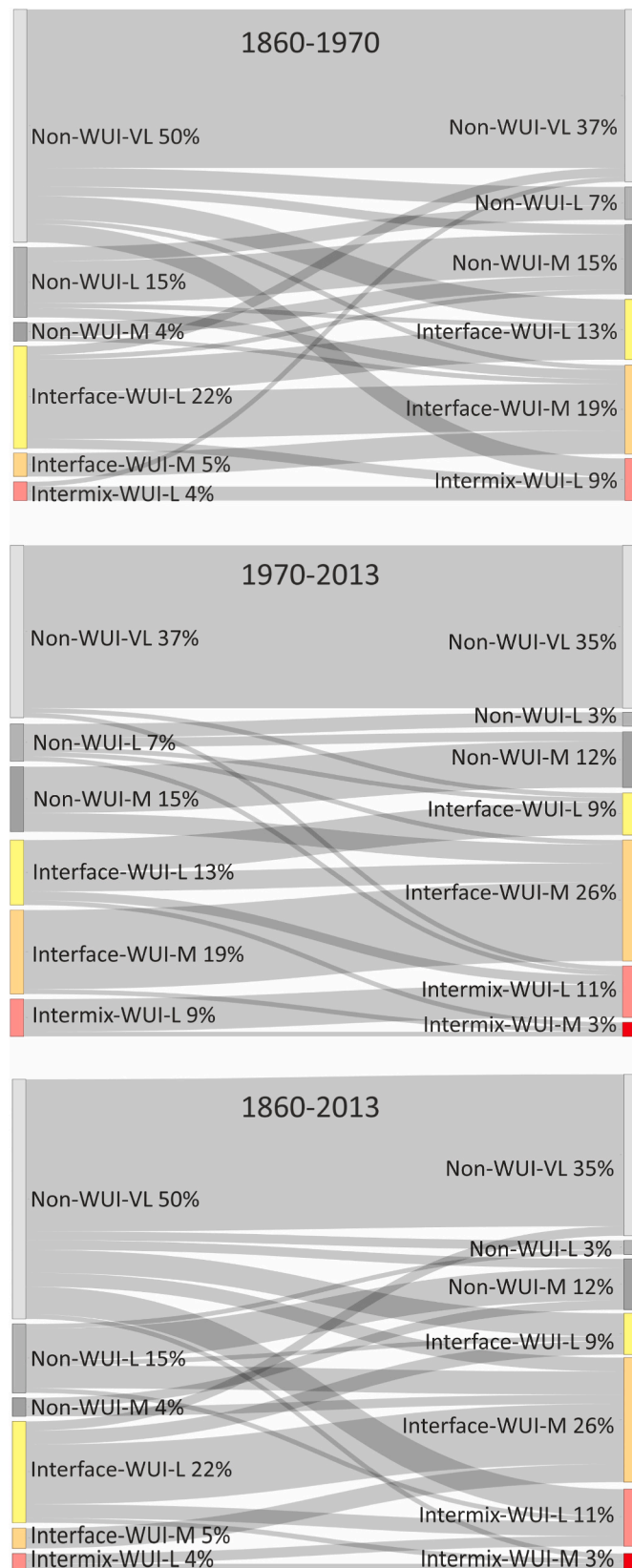


Fig. 3. WUI transitions for the different time periods that we analysed. *Note:* Transitions were calculated for the study area of the 1860s, which is the reason for in minor differences in WUI shares in the later periods (see Methods for details). Only classes with a share of > 1% are included; VL – very low, L – low, M – medium building density.

changes from the 1970s to 2013, there was a higher similarity of the actual 2013 WUI map with 1970s buildings and 2013 forest scenario (51.5%), albeit with a strong difference between northern and southern part of the study area (Fig. 5).

Stepwise regressions showed that for the 1860s, average nearest neighbor distance among buildings, share of forest cover and mean slope were the most important positive determinants of WUI occurrence, while distance to railways was an important negative determinant, indicating that there was more WUI near railroads (Table 2). Building density and forest largest patch index also had positive effects on WUI occurrence, but appeared only in some models (Table 2).

In the 1970s the legacy effect of the WUI from the past (1860s) was the most important positive determinant of WUI occurrence. Other positive spatial determinants were tourist trail density, mean slope, forest cover, and proximity of regional administrative center. Average nearest neighbor distance among buildings and forest largest patch index remained important, but their effect on WUI became negative, while the role of elevation varied among models (Table 2).

