

Rewilding and Forest Transition in Polish Carpathians:

An assessment of the connectivity of potential wolf habitat patches for the period 1970 and 2013

HERNANDO Daniel

Supervisor: Prof. Van Rompaey , Anton
KU Leuven

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1. Introduction

Land abandonment and forest succession in the Polish Carpathians have triggered diverse landscape impacts, ranging from benefits to biodiversity to the loss of socio-cultural agricultural practices in mountainous regions (Kolecka et al., 2017). This research endeavors to examine the processes leading to the decline of human populations and the abandonment of agricultural activities, thereby facilitating the resurgence of forests in the Polish Carpathians and contributing to the repopulation of numerous wildlife species. Theoretically, the increase in forest cover observed during the 20th century has expanded the extent of wildland areas. However, at the same time the proliferation of human settlements within forested regions has rendered these areas ineligible to be considered "wildlands" in the traditional sense. Consequently, a pertinent question arises regarding the suitability of these new habitats for the resurgence of large carnivores in Poland.

The resurgence of forests in the Polish Carpathians has significantly bolstered the wolf population. This positive effect can be attributed to the increasing availability of suitable habitats for large carnivores and other significant mammalian species since 1980 (Gula et al., 2020). Moreover, the implementation of protective policies for various large mammal species during the 1990s acted as an additional contributing factor, resulting in the growth of the wolf population (Niedziałkowski & Putkowska-Smoter, 2020). As a result, the forest cover expansion has had favorable implications for the wolves, with wildlife protection policies playing a crucial role in the context of forest resurgence in the Polish Carpathians.

Within the framework of the need of better policies for wildlife protection that guarantee the ecological sustainability in the Polish Carpathians, this work focuses on how the increases in forest cover can be analyzed in relation to the wildland-urban interface (WUI) areas in order to determine if forest expansion in Polish Carpathians can be translated in suitable habitats for wolves. The definition of WUI are all the areas where houses meet or intermingle with undeveloped wildland vegetation (Radeloff et al., 2005). Why is it important to consider WUI areas when we talk about wildlife protection policies? One of the main reasons is because it has been stated that WUI plays a relevant role for the creation of indicators that assess wolf-human conflicts, since it is considered that WUI areas with high population density are more susceptible to conflicts rather than Non-WUI areas (Olson et al., 2019; Radeloff et al., 2005). Therefore, the analysis of potential habitats with wildland-urban interface (WUI) areas poses a question regarding whether the observed increases in forest cover really means more adequate habitats for the wolves.

Conducting a WUI analysis to investigate potential wolf habitats holds significance due to the species' preference for habitats characterized by high forest cover, low forest fragmentation, and low human population density (Gula et al., 2020; Karlsson et al., 2007). Human settlements serve as a primary disrupting factor, undermining the spatial and functional continuity of habitats and wildlife corridors (Ibisch et al., 2016; Kaim et al., 2019; Selva et al., 2015). Consequently, WUI areas may not be deemed the most suitable habitats for wolves, as the presence of WUI can contribute to habitat fragmentation based on varying levels of population density. Addressing the challenges posed by habitat fragmentation in human-dominated landscapes necessitates the implementation of wildlife corridors. Within the context of forest resurgence, it becomes imperative for this study to analyze the ecological corridors for wolves and assess their connectivity.

In order to address these issues, this thesis aims to conduct a comprehensive two-pronged analysis. Firstly, we will evaluate the proportion of wildland-urban interface (WUI) areas that intersect with forest cover in the study area, utilizing two robust datasets spanning the periods of 1970 and 2013. Recognizing that forest cover constitutes a critical factor in defining suitable habitats for wolves, this

analysis will enable to determine the extent to which the expansion of suitable habitats coincides with different types of WUI areas.

Secondly, we will evaluate the connectivity between potential habitat patches for wolves by employing optimal path algorithms. These results will be juxtaposed with the presence of Wildland Urban Interface (WUI) areas during the periods of 1970 and 2013. Through this analysis, I will discern the extent to which the observed increases in forest cover translate into more suitable habitats for wolves, characterized by enhanced interconnectivity among these patches.

The intersection between wildland-urban interface (WUI) areas and potential suitable habitats, represented by forest cover, underscores the necessity of comprehending the impacts of human activities on the wildlife of the Polish Carpathians. The expansion of human settlements and the intensification of agricultural land use can lead to habitat fragmentation and disturbances in wildlife populations. Recent research has emphasized the significance of WUI areas as focal points for human-wildlife interactions and the challenges they pose to conservation endeavors (Carlson et al., 2022; Kaim et al., 2023; Petriello et al., 2023; Schug et al., 2023). Consequently, the inclusion of WUI areas in the analysis assumes critical importance in determining the extent to which we can consider these potential habitat patches as new suitable habitats for wolves. By incorporating WUI areas into our examination, we gain crucial insights into the complex dynamics shaping the potential for establishing viable wolf habitats amidst human-dominated landscapes.

It is important to study the link between the positive changes in forest cover and the intersections with Wildland Urban Interface areas in the Polish Carpathians as a way to assess if there is an improvement of habitat patches for wolves. The increase of forest cover, which is in close proximity or overlapping with WUI, may result in fragmentation of the newly established forests and may not necessarily translate into potential habitats for the species. Thus, a prospective research issue is to gauge the extent to which the expansion of forest cover is intersecting WUI and to determine if such intersections impact the connectivity of potential habitat patches for wolf and the habitat quality.

Hence, this work aims to address the aforementioned problem through the following research questions:

1. To which extent the increase in the forest cover between 1970 and 2013 for the study area are intersected with Wildland Urban Interface areas? and
2. What is the impact of changes in forest cover on the habitat connectivity patches for wolves, and how does the presence of Wildland Urban Interface (WUI) areas affect this connectivity?

This work focuses on the analysis of the connectivity of habitat patches for wolves, taking into account the variable WUI. Such analysis will be able to show the effects of WUI areas on the quality of habitat connectivity for wolves. Why is it important to study habitat connectivity? This is relevant since a poor connectivity caused by human factors is susceptible to promote isolation of wildlife populations, reducing the gene flow, and increasing the risk of local extinction (Hefty & Koprowski, 2021; Kiffner et al., 2022). Therefore, the evaluation of the connectivity of potential habitat patches for wolves is essential for understanding the implications of land cover and land use changes on the creation of new suitable habitats.

In conclusion, this research endeavors to investigate the intersection between potential wolf habitats and the wildland-urban interface (WUI) areas within the context of observed changes in forest cover. It is anticipated that the findings of this study will provide valuable insights into the impacts of human activities on wildlife populations in the Polish Carpathians. Furthermore, it is hoped that this work will contribute to the ongoing discourse surrounding ecosystem restoration and rewilding initiatives in Europe. By elucidating the relationship between habitat suitability, WUI areas, and forest cover

dynamics, this research can inform evidence-based conservation strategies aimed at fostering harmonious coexistence between humans and wildlife in the region, while also fostering the potential for ecological restoration efforts.

2. Status of the study area

2.1. Description of study area

The Polish Carpathians are a mountain range located in Southern Poland, characterized by a mosaic of forests, meadows, pastures, and cultivated fields, that have been shaped by human activities for many centuries. The area is part of the Carpathians and is divided into three main ranges: Western Carpathians, the Eastern Carpathians (in Poland only Bieszczady Mountains), and the Central Carpathians (incl. Tatras and Pieniny Mts). The following figure shows the location of the study area.

Fig. 1. Study Area: The Polish Carpathians



Source: Own elaboration

The region has a complex history of land use changes, with agricultural practices and rural abandonment, which have played a critical role. For example, for the Eastern part of the region between 1930 and 1970, agricultural land abandonment was triggered due forced displacements caused by armed conflicts, and this brought an increasing in the forest cover which change from 115,000ha to 181,000ha (Affek et al., 2021). Hence, it can be asserted that the study area has a history characterized by the development of agricultural practices, followed by processes of rural abandonment, ultimately leading to the expansion of forest cover. These findings underscore the significance of comprehending the interplay between social and environmental factors in shaping landscape evolution.

The Polish Carpathians are also home to a rich biodiversity, including many rare and endangered species and still is a place where not all the species haven't been fully inventoried (Gurung et al., 2009). The study area has been object of conservation efforts, and there are several protected areas, including

national parks and nature reserves. Among protected areas in Polish Carpathians we can mention at least the Bieszczady National Park, the Tatra National Park, and the Magura National Park, which are home to rare and endangered species, including the brown bear, the wolf and the lynx (Noga, 2019).

Therefore, the Polish Carpathians are a unique region characterized by a complex history of land use changes and a rich biodiversity. The impact of human activities on the environment and wildlife has been significant, with agricultural practices and rural abandonment leading to a forest return process that has been beneficial for species such as the wolf. However, other activities, such as tourism and infrastructure development, have also had an impact on the landscape, and there is a need for integrated management strategies that consider the ecological, economic, and social aspects of the region. The Carpathians are a priority area for conservation efforts, and better monitoring and management strategies are needed to ensure the protection of its unique biodiversity.

2.2. The process of land abandonment

As it has been mentioned before, forced resettlements can be labeled between the first main events that contributed to land abandonment after the second World War. But also, after 1970 land abandonment process in the study area is linked with the decline of agriculture. And this process was further compounded by two key events, as identified by Kolecka and Kozak (2019)

1. The first was the dissolution of the socialist regime and the subsequent introduction of an open-market economy that supplanted the centralized economy from the former communist regime.
2. The second event was Poland's accession to the European Union and the subsequent implementation of the Common Agricultural Policy in 2004.

About collapse of socialist regime, the transition period resulted in an urban sprawl, as well as an incapacity to reassign the former state-owned lands due to institutional limitations to privatize them (Prishchepov et al., 2012). According to Csaki and Lerman (2002), before the transition period, the state owned 24% of all agricultural land in Poland. By 1997, this percentage declined to 20%, this indicates that there were certain difficulties to assign an active agricultural use to these lands.

Regarding this situation, studies like Goetz, et al. (2002) supports the assert of institutional challenges during the next decade after the collapse of communist regime in the country which delayed the transfer of land assets to more entrepreneurial farmers. Moreover, the phenomenon of land abandonment has occurred predominantly on mountain hillslopes, primarily due to their unfavourable conditions to compete in the global market(Lasanta et al., 2015).

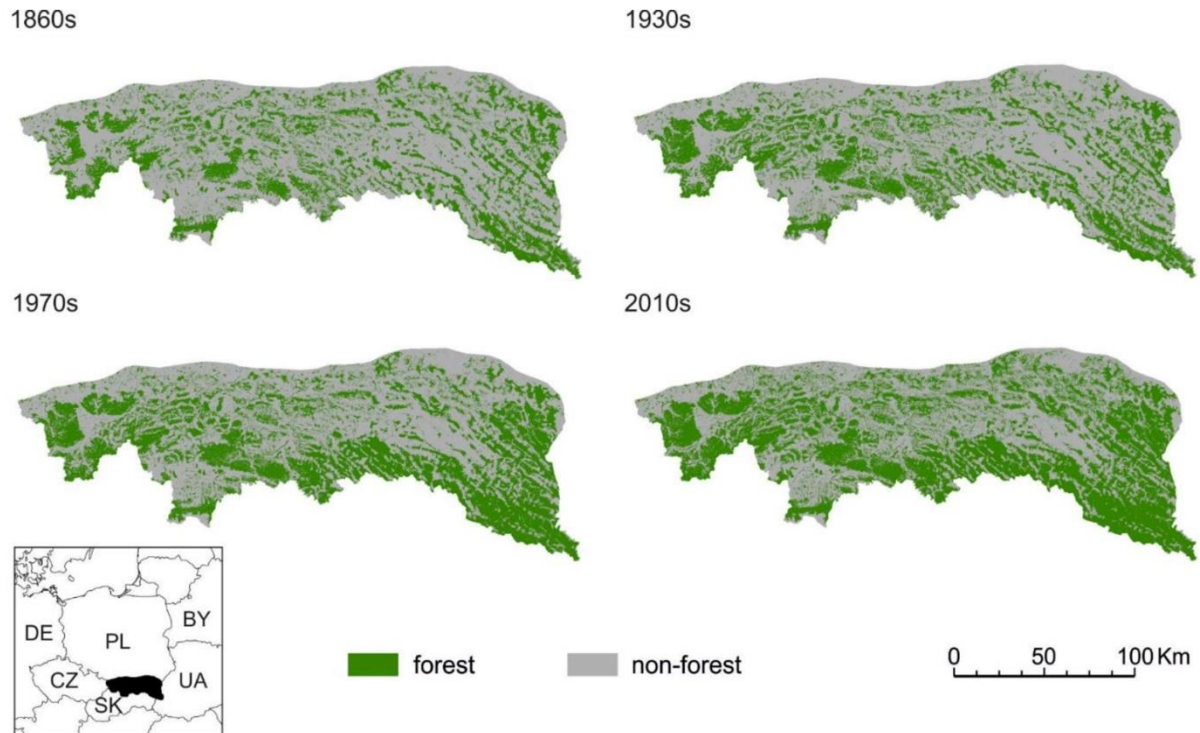
On the other side, there is evidence to suggest that Poland's accession to the European Union and the implementation of the Common Agricultural Policy in 2004 had an impact on land abandonment in the Polish Carpathians. According to Bucała (2014), the transition from a smallholder economy with a high degree of state control to a free-market economy favored off-farm employment in rural areas. Kolecka and Kozak (2019) also note that the introduction of an open-market economy in the 1990s and the subsequent accession to the European Union played a role in the decline of agriculture in the Carpathians, which contributed to land abandonment.

2.3. The return of forest cover and habitat fragmentation

The initial premise about the increase in forest cover is that it has a positive impact on the creation of suitable habitats for large mammal species such as the wolf. In the case of the Polish Carpathian, the process of return to forest started in the mid-19th century until the beginning of 21st century as it can be seen in the maps from Figure 2 (Kozak et al., 2018). The map for the year 1970 already depicts a notable increase in forest cover within the SouthEastern region, which was consolidated during the

initial decade of the 21st century. On the other hand, the maps for 1970 and 2010 unveil that the non-forest cover in the central segment of the study area underwent one of the least significant transformations.

Fig. 2. Forest cover in the Polish Carpathians



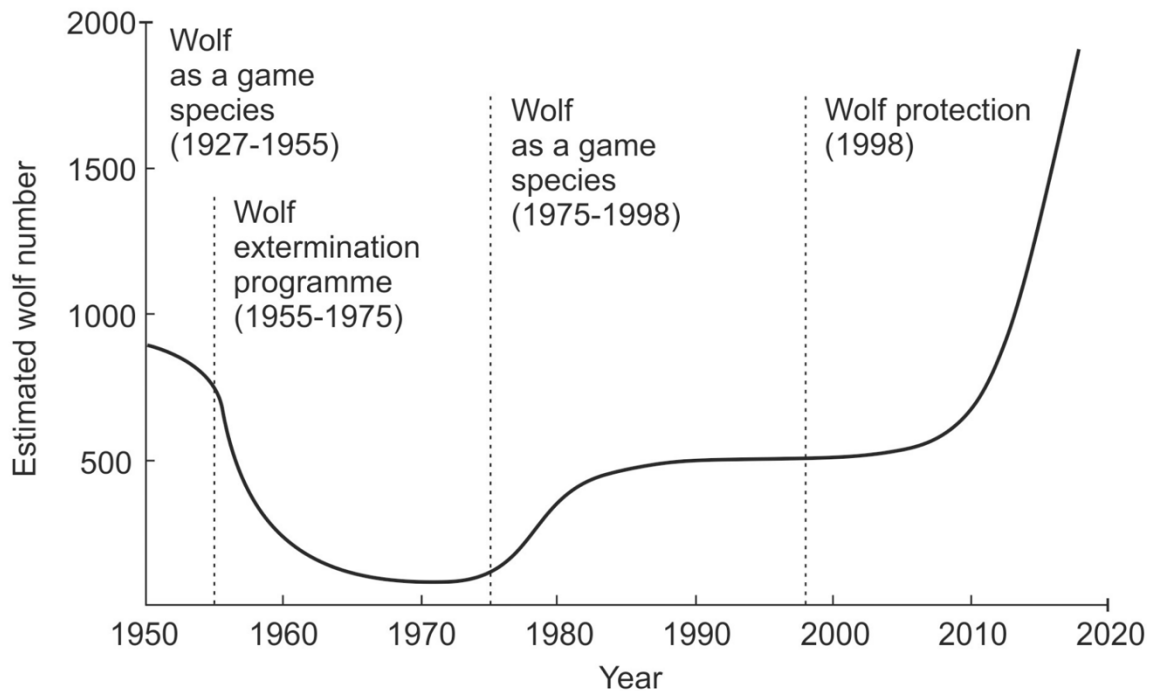
Source: Kozak et al. (2018)

For the case of the Polish Carpathians one item on the research agenda is to assess how increased forest cover may be linked to different levels of habitat fragmentation for species such as wolves (Kozak et al., 2018). Why does it matter to study habitat fragmentation? Because it has effects on the dynamics of displacement and territory occupation for different species, as both variables are negatively affected when there is high population density around the habitats' areas (Stoner, 2011).

2.4. Rewilding and Conservation status

Afterwards the land abandonment process, there has been an increase of suitable habitats for wildlife in the region, and this includes wolves. As a result, there has been a growing interest in conservation policies aimed at promoting the restoration of ecosystems and the protection of wildlife populations in the area. One of the main focuses has been on the conservation of large carnivores. The wolf protection policy enacted in Poland in 1998 changed positively the status of wolf population as we can see in the following figure (Niedziałkowski & Putkowska-Smoter, 2020).

Fig. 3. Estimated number of wolves in Poland and the legal status of the species (1950–2018)



Source: Niedziałkowski & Putkowska-Smoter (2020)

In 2005, the Polish government launched the Carpathian Convention, which aimed to promote sustainable development and biodiversity conservation in the Carpathian region. As a part of this convention, the "Carpathian Large Carnivores Initiative" was established to protect large carnivores, including wolves, by promoting the coexistence of these animals with humans in the region. This initiative has led to the implementation of various conservation measures, including the establishment of protected areas, reintroduction programs, and the provision of financial support for local communities.

One of the most significant conservation policies implemented in the Carpathians is the Natura 2000 network, a European Union initiative aimed at protecting endangered species and habitats. The network covers over 900,000 hectares of land in the Carpathians, including areas inhabited by wolves. The designation of these areas as Natura 2000 sites has led to the implementation of various conservation measures, including habitat restoration, population monitoring, and the development of management plans (Bucala, 2014). Nevertheless, Natura 2000 is criticized since the network mainly doesn't overlap the priority areas for conservation, this has brought that distribution for protected areas in the program is uneven, and specially biased in the South and East of Poland (Diserens et al., 2017).

Following Poland's accession to the European Union, the Common Agricultural Policy (CAP) was reformed in 2003 to include the decoupling of payments from production and cross-compliance. This meant that direct payments for agricultural land were granted upon meeting environmental protection, public health, and animal welfare requirements. In Poland, cross-compliance was implemented through various payments, including Natura 2000 compensation for farmers, agri-environmental commitments, payments for unproductive on-farm investments, and payments for forest extension or improvement. The sustainable development of rural areas was carried out in accordance with Council Regulation (EC) No. 1698/2005 (Ortyl & Kasprzyk, 2022).

In addition to these initiatives, the Polish government has also implemented various policies aimed at promoting sustainable forestry practices in the Carpathians. One such policy is the Forest Stewardship Council (FSC) certification, which requires forest managers to adopt sustainable management practices that promote the conservation of biodiversity and ecological processes (Skrzecz & Perlińska, 2018).

3. Literature Review

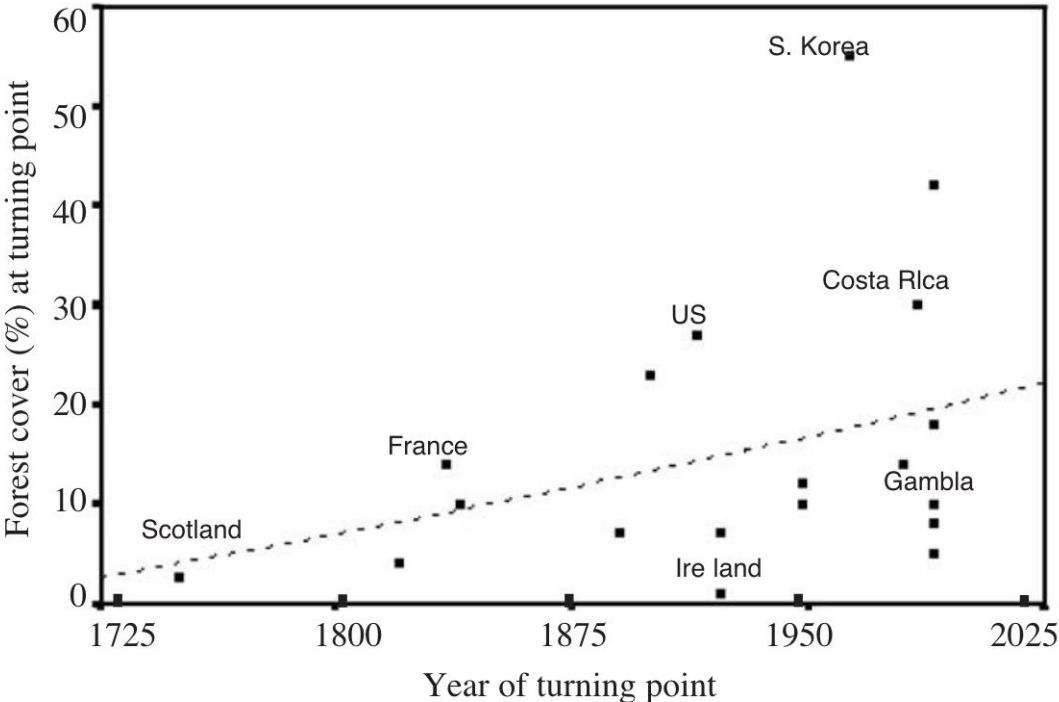
3.1. Forest transition

The concept of forest transition refers to the recovery of forest after a stage of decline in forest cover, this process is usually linked to major economic and social changes (Mather, 1992). For example, forest transition in Europe, is associated with migratory events from rural areas triggering the abandonment of agricultural land, which caused the return of forest cover in these territories (Kolecka et al., 2017; Rudel et al., 2005).