For the 2013 WUI, the short-term, 1970s legacy effect was slightly more important than the long-term, 1860s WUI legacy effect (Table 2). The most important determinants with positive effects on WUI area were tourist trail density and proximity to the main regional center. Negative determinants on WUI area were the presence of an orthodox church in a municipality in the 1850s, average farm size, elevation range and forest largest patch index (Table 2).

To check for the effects of spatial autocorrelation, we compared the highest-ranked simple OLS models with a spatial regression models with the same variables for each of the analysed time periods and found that accounting for spatial covariance had very minor effects on the significance of our variables, and improved the explanatory power somewhat. Specifically, the best OLS model for 1860s explained 42% of the variance, while the spatially-lagged model explained 50% (Table 3), and only building density was no longer significant. Similarly, for the 1970s, the spatial model was slightly better than the OLS model, although the difference was not high ($R^2 = 0.72$ vs 0.74), and all variables remained significant. For 2013, the OLS model explained 84% of the variance, while the spatially-lagged model explained 88% (Table 3), and only orthodox church municipality in 1857 was no longer a significant variable. These results suggest that our analysis of the large number of OLS regression models were robust, and not greatly affected by spatial autocorrelation.

4. Discussion

4.1. Long-term WUI change

When analysing long-term WUI expansion in the Polish Carpathians, we found that the area of WUI increased substantially from 30.4% in the 1860s to 40.6% in the 1970s and 48.9% in 2013. This means that even though WUI occupied already a substantial part of the Polish Carpathians in the mid-19th century, it grew substantially thereafter, and much faster in the half-century after 1970 than in the full century before. A similar increase in WUI growth rates occurred over the 20th century in Italy (Biasi, Colantoni, Ferrara, Ranalli, & Salvati, 2015). Other areas, such as parts of Argentina (Godoy et al., 2019), France (Fox et al., 2018) and the conterminous US (Radeloff et al., 2018) also experienced rapid WUI growth in the recent decades, but there is no information available for their earlier WUI growth rates.

Apart from an increase in area, we found that WUI building density and share of buildings in WUI also increased substantially. This means that various ecological problems that are concentrated in the WUI, such as higher probability of human-wildlife interactions (Allredge, Buderman, & Blecha, 2019; Evans, Rittenhouse, Hawley, & Rego, 2017), zoonotic disease spread (Larsen, MacDonald, & Plantinga, 2014), invasive species introduction (Gavier-Pizarro et al., 2010), light pollution (Ditmer et al., 2021) and wildlife-pet contacts (Gramza, Teel,