On the other hand, forest transition is a process that have been taking place in different regions around the world, such as Asia, the Caribbean or Europe; therefore, it is suggested the importance of distinguishing between the different conditions that promote forest transition. In accordance with De Jong (De Jong, 2010) among the factors that have promoted these transitions processes there are the economic growth, the increase in the cost of labor, the technological transformation of agriculture or the implementation of policies for promoting forests' restoration.

Since forest transition initiated at different stages in time for many countries, there are different turning points to forest started before 20th century. According to Rudel et al., (2005), the turning point from deforestation to forest transition have occurred in several countries over the last 200 years following the onset of industrialization (See Figure 4).

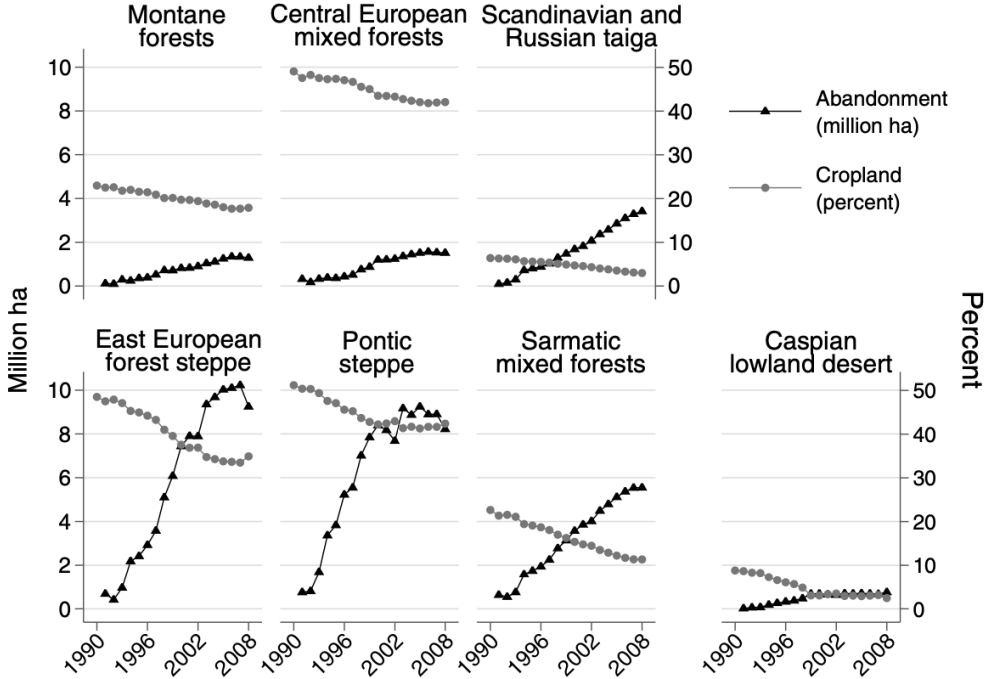
Fig. 4. Forest Cover at the Turning Point for different countries



Source: Rudel et al., 2005

In the European case, the concept of forest transition was first documented in France during the 19th century (Mather et al., 1999). According to Schierhorn (2013) we can see in the following figure how the abandonment of agricultural land tends to begin to coincide with the period of the fall of communist regimes during the early 1990s.

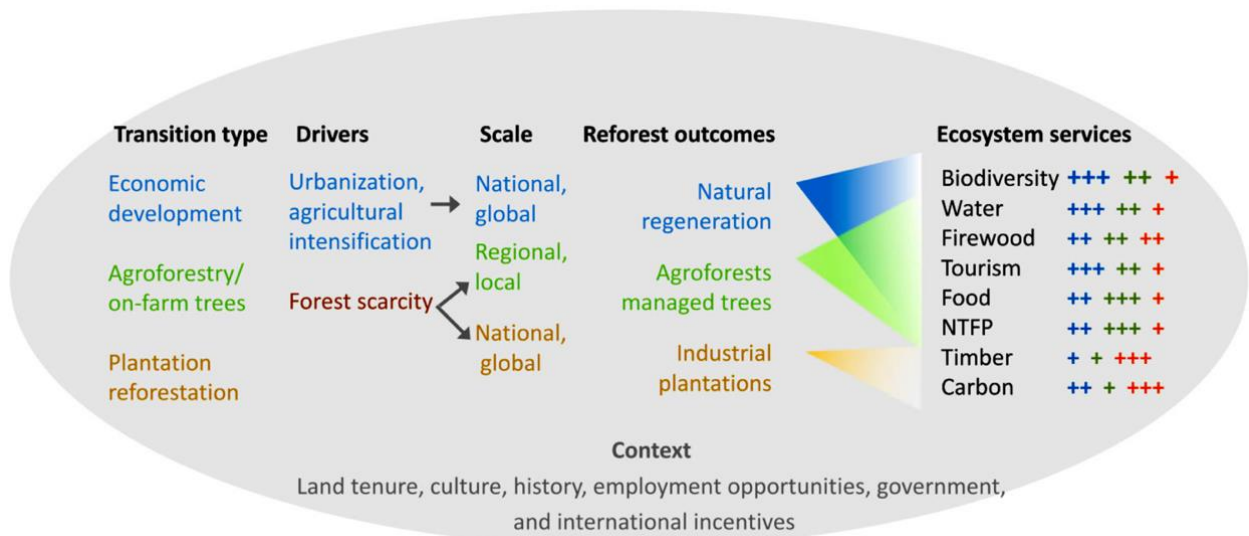
Fig. 5. Cropland abandonment (Mha) and cropland (percentage of total land by Ecoregion in Eastern Europe



Source: Schierhorn, F., Müller, D., Beringer, T., Prishchepov, A. V., Kuemmerle, T., & Balmann, A. (2013).

A typology of forest transition would help to better understand the different motives and impacts generated by this process. Three types of transitions are used to illustrate these processes: economic growth transitions, reforestation with industrial plantations and smallholder agroforestry (Lambin & Meyfroidt, 2010; Mather, 1992; Rudel et al., 2005). The following figure represents the three types of transition already mentioned.

Fig. 6. The three forest transition pathways, their drivers, and their relative ecological outcomes (Wilson et al., 2017)



Source: Wilson, S. J., Schelhas, J., Grau, R., Nanni, A. S., & Sloan, S. (2017).

According to Wilson et al. (2017), economic development is associated with economic growth in urban areas, which generates migrations from rural to urban areas, and the growth of new forest areas in abandoned territories. On the other hand, the transition through reforestation by industrial plantations is usually implemented by strong governments and commercial interests in the forest industry. And for the transition by smallholder agroforestry is usually initiated to satisfy the demand for scarce forest goods and services within the locality. For the case study in this paper, the economic development typology is closest to the transition in the Polish Carpathians, where the outcome has involved the restoration of biodiversity, water bodies and the promotion of tourism.

Finally, from a sustainable development approach, forests are an important factor from an economic, social and environmental point of view, since they are not only linked to agroforestry activities, but also to the restoration of ecosystems, which in turn, provide well-being to people (Gratzer & Keeton, 2017). For example, there is a close relationship between the sustainable development objectives and the forest transition, which is described in the following table.

Table 1. Linkages between SDG and Forest Transition

Sustainable Development Goal (SDG)	Relation of SDG with Forest Transition
SDG1: No poverty	The return of the forest implies the use of ecosystem services, especially through smallholder agroforestry transitions. According to Sunderling et al. (2007) there is a correlation between the increase in forest cover and the impact on poverty reduction.
SDG11: Sustainable Cities and Communities	Forest transition is a process that can occur in Wildland Urban Interface areas, and therefore requires forest management that promotes sustainable cities (Baumgartner, 2019) .
SDG13: Climate Action	A faster forest transition would imply a larger forest size, and with it a greater carbon sequestration that could alleviate the effects of climate change on our planet (Rudel et al., 2020).

SDG15: Life on Land	SDG 15 focuses on the protection, restoration and sustainable use from ecosystem services, and these processes can be benefitted from forests transition(Gong et al., 2020).

Source: Own elaboration

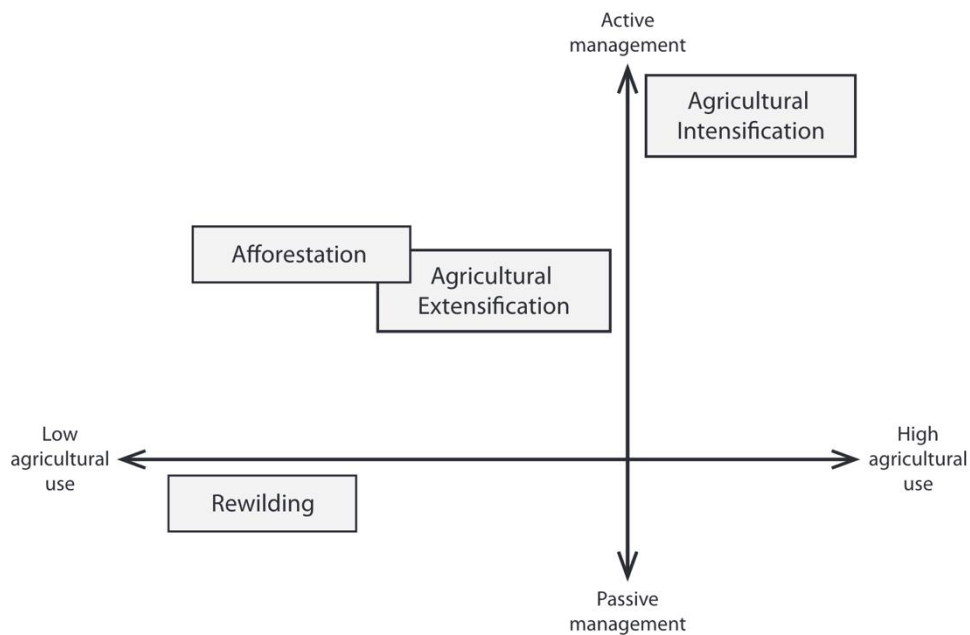
3.2. Rewilding

On the other hand, this work addresses the process of rewilding as an approach that seeks to manage and restore the ecological processes in a territory, taking as a reference the return of old species that previously formed the ecosystem, or similar species, in order to restore biodiversity in the ecosystem in a sustainable manner and eventually with the least possible human intervention (Dunn-Capper et al., 2023; Gillson et al., 2011; Pereira & Navarro, 2015). On the other hand, rewilding processes can range from the restoration of trophic rewilding of megafauna to restore top-down trophic cascades, to a much more passive rewilding where the emphasis is on the immediate decrease of human intervention (Dunn-Capper et al., 2023).

Likewise, the rewilding process is closely related to that of forest transition, since the processes of reintroduction and/or return of species in an ecosystem are influenced by changes in the composition of the forest cover over time, which in turn determines the level of connectivity of different habitats, as well as different levels of interaction with human groups (Grau et al., 2020; Speed et al., 2019). Therefore, rewilding and forest transition are processes that can be complementary in strategies to combat biodiversity loss, and therefore climate change.

In the European case, landscape management efforts have focused on active management through strategies such as afforestation, agricultural extensification or agricultural intensification, but not so much on passive strategies such as rewilding (Bauer et al., 2009; Pereira & Navarro, 2015). The following figure shows the typologies of landscape management strategies based on their categorization as either active or passive, alongside their association with agricultural land use.

Fig. 7. Landscape Management Strategies according to agricultural use intensity and level of management



Source: Pereira, H. M., & Navarro, L. M. (Eds.). (2015).

Between passive and active strategies, it was found that the results between passive forest restoration processes can have similar results to those of active restoration, in addition to mentioning that restoration through rewilding is usually less costly than active strategies (FAO, 2011; Rey Benayas & Bullock, 2012). This is one of the reasons why a landscape management strategy in Europe has proven to be an attractive alternative for ecosystem restoration on the continent.

As evidence of the growing popularity of the rewilding strategy in Europe, Figure 8 shows the five rewilding cases that have been carried out and four new areas to be incorporated into the framework of this new strategy. As can be seen in the figure, it covers a broad spectrum of territory within the European continent (Helmer et al., 2015). However, the rewilding process faces a challenge in terms of financing, since its main mechanisms can be identified in two types:

- Market-based mechanisms
- Non-market based mechanisms

While non-market-based mechanisms do not imply an economic return, market-based mechanisms are based on financing that is considered an investment and therefore must have some return. Given this scenario, there is a need to broaden the financing channels for rewilding, as well as to reduce the economic risk of this type of investment. A mixed financing model with public and private funds and other forms of innovation in financing are necessary to reduce the gap between the potential actors that finance and those that design and implement rewilding interventions (Dunn-Capper et al., 2023).

Fig. 8. Existing Rewilding areas in 2013 and candidate areas for new Rewilding Spots



Source: Helmer, W., Saavedra, D., Sylvén, M., & Schepers, F. (2015)

3.3. Wildland urban interface areas

The concept of Wildland Urban Interface (WUI) areas was developed in the USA in 1970 to identify those transition zones between human settlements that are located within or adjacent to wildland vegetation, the original interest of identifying these infrastructures was to analyze risks against wildfires. (Carlson et al., 2022; Ganteaume et al., 2021; Johnston et al., 2019; Radeloff et al., 2005). However, in accordance with Bar-Massada et al. (2014) WUI areas are not only limited to wildfire analysis, but also to at least two other types of phenomena:

- a) Fragmentation of habitats due to the expansion of infrastructure.
- b) The effects of anthropogenic activities on neighboring ecosystems.

Therefore, the scope of WUI areas requires that these spaces be analyzed as socioecological zones that have their own particularities and different impacts on the configuration of the landscape. Likewise, WUI areas can also be understood from a typology that includes WUI areas (within this category there is Intermix WUI and Interface WUI); and Non Wui areas (Johnston et al., 2019).

For this work, the classification of WUI areas in the data follows the typology established by Carlson et al. (2022) as detailed in the Table 2. The WUI maps for 1970 and 2013 can be seen in the Annex section.

Table 2. WUI Typology

		Housing density (Units units/Km ²)	Percentage of Wildland vegetation
Intermix WUI	High housing density	>741.31	Land cover is at least 50% of wild vegetation
	Medium housing density	49.42 – 741.31	
	Low housing density	6.17 – 49.42	
Interface WUI	Medium housing density	49.42 – 741.31	Land cover is under 50% wildland vegetation. But also within a distance of 2.4Km of a wildland vegetation patch at least 5 Km ² in area that contains at least 75% of vegetation
	Low housing density	6.17 – 49.42	
Non WUI	High housing density	>741.31	Contains less than 50% of wild vegetation in the land area or is not so close to large wildland patches
	Medium housing density	49.42 – 741.31	
	Low housing density	6.17 – 49.42	
	Very low housing density	0 – 6.17	

Source: Carlson et al. (2022) & (Bar-Massada et al., 2013)

The following figure helps to illustrate what an Interface and Intermix WUI area would look like:

Fig. 9. Intermix (Left) and Interface (Right) WUI areas



Source: Kaim et al. (2018)

4. Materials and methods

4.1. Approach

The research process to study the changes in forest cover along with the impacts of the WUI areas was carried out through a spatial analysis divided into two stages. The first part of the analysis consisted of

using the 1970 and 2013 forest data to identify how the changes of area for the forest covers in both years. The Software Arcgis Pro, version 10.8.2, was used to execute all the spatial analysis required for this work.

In the subsequent phase of the analysis, an intersection operation was employed to merge the raster information of the wildland-urban interface (WUI) areas with the corresponding datasets representing forest cover for the years 1970 and 2013, respectively. The primary aim of this operation was to determine the degree to which the WUI areas were spatially coincident with the forest cover during each period of investigation. By performing this intersection analysis, we sought to identify and quantify the extent of overlap between the WUI areas and the forest cover, thereby facilitating a comprehensive assessment of the spatial relationships between these two critical variables.

The second phase of the analysis entailed the utilization of the Linkage Mapper tool, the objective in this stage was to generate maps depicting potential corridors for wolves characterized by the least travel cost. These paths serve as routes for species movement between distinct core habitats of interest. Consequently, the tool enables the visualization of routes that require minimal effort and collectively provides a representation of habitat connectivity and potential species movement within the designated area of interest. By employing the Linkage Mapper tool, we aim to capture the underlying patterns of connectivity, which play a crucial role in assessing the potential for gene flow, population dispersal, and overall landscape permeability for the focal species.

For the analysis of connectivity between habitat patches, the index of path tortuosity was used, which measures the deviation of a path in relation to the Euclidean distance between habitat patches; values closer to one in the index mean that the path is more efficient, which would favor the connectivity and mobility of the species between habitat patches. While values of the index far from 1 imply a greater deviation, which would mean difficulties for the displacement of the species (Kaim et al., 2019). On the other hand, the data on the distance of the optimal paths proposed by Linkage Mapper was used to compare through boxplots the distributions of these distances and to make a comparative analysis of the connectivity between habitat patches of the different periods.

Lastly, it is noteworthy to mention that the selection of habitats for wolves adhered to the criteria outlined by Nowak et al. (2008) According to their findings, the average territory size of wolves is estimated to be 158 km², with a standard error of 26.7. In light of this reference data, the current study considers forest patches of 150 km² and larger for inclusion in the connectivity analysis conducted using Linkage Mapper. This threshold ensures that habitat patches of sufficient size and extent are encompassed, aligning with the estimated territory requirements for wolves. By adopting this criterion, we aim to assess the connectivity and potential dispersal capabilities of wolves within the study area, focusing on forest patches that meet or exceed the minimum size threshold of 150 km².

4.2. Datasets

The primary datasets employed in this study, were two

1. Forest cover for 1970 based on the work of Ostafin et al., (2017a) and the forest cover of 2013 based on the work of Dobosz et al. (2019)
2. Wildland-urban interface (WUI) areas for 1970 and 2013

Both were sourced from the forthcoming paper by Kaim et al. (in preparation).

For the case of the buildings for 1970, these ones were obtained automatically through deep learning from 1:10 000 topo maps by Piotr Szubert, PhD student from Jagellonian University, and then the data was used to create WUI map.

For the 2013 forest layer, this was obtained from the work done in the paper by Dobosz et al. (2019) where the forest information was constructed from four datasets:

Table 3. Data sets used for defining forest areas for 2013

Datasets	Description
BDOT10k	The main dataset was BDOT10k, which is a nationwide topographic database in Poland at a scale of 1:10000. The definition of forest is determined on the basis of cover.
SILP	Forest information system covering about 50% of the forests in the Polish Carpathian Mountains
LMN	This is the digitized map that represents the forest cover based on SILP information. The map is at a scale of 1:500.
Topo 70	It is a topographic map at a scale of 1:25000 with information on forest cover in Poland. This map was used for identification of forest loss areas.

Source: Own elaboration. Information from Dobosz et al. (2019)

The methodology followed by the paper of Dobosz et al. (2019) started from the information proposed by the BDOT10k dataset, to later add the forest cover information from the rest of the data sets. Regarding the infrastructure data for the 2013 map, these were obtained from the Polish Topographic Database¹.

According with Kaim et al. (2018), The raster WUI for both years of the study were constructed based on the methodology proposed by Radeloff et al. (2005) and Bar Massada (2014). The steps followed for the preparation of both rasters are detailed as follows:

Table 4. Classification WUI according two categories: Interface and Intermix WUI

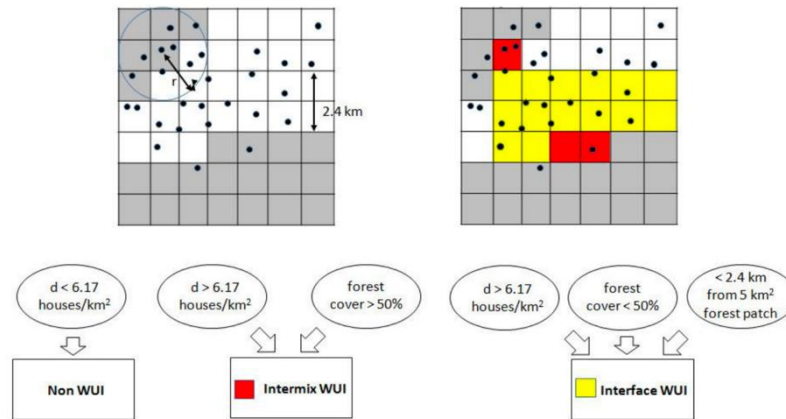
Steps	Description
1. WUI Conceptual definition	The Interface and Intermix WUI classification shown in section 3.3 is used. In a WUI interface the infrastructure is located next to the wildland vegetation. Whereas in an Intermix WUI it is usually scattered houses interspersed with wildland vegetation.
2. Housing density calculation	It was calculated from a ratio of 500 meters. When the density is greater than 6.17 housing/Km ² the area can be defined as WUI.
3. Vegetation assesment	Considering the areas identified in step 2, a buffer of 500 meters was established. When the forest cover within this buffer is greater than 50%, the area is considered as Intermix WUI.
4. Forest patches definition	All forest patches with an area greater than 5 km ² are identified and then a ratio of 2.4 km ² is established around these patches.
5. Final Classification	When the housing density is 6.17 housing//Km ² , the forest cover is less than 50%, and the area is within the 2.4Km ratio, then the area is classified as Interface WUI.

¹ <https://www.geoportal.gov.pl/en/dane/baza-danych-obiektow-topograficznych-bdot>

Source: Own elaboration. Information from Kaim et al. (Kaim et al., 2018)

It is pertinent to note that the calculation of housing density in this study was based on point-level data, as data for all individual buildings was available. The classification process described in the preceding table is visually depicted in the subsequent figure for clarity and reference. This approach allowed for a more precise assessment of housing density, as each individual building was accounted for in the analysis. The next figure provides a visual representation of the steps undertaken in the classification process, aiding in the understanding and interpretation of the results presented in this study:

Fig. 10. Classification process for Interface and Intermix WUI



Source: Kaim et al. (Kaim et al., 2018)

4.3. Matrix of Cost Values Movement

This section works with two tables of movement cost, the first one for the layer of forest, which would be the starter point to calculate the values for the second map, which will be the raster of movement cost values for the WUI areas. To date, there are no works that have defined the value of these movement costs regarding WUI areas within the Polish Carpathians, so the following tables of movement values constructed here intend to be proxy values. This section presents two tables of movement costs: the first for the layer of forest, and the second for the WUI raster.