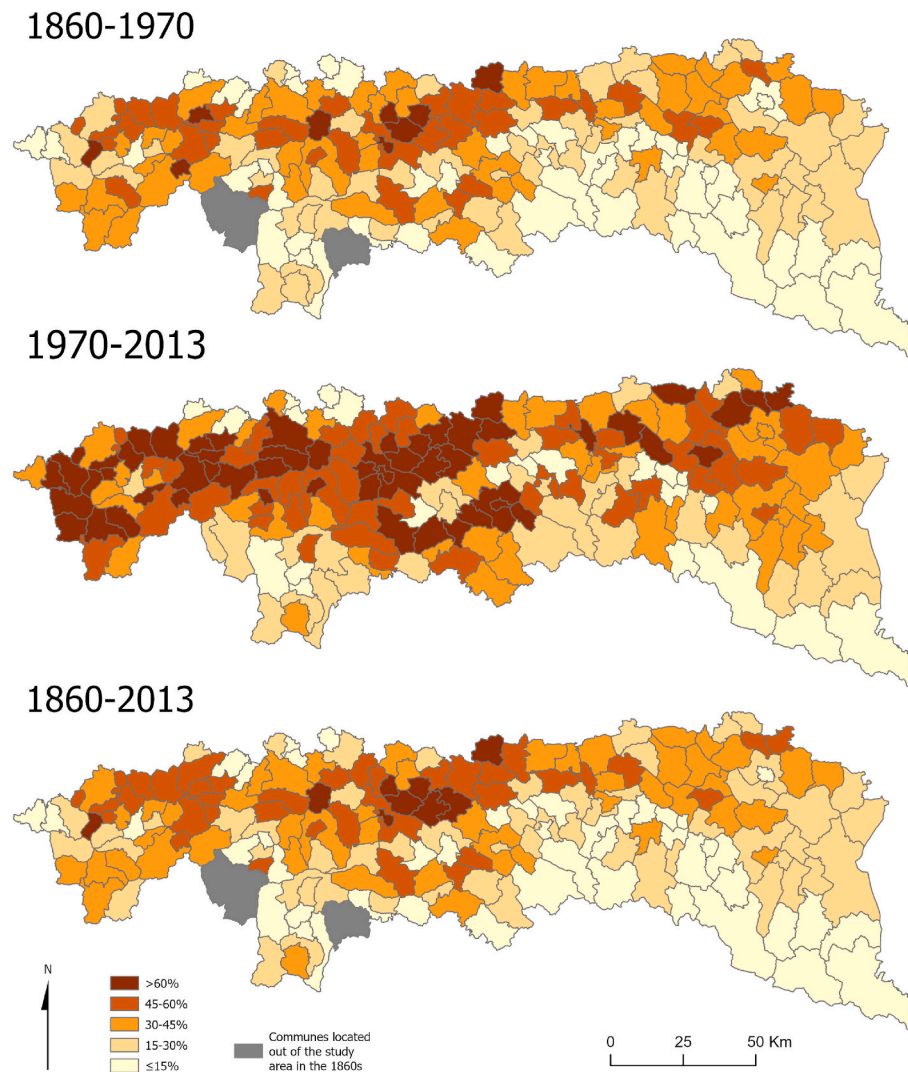


Fig. 4. Percentage of WUI in a given period that was already WUI in a previous period.

VandeWoude, & Crooks, 2016) have potentially intensified. Especially the substantial increase in the medium-building density areas may have profound implications, because medium-, rather than low- or high-building density in WUI is particularly attractive for large carnivores searching for food close to people in relatively safe conditions (Tri et al., 2017) due to easy energetic rewards (Blecha et al., 2018). Given that large carnivore populations are recovering in human-dominated landscapes across Europe (Bautista et al., 2021; Chapron et al., 2014; Gula, Bojarska, Theuerkauf, Król, & Okarma, 2020), there is a growing probability that WUI will become even more a focal area for human-wildlife interactions in future.

4.2. Spatial determinants of WUI and their changes

Our long-term analysis of WUI change showed that the relative importance of the main determinants of WUI growth, that is housing and forest cover, varied over space and over time. For the 1970s WUI, housing growth since the 1860s was more important than forest increases. However, only the western Polish Carpathians had substantial housing growth over time, whereas the eastern Carpathians witnessed substantial decrease in housing, accompanied by a forest cover increase, following the forced resettlements there after WWII (Affek, Wolski, Zachwatowicz, Ostafin, & Radeloff, 2021). This means that while new housing growth triggered WUI growth in the western part of the

Carpathians, the decrease in housing density reduced WUI area in the eastern part. For the 2013 WUI, there was also a clear spatial division in how forest cover and housing growth influenced WUI changes. In the southern part of Polish Carpathians, housing growth caused most of the WUI growth, even though forest cover increased substantially (Kozak, 2003). In contrast, in the northern part of the Polish Carpathians, the main determinant for WUI growth was forest expansion. The reason for this difference was that building density in the northern part of the study area was already high in the 1970s, and lack of forest cover was the main constraint for WUI. During the political and economic transformation of the 1990s, widespread land abandonment was triggered by declining profitability of agriculture (Kolecka et al., 2017), eventually resulting in forest cover expansion, often close to settlements, and hence substantial WUI growth. This is different than, for example, in the US, where from the 1990 to 2010, 97% of new WUI areas were caused by new housing (Radeloff et al., 2018). Our results highlight that the Europe's long-term land use history may exert legacies on current WUI dynamics that differ profoundly from those in the US, where such legacy effects appear to be weaker due to a shorter history of European-style land use, plus a very different regulatory environment.