The first table used as input comes from Kaim et al. (Kaim et al., 2019) is the following

Table 5. Movement Cost Values for Wolves in Polish Carpathians

Land Use Class	Wolf Cost	Lynx Cost
forest	8	16
overgrown	32	43
grassland	46	62
arable land	100	100
settlements	68	72

Source: Kaim et al. (2019)

The table above was used to build the first costs of movement for wolves in the study area. At first the value for forest remained the same as the table above, but then considering WUI areas, the values will change according to Table 8. And the value for the other non-forest areas for the following table was the average of the other non-forest categories presented in the previous table (Average = 62), WUI was not used so far to assess the cost of movement, so I had to use proxy value for defining it. Here the resulting table:

Table 6. Movement Cost Values for Forest Layers

Type	Value
Forest	8
Non forest	62

The second table used as input the table of ecogeographic variables used for ENFA (Ecological Niche Factor Analysis) shown in the work of Huck et al. (2010), showing the value of movement costs for wolves in Poland according to a categorization of land uses and land covers constructed from the Corine Land Cover map dataset². The following table shows below the movement cost information developed by Huck:

Table 7. Ecogeographical variables used for ENFA

Original CORINE code (for habitat types)	Detailed	Data input	Cost wolf	Cost lynx
211, 213, 241, 334	ARABLE land	69 or 177 km ² circle	100	100
312	CONIFEROUS forest	69 or 177 km ² circle	18	37
311	DECIDUOUS forest	69 or 177 km ² circle	1	1
Derived variable	Distance to HUMAN	distance	–	–
Derived variable	Forest size	9 km ² circle	–	–
111–112, 121–124, 131–133, 141–142, 221–222, 242	HUMAN	69 or 177 km ² circle	68	72
313	MIXED forest	69 or 177 km ² circle	4	10
243	Natural meadows (NATMEAD)	69 or 177 km ² circle	56	65
231	PASTURE	69 or 177 km ² circle	36	59
Main/secondary roads	ROAD	distance	46/23	73/37
321–324, 331–333	TRANSITIONAL (scrub, natural open, transitional forest)	69 or 177 km ² circle	32	43
411–412, 421–423, 511–512	Wetland and water bodies (WET)	distance	47	64

Source: Huck et al. (2010)

The data in the table above served as a reference for constructing the matrix of movement costs for the WUI rasters in the study area. The process for the construction of the matrix began by creating a table with the categories of the WUI raster attributes from the work of Kaim et al (In preparation) (See first column of Table 8). Subsequently, it was determined that the value of resistance to movement corresponding to human presence (68) in Table 7 was the closest to the Non WUI high housing density category in Table 8.

For the Non WUI very low housing density category in Table 8, the average of the values corresponding to arable land, meadow and pastures in Table 7 was calculated as an approximation of the movement cost since Non WUI areas might be either forest, agriculture or settlements. The resulting value here was 64. For the Non WUI very low housing density category equal to 0 / Km² (Table 8), it was established that its movement cost was closer to the value of the movement cost of wolves within forests presented in Table 5. However, since these areas may have some type of human presence in a very atypical way, it was decided to use a slightly higher cost value, so a value of 10 was selected.

For the cost of Non WUI low housing density from Table 8, the average of the costs corresponding to the categories Non WUI very low housing density and Non WUI high housing density was calculated.

² <http://dataservice.eea.europa.eu/dataservice/>

For the cost of Non WUI medium housing density, the average of the values corresponding to Non WUI low housing density and Non WUI high housing density was calculated, resulting in a value of 67. For the values of Interface WUI, a slightly higher transit cost value (15) through the forest was considered, since these are closer to human settlements. Each WUI interface category was obtained by averaging the value 15 with the corresponding value of the non WUI categories, the detailed example can be seen in the following table. Finally, for the intermix values, the forest movement costs of Non WUI very low housing density 0/Km² (10) were averaged with the corresponding non WUI categories, the values obtained are presented in the following table:

Table 8. Movement Cost Values for Wolves in Polish Carpathians

WUI Categories	Cost Value	Details
NON WUI - very low housing dens 0 /km ²	10	Step 2: Here the cost was closer to the value of the cost of wolf movement within forests presented in Table 5. However, since these areas may have some human presence, it was decided to use a slightly higher cost value, so a value of 10 was selected.
NON WUI - very low housing dens 0–6.17 h_u/km ²	64	Step 3: Average value from arable land, meadows and pastures from Table 7.
NON WUI - low housing dens 6.17–49.42 h_u/km ²	65	Step 4: The average of the costs corresponding to the Non WUI very low housing density and Non WUI high housing density categories
NON WUI - medium housing dens 49.42–741.31 h_u/km ²	67	Step 5: The average of the costs corresponding to the Non WUI low housing density and Non WUI high housing density categories
NON WUI - high housing dens > 741.31 h_u/km ²	68	Step 1: This value is equal to that of human presence (68) in Table 7.
Interface WUI - low housing dens 6.17–49.42 h_u/km ²	40	Step 8: For Interface WUI categories, a slightly higher transit cost value (15) through the forest was considered since they are closer to human settlements. Then it was calculated the average of Non WUI low housing density (65) with the 15 value that represented the resistance to movement in forest for this area.
Interface WUI - medium housing dens 49.42–741.31 h_u/km ²	41	Step 9: Similar process than Step 8. Only this time it was used the value of Non WUI Medium housing density (67)
Interface WUI - high housing dens > 741.31 h_u/km ²	42	Step 10: Similar process than step 8. Only this time it was used the value of Non WUI high housing density (68)
Intermix WUI - low housing dens 6.17–49.42 h_u/km ²	38	Step 6: Intermix has much more forests (according to the definition it is > 50%) so here it is proposed the addition of the cost value Non WUI very low housing density (10) with the with the cost value for Non WUI low housing density (65) minus the value of Non WUI very low density (10) and this result divided by 2. The final result is 38
Intermix WUI - medium housing dens 49.42–741.31 h_u/km ²	39	Step 7: This process is similar to step 6. Here also is proposed an addition of the cost value Non WUI very low housing density (10) with the with the cost value for Non WUI medium housing density (67) minus the value of Non WUI

		very low density (10) and this result divided by 2. The final result is 38
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Source: Own elaboration

5. Results

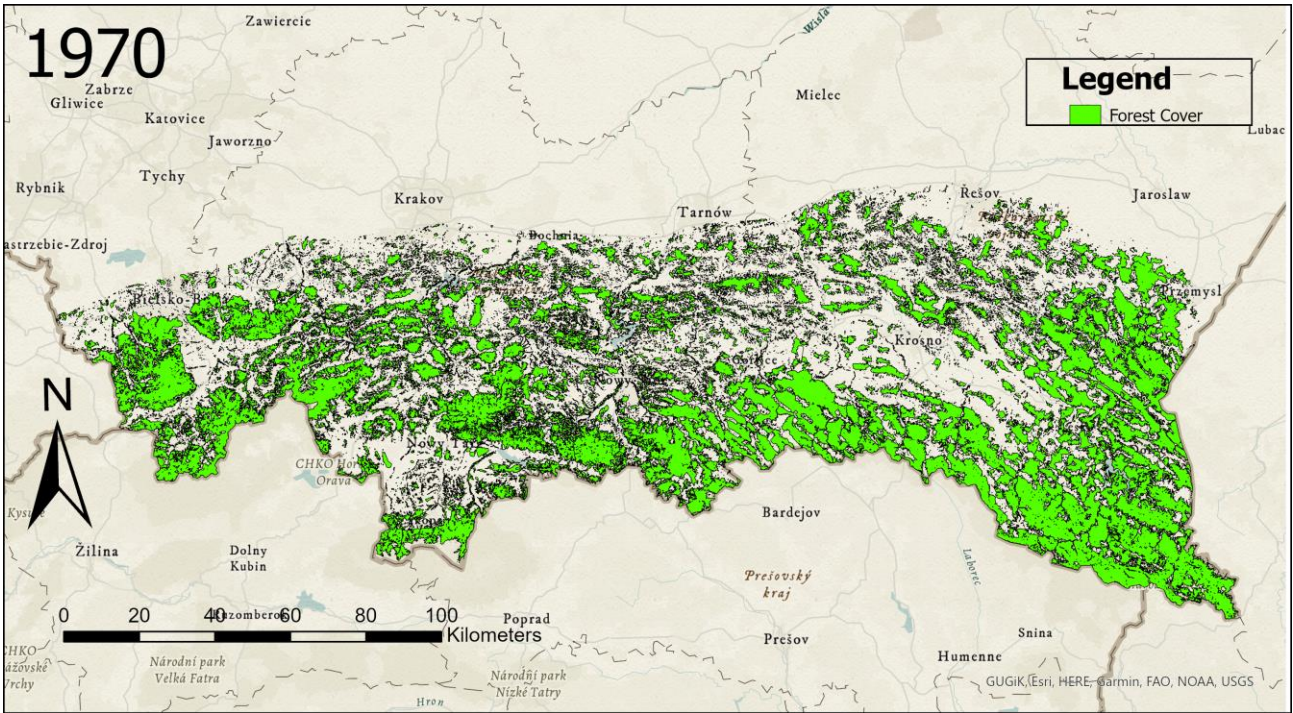
5.1. The increases of forest cover and their linkage with WUI typology

5.1.1. About the expansion of forest cover in Polish Carpathians and its linkage with the idea of having better habitats for wolves