Our detailed analysis of the spatial determinants of WUI existence revealed interesting patterns. First, WUI was very persistent over time, and the share of WUI in the past was among the most important explanatory variables of later WUI area. Second, the patterns of both

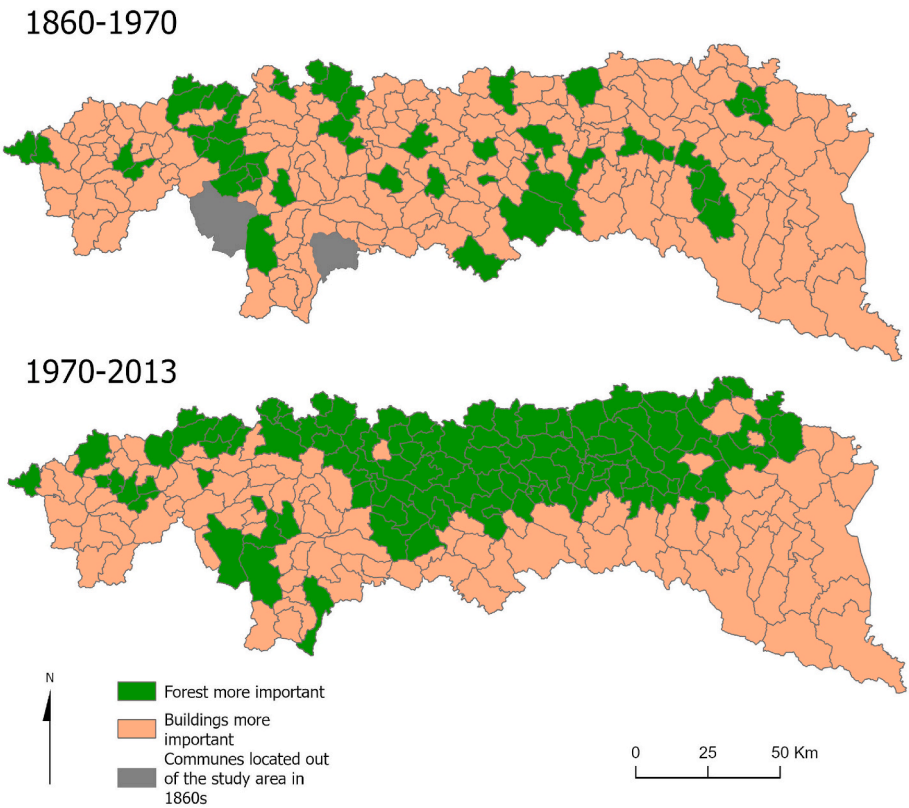


Fig. 5. Jaccard Index comparison between factual and *counterfactual* WUI maps for two periods: 1860–1970 and 1970–2013.

Table 3
Comparison of the best-ranked simple OLS regression models explaining WUI occurrence with spatial lag models of the same variables.

Model	R ²
OLS 1860	
+ Mean slope *** + Building density ** + Average nearest neighbor among building ***	0.42
- Distance to rivers wider than 10m *** - Distance to railways ***	
SLM 1860	
+ Mean slope *** + Building density + Average nearest neighbor among building ***	0.50
- Distance to rivers wider than 10m *** - Distance to railways ***	
OLS 1970	
+ % WUI in 1860*** + WUI_ALL_PERC 1970* + FOREST_PERC_1970***	0.72
- Average nearest neighbor among building *** + Distance to rivers wider than 10m **	
SLM 1970	
+ % WUI in 1860*** + WUI_ALL_PERC 1970** + FOREST_PERC_1970***	0.74
- Average nearest neighbor among building *** + Distance to rivers wider than 10m **	
OLS 2013	
+ % WUI in 1860*** + % WUI in 1970*** - Orthodox church in municipality in 1857**	0.84
- Elevation range *** - Forest largest index patch ***	
SLM 2013	
+ % WUI in 1860** + % WUI in 1970*** - Orthodox church in municipality in 1857 - Elevation range *** - Forest largest index patch ***	0.88

Variable significance (* ≤ 0.10; ** ≤ 0.05; *** ≤ 0.01).

housing and forests were among the most important WUI determinants, regardless the period (Table 2). These findings have important implications for many areas where WUI already exists, indicating the crucial role of planning policies and procedures, if limiting the negative consequence of WUI is a management goal (Fox et al., 2018; Gonzalez-Mathiesen et al., 2021). In Poland, for example, WUI has yet to be included in spatial planning procedures, although the negative

consequences of the inability of current procedures to prevent the uncontrolled sprawl are clear (Niedziałkowski & Beunen, 2019; Ćwik & Hrehorowicz-Gaber, 2021; Śleszyński, Kowalewski, Markowski, Legutko-Kobus, & Nowak, 2020). Similarly, a common framework to define WUI for the EU, for example for fire risk management, does not exist (Bar-Massada, Alcasena, Schug, & Radeloff, 2023; Modugno, Balzter, Cole, & Borrelli, 2016). Our results indicate that there is a need to include WUI in spatial planning and management, both in theory and practice, because of profound implications of WUI for a host of environmental problems. For instance, during 2003–2020 more than 60% of all people affected by wildfires globally, lived in the WUI (Schug et al., 2023).

Environmental variables were also important for WUI occurrence. For example, mean slope had a positive effect on WUI in each time period, but effect of altitude varied and was often negative, especially in 2013. This suggests that WUI is increasingly appearing at lower elevations, because municipalities with small elevation ranges are located in the foothills. The importance of slope shows that in the 1860s, the WUI pattern in mountains was different, probably due to the traditional land use model, where settlements were located close to or in valley floors, whereas forests occurred on more distant, steep slope sections, with a wide belt of agricultural land in-between (Kozak, 2003). However, the declining role of agriculture, combined with the expansion of buildings on steeper slopes contributes to new WUI. Interestingly, in the 1860s, when the total number of buildings was relatively low, the average distance among them was positively associated with the amount of WUI area. In later time periods, however, when the total number of buildings increased substantially and forests started to expand into lower elevations, WUI occurred more often where houses were close to each other (Table 2), presumably due to the concentration of agricultural land abandonment on steep slopes. Accordingly, we found a substantial WUI increase from the 1970s to 2013 in the Carpathian foothills. The transformation of 19th century land use system, and the declining role of agricultural lands with subsequent abandonment occurred also in many

Mediterranean landscapes since the mid-19th century (Abadie et al., 2018; Barton, Ullah, & Bergin, 2010; Galiana-Martín, 2017) and is one reason why WUI is so widespread there.

Since the 1970s, WUI has been positively associated with density of tourist trails. Such trails are typically located in the most attractive landscapes and reflect the overall tourism attractiveness. Our results show that WUI may be associated with tourism attractiveness also in the Carpathians, similarly to what is the case in Florida (Kil, Stein, & Holland, 2014) and in Colorado, USA (Kellner et al., 2017). Usually settlements located close to nature and in attractive landscapes are popular for both local residents (Garrison & Huxman, 2020), and for hotels and second homes (Li, 2022). Indeed, second homes are widespread in many countries, accounting for 3.1% of the housing stock in US, 5% in Switzerland, and 26% in Norway (Sheard, 2019). Our data did not allow us to analyze second homes explicitly, but second-home growth may be another cause of WUI expansion. Whether or not houses are primary residences or second homes, buildings require roads, which triggers landscape fragmentation, and contribute to noise and light pollution and other negative consequences of WUI for local environments (Bar-Massada et al., 2014).

5. Conclusions

We found substantial long-term WUI growth in the Polish Carpathians. However, as early as the 1860s, WUI occupied already a substantial part of the area. Thereafter, WUI grew due to either housing growth or forest cover increase, depending on the local context and on the time period under consideration with forest cover increase being especially important recently. WUI was very persistent form of land use and only rapid resettlement actions after WW II triggered a localized decrease of WUI from the 1860s to the 1970s in the eastern Carpathians. Our analysis showed also that environmental factors were losing their importance in explaining WUI patterns over time, most likely due to the gradual decline of agriculture and its role in the mountains since the mid-19th century. With forests regrowing on former agricultural lands, the relative importance of other factors increased. To our knowledge, our study is the first WUI change study covering such a long period and large area at the same time, showing that WUI is not a recent phenomenon, and strongly depends on land use legacies. We suggest that these legacies will likely shape future growth as well, both in the Carpathians and elsewhere, which suggest that current WUI patterns should be accounted for in spatial planning policies and procedures.

Declaration of competing interest

Authors have no conflict of interest to declare.

Data availability

Wildland-Urban Interface maps for the Polish Carpathians for 1860s, 1970s and 2013 are available in the approved data repository at <https://doi.org/10.5281/zenodo.10135054>.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apgeog.2023.103180>.

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