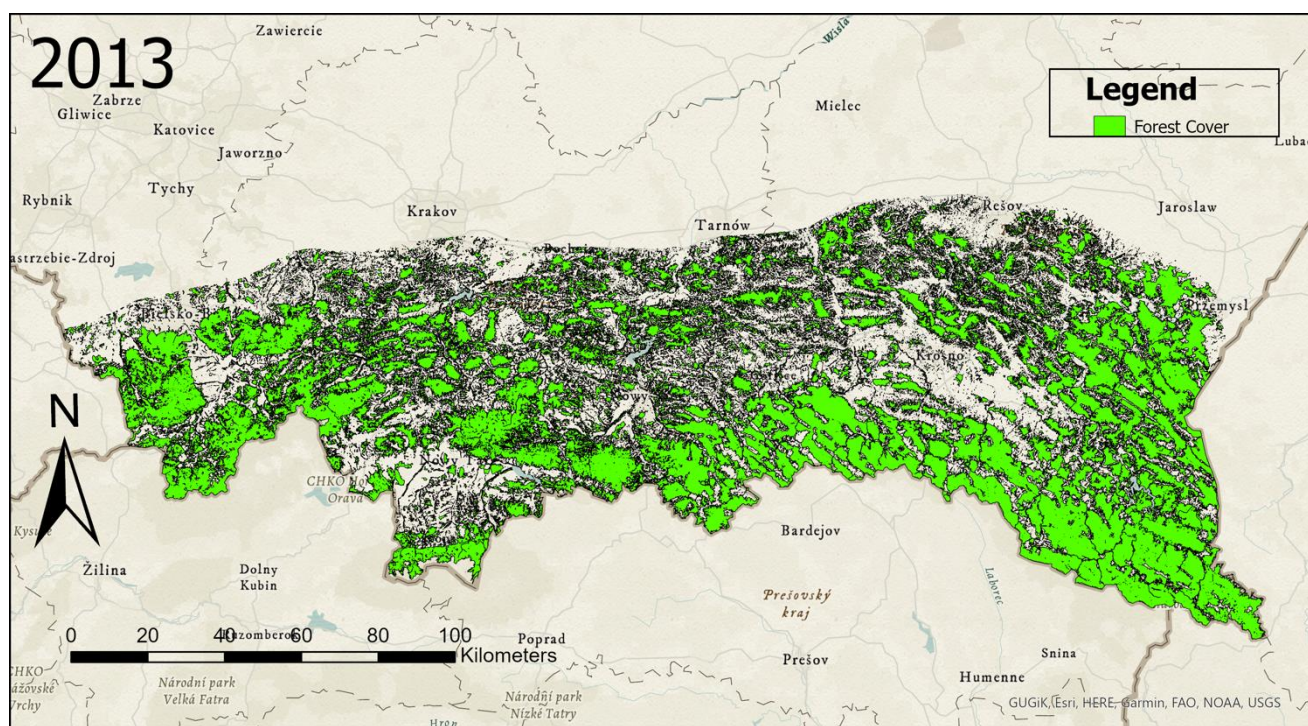
The first part of the analysis focused on finding the differences between the areas of forest cover between the years 1970 and 2013. The results found that there was an increase in forest cover from 7992.57Km² to 9485.22 Km², which represents an increase in forest cover from 39% to 47% within the study area. This result suggests that these increases are a positive aspect for the recovery of ecosystems in the Polish Carpathians. Figure 12 shows the changes in forest cover in the mentioned period.

Fig. 11. Forest Cover in Polish Carpathians – 1970 and 2013

(a)



(b)



Source: Kaim D., Szubert P., Shahbandeh M., Kozak J., Ostafin K., Radeloff V.C., in preparation, Growth of the Wildland-Urban Interface and its Spatial Determinants in the Polish Carpathians

The following table presents the changes in forest cover for the years 1970 and 2013:

Table 9. Forest Cover changes between 1970 & 2013

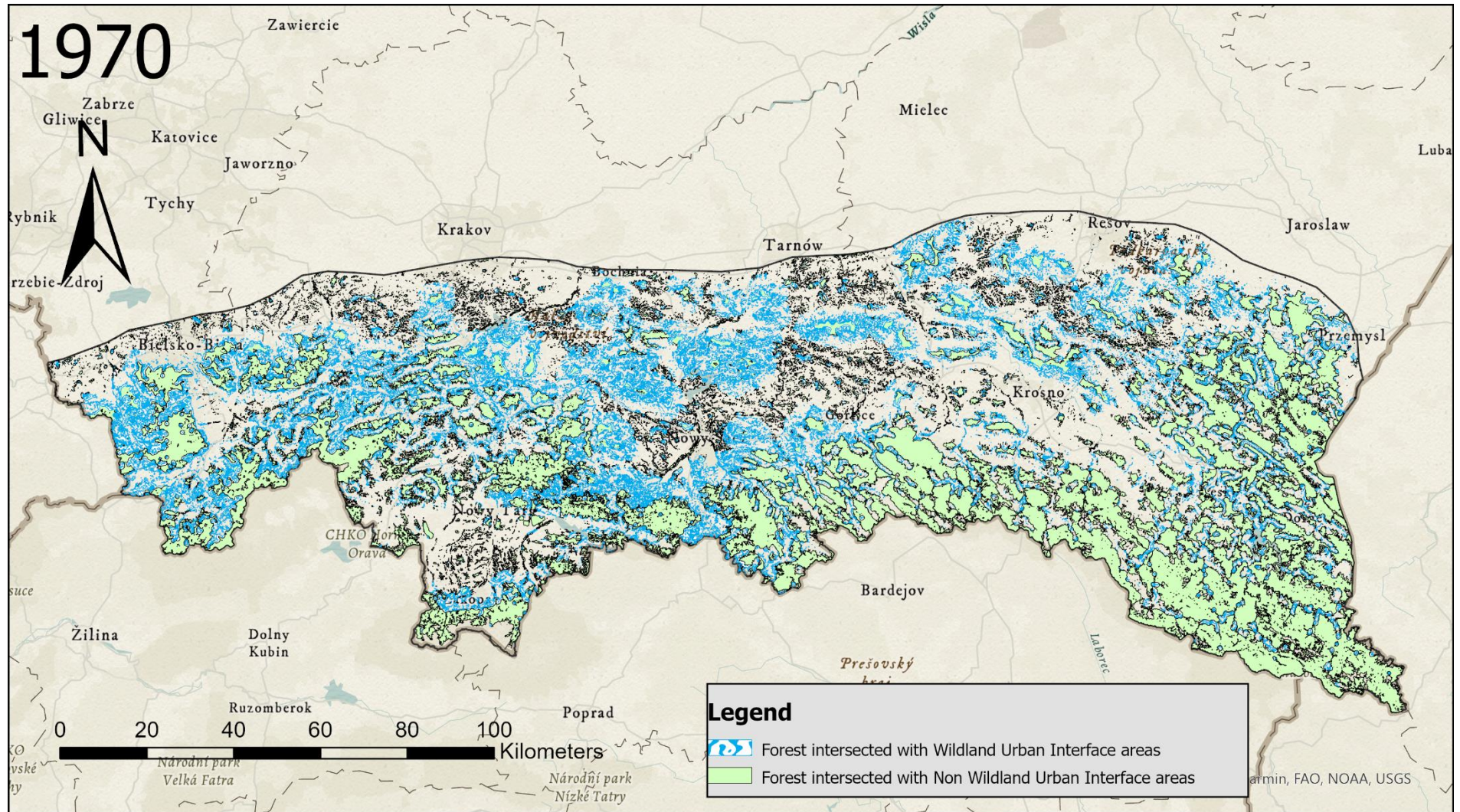
Year	Km ²	Percentage	% Variation	Average Annual Growth Rate
Forest 1970	7992.57	39%	+18%	+0.40% per year
Forest 2013	9485.22	47%		

However, the analysis of the effects of increased forest cover on the recovery of ecosystem services must consider the role of humans (Marull et al., 2015). For example, even if there is an increase in forest, connectivity between different habitats would not necessarily improve if there is also an increase in population density within the same area where the forest area was increased. According to González-Moreno et al. (2013) the expansion of forest cover near human settlements can contribute to different levels of forest fragmentation. Since WUI areas are constructed considering housing density criteria, this is a useful element to assess the connectivity of wolf habitats in the context of increasing forest cover within the Polish Carpathians.

5.1.2. The increase of forest cover areas intersected with WUI areas in 2013

This part of the analysis evaluates the increases in forest cover in relation to the overlapping of WUI areas, identified from the criteria mentioned in Section 3. The objective of the analysis was to make visible the intersections between forests and WUI areas since the increase in forest cover that is close to or overlapping with WUI areas may result in fragmentation for the newest forest cover, which would not imply an improvement of potential habitats for wolves. As a result, the maps in Figure 13 are presented.

Fig. 12. Forest areas intersected with WUI and Non WUI areas – 1970 and 2013



(a)

When evaluating the data from the maps, it was confirmed that there is indeed an increase in the WUI areas intersected with forest, as shown in Tables 10.

Table 10. WUI areas intersected with Forest covers in Km² - 1970 & 2013

		Area in Km ²	Percentage
WUI intersected with forest	1970	795.42	3.92%
	2013	1,244.42	6.14%

The consolidated data in Table 10 provides evidence that the growth of WUI areas has taken place together with the forest expansion process described in the previous section. Finally, when analyzing the percentage of WUI areas in Table 11, it is shown that the percentage of WUI areas in 2013 is higher than non-WUI areas in 1970.

Table 11. WUI and Non-WUI areas by percentages - 1970 & 2013

	1970		2013	
WUI	8241.19	40.6%	9924.23	48.94%
No WUI	12038.22	59.4%	10355.17	51.06%

The first thing that is evident in Figure 13 is the increase in the intersections between WUI areas with forest areas by 2013, as seen in the light blue areas in both maps. These changes occur most notably in the central and Western areas, which would indicate that there is a greater presence of areas of forest cover, intersected with larger areas of human settlements. As mentioned in section 3.3, the expansion of human infrastructure is one of the causes of habitat fragmentation for wolves. With these results, it can be posited that the central and Western areas might show a lower level of connectivity between potential habitats compared to other areas of the Polish Carpathians.

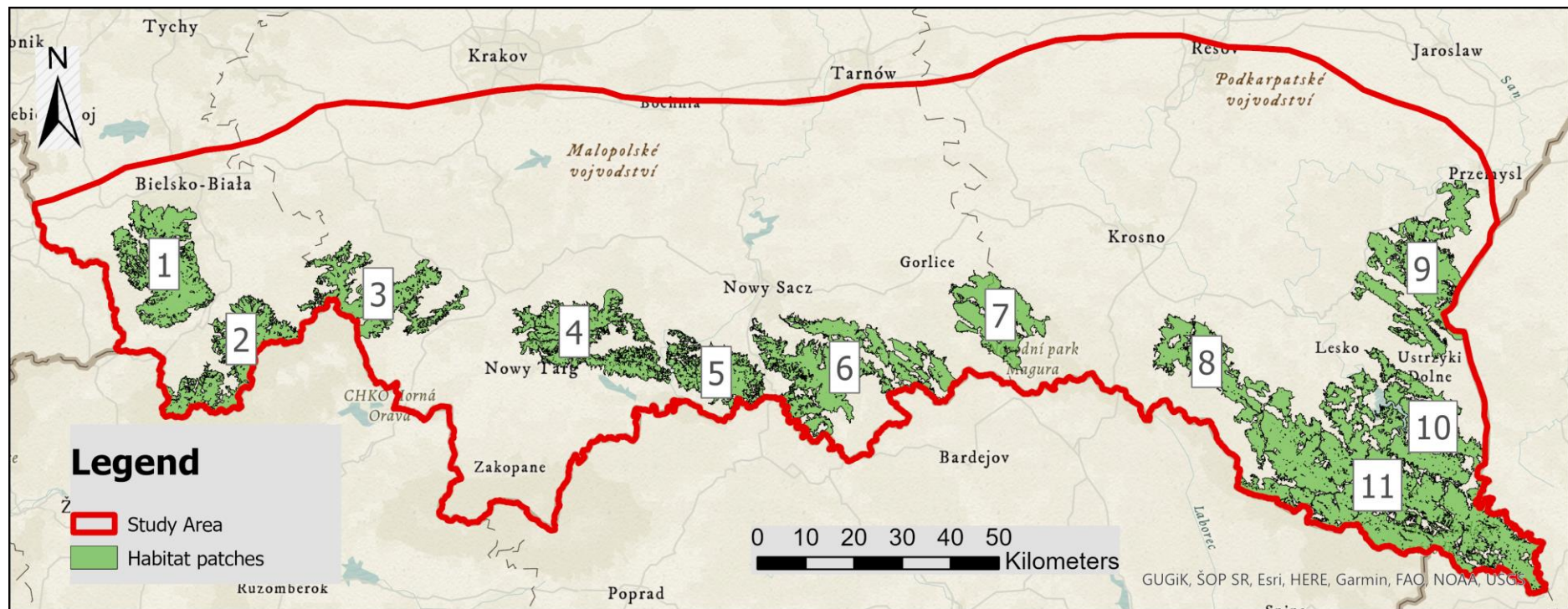
Finally, the Eastern part of the Polish Carpathians the increase in intersection areas between forest and WUI is relatively lower compared to other regions within the study area. This is attributed to a higher presence of forests and relatively less human infrastructure growth, which is a potential factor leading to habitat fragmentation. Consequently, it can be inferred that the Eastern Polish Carpathians offer more favorable conditions for the connectivity between potential wolf habitat patches in the Polish Carpathians in 2013.

5.2. A corridor analysis to assess the connectivity of the habitat patches

5.2.1. The positive changes in potential habitat patches

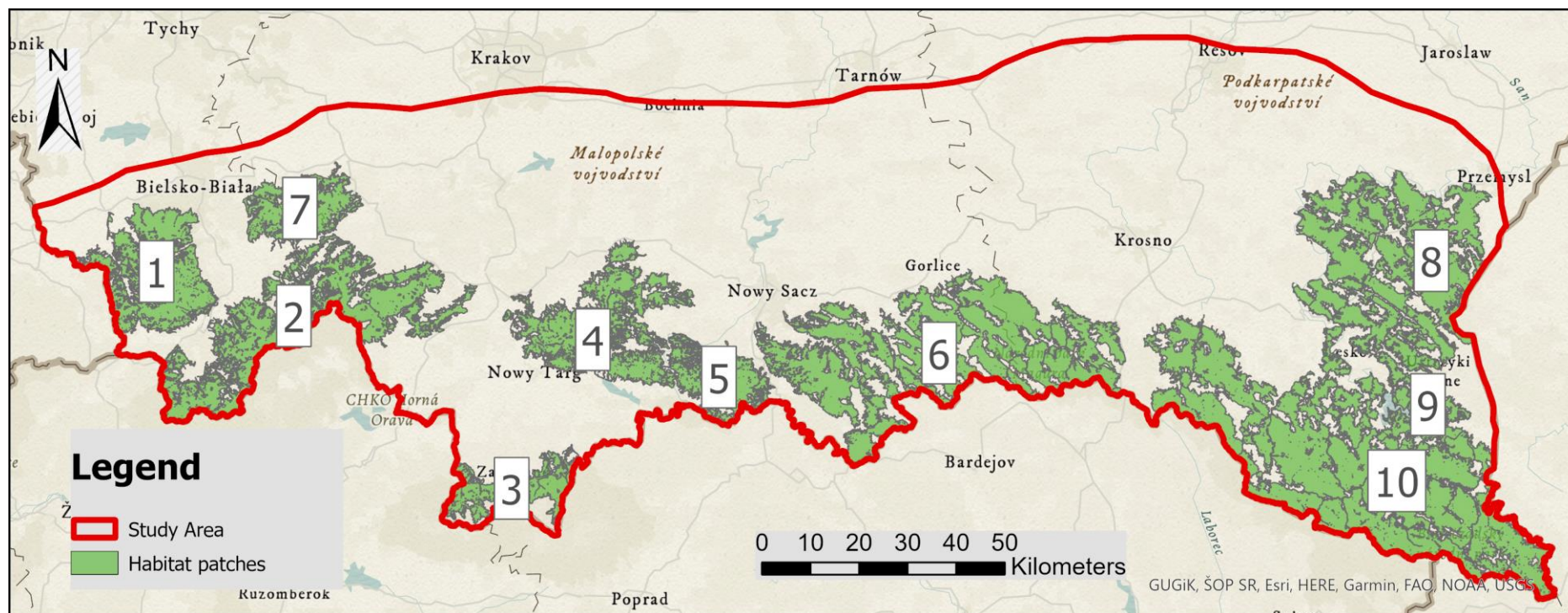
Before starting the corridor analysis, it was necessary to identify all those forest patches with areas from 150Km² (Nowak et al., 2008) onwards since these are defined here as potential habitat patches for wolves in the Polish Carpathians. Following this criterion, the following maps were obtained for the years 1970 and 2013:

Fig. 13. Potential Habitat Patches for wolves in 1970



Source: Own Elaboration. Dataset from Kaim D., Szubert P., Shahbandeh M., Kozak J., Ostafin K., Radeloff V.C., in preparation, Growth of the Wildland-Urban Interface and its Spatial Determinants in the Polish Carpathians

Fig. 14. Potential Habitat Patches for wolves 2013



Source: Own Elaboration. Dataset from Kaim D., Szubert P., Shahbandeh M., Kozak J., Ostafin K., Radeloff V.C., in preparation, Growth of the Wildland-Urban Interface and its Spatial Determinants in the Polish Carpathians

When evaluating the potential habitat patches, the first thing that can be observed is that the areas of habitat patches in 2013 is higher than in 1970. The following table shows the areas of each habitat patches for both years of study:

Table 12. Forest patches areas – 1970 and 2013

1970		2013	
Forest Patch ID	Area Km ²	Forest Patch ID	Area Km ²
1	277.42	1	371.21
2	212.39	2	622.97
3	219.95	3	151.24
4	252.03	4	416.39
5	151.6	5	185.79
6	367.55	6	1022.1
7	181.26	7	186.16
8	172.5	8	823.82
9	327.58	9	240.53
10	222.75	10	1412.87
11	951.26	Total	5433.08
Total	3336.29		

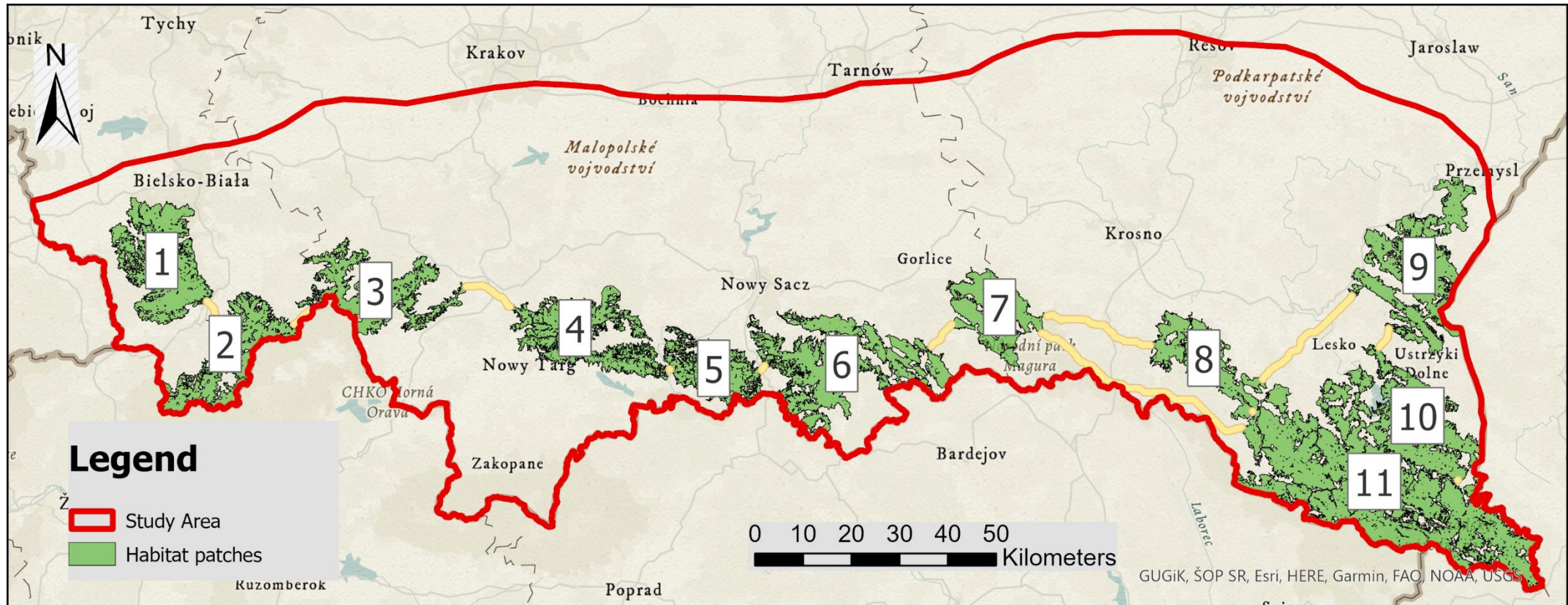
This data is consistent with the information presented in Figure 12 and Table 9, which confirms the increase in forest areas. On the other hand, it can be observed that the growth of habitat patches has not occurred in those areas where the expansion of WUI areas was more intense, i.e., in the northEastern and north-central areas of the Polish Carpathians. On the other hand, despite the expansion process of WUI areas in the territory, it can also be stated that after the forest transition stage, there has been an increase of potential habitat patches for wolves within the territory, especially in the southern part of the territory. For example, patches 1, 2 and 3 from 1970 (Fig. 14) have increased in area by 2013 (Fig. 15). A similar situation can be observed in the patches of the Central and Eastern zones.

Finally, Fig. 15 shows the consolidation of larger habitat patches in 2013, mainly in the SouthEastern and South-central area. Thus, the presence of larger habitat patches in 2013 (Example: see habitat patches N° 8, 9 and 10 in Figure 15) suggests a greater availability of suitable habitats for wolves since given their greater extension they are able to offer refuge areas and food resources. On the other hand, the map in Figure 15 shows not only a greater size of habitat patches but also a greater proximity between them (In Figure 15, see the group of habitat patches N° 8, 9 and 10; or the group formed by habitat patches N° 4, 5, 6) in comparison with the habitat patches of 1970 (Figure 14). Therefore, the presence of larger and closer habitats may offer better mobility and dispersal possibilities for wolves according to the maps presented in this section. However, it is necessary to perform an analysis that considers anthropogenic barriers that may affect connectivity between the habitat patches shown in the maps.

5.2.2. Optimal paths for potential habitat patches

Figures 16 and 17 show the main optimal paths between the habitat patches presented above for the periods 1970 and 2013.

Fig. 15. Optimal Paths for connectivity of potential habitat patches in 1970



Source: Own Elaboration. Dataset from Kaim D., Szubert P., Shahbandeh M., Kozak J., Ostafin K., Radeloff V.C., in preparation, Growth of the Wildland-Urban Interface and its Spatial Determinants in the Polish Carpathians

Fig. 16. Optimal Paths for connectivity of potential habitat patches in 2013

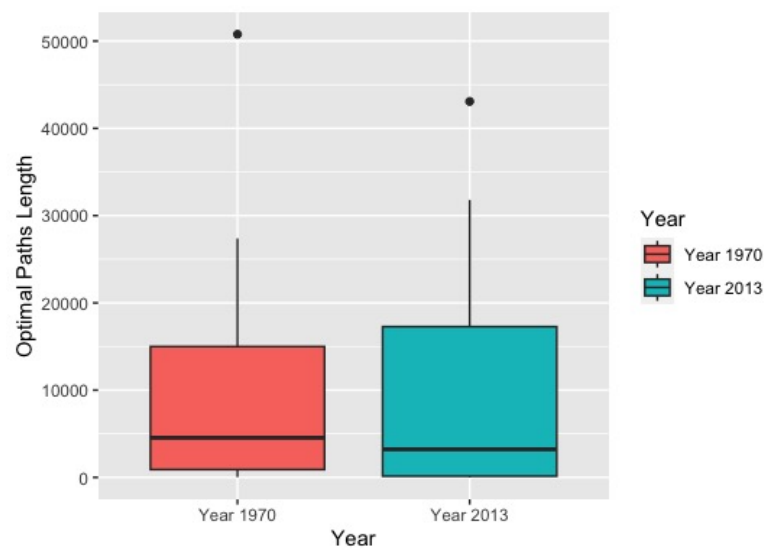


Source: Own Elaboration. Dataset from Kaim D., Szubert P., Shahbandeh M., Kozak J., Ostafin K., Radeloff V.C., in preparation, Growth of the Wildland-Urban Interface and its Spatial Determinants in the Polish Carpathians

From the two maps presented above, it is evident that there has been an increase in the areas occupied by habitat patches between 1970 and 2013. How are the 1970 and 2013 habitat patches connected through optimal paths calculated by least cost path algorithm? How easy or difficult to traverse are the proposed optimal paths for 2013, regarding to 1970? Optimal paths help to identify the corridor's connections among potential habitat patches in this work, which have already been mentioned are crucial for facilitating wolf movement between patches, gene flow, and also analyzing changes in the spatial distribution of the species within the study area. To answer the above questions, the following boxplots were constructed showing the distribution of the data on optimal path distances between habitat patches (Figure 18), as well as the distribution of tortuosity index (Figure 19) from the information presented in Table 13.

Figure 18a represents the distribution of optimal path distances for the entire region of the Polish Carpathians, where for the year 2013 the interquartile range is slightly bigger compared to 1970, which would indicate that in general in the study area there are greater distances to travel on the optimal paths for the last study period. The lower median in the 2013 boxplot compared to 1970 suggests that, on average, optimal paths in 2013 are shorter than in 1970. This indicates a trend towards shorter distance between patchy habitats in 2013, which may be positive for connectivity and species movement. However, it is important to note that a greater variability in distances (reflected in the wider interquartile range) may imply that some paths are longer and more complex, which may affect connectivity and species dispersal across the landscape.

Fig. 17(a). Optimal Paths (O.P) Length for Polish Carpathians

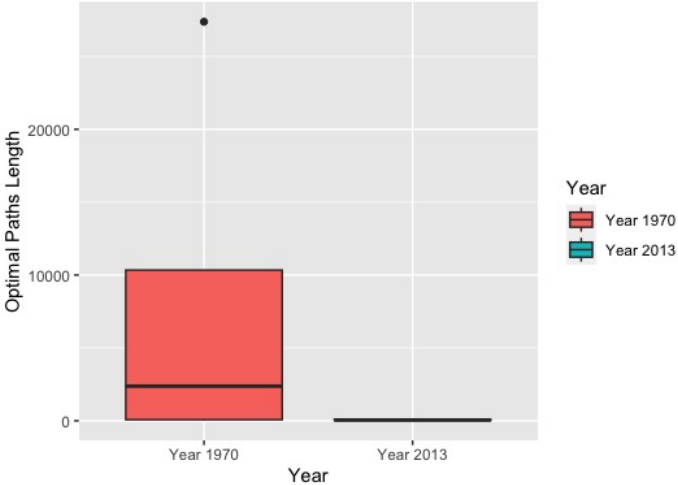


To explore distinct dynamics in the connectivity of habitat patches, the data was disaggregated into three sub-areas as is shown in the next table. Subsequently, box plots were constructed to analyze optimal path distances and the tortuosity index:

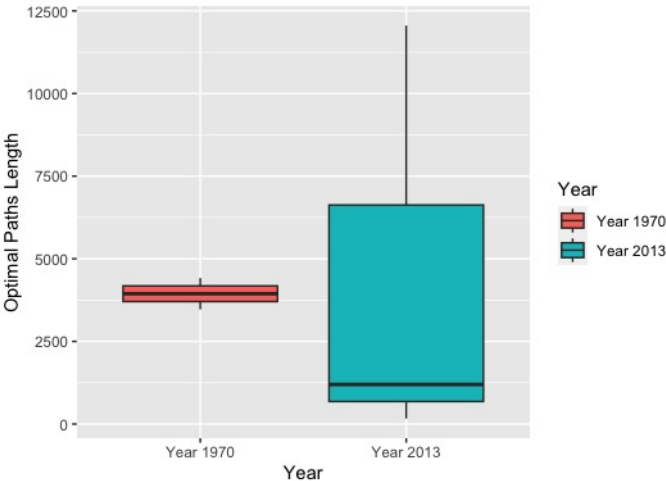
	ID of Habitat Patches	
	1970	2013
Eastern area	8, 9, 10, 11	8, 9, 10
Central area	4, 5, 6, 7	3, 4, 5, 6
Western area	1, 2, 3	1, 2, 7

The optimal paths in the Eastern area (Fig. 18b) show that both the dispersion and median distances of the 2013 optimal paths are shorter than in 1970, indicating that there is less variability in distances, and this would imply the possibility of more efficient paths compared to 1970. Likewise, a lower dispersion in the distances of the optimal paths is Eastern area for 2013 also indicates that the habitat patches are closer together, implying a much less fragmented habitat compared to the dispersion shown for the Western (Fig. 18c) and Central (Fig. 18d) zones. On the other hand, it is worth mentioning the increase of the median in the Central area (Fig. 18d), where the median of the 2013 boxplot is higher compared to that of 1970. This increase suggests that in general, optimal roads are more extensive and/or complex than in 2013, possibly due to the creation of new forest patches and urban sprawl, which may have affected the landscape configuration.

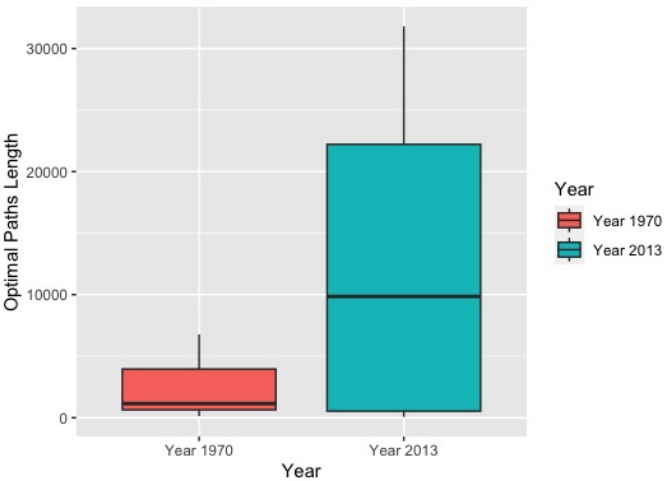
Fig. 18 (b) O.P. Length for Eastern Area of Polish Carpathians



(c) O.P for Western Area

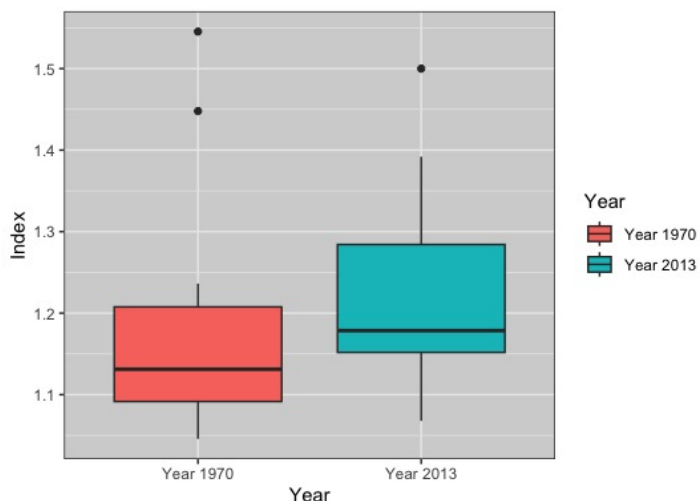


(d) O.P for Central Area



As mentioned before the path tortuosity index gives us a better idea about how easy or difficult it is to traverse these paths, as the higher the index, the lower the potential for connectivity between different habitat patches (Kaim et al., 2019). The boxplot of the tortuosity index for the study area (Figure 19a) shows that the median for 2013 is slightly higher than in 1970, which would represent a greater curvature or sinuosity of the roads.

Fig. 18(a). Path Tortuosity Index for Polish Carpathians



When the information is disaggregated into sub-areas, it is observed that the tortuosity indexes show different dynamics depending on the location. For example, the higher medians in the 2013 Boxplot for the Eastern (Fig.19b) and Central area (Fig.19d) indicate a higher complexity in the optimal paths compared to those in the Western area (Fig.19c).

Fig.19(b) Index for Eastern Area

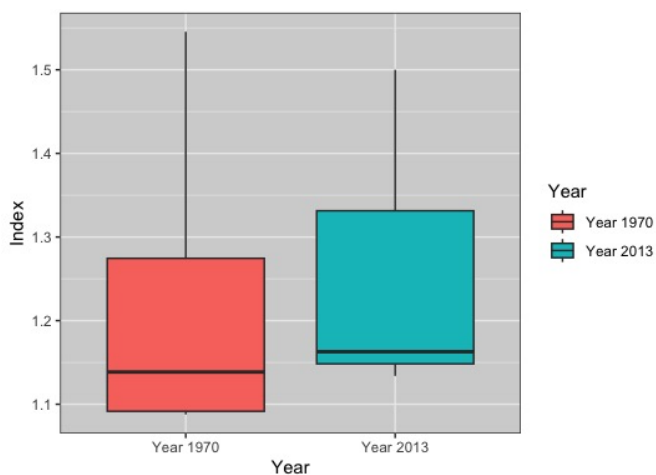


Fig. 19(c) Index for Western Area

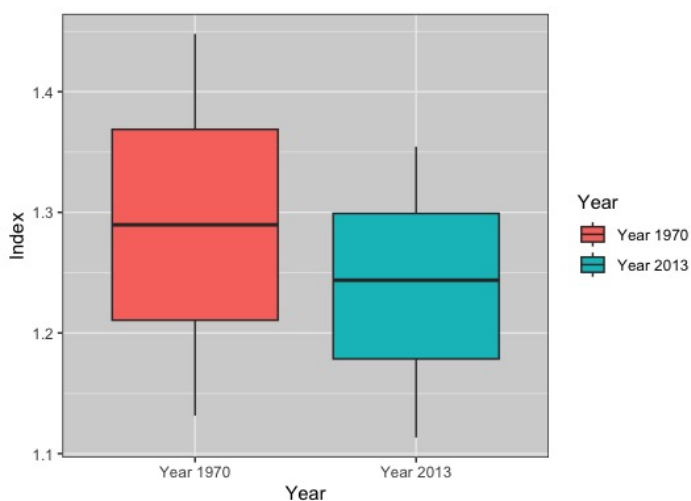


Fig. 19(d) Index for Central Area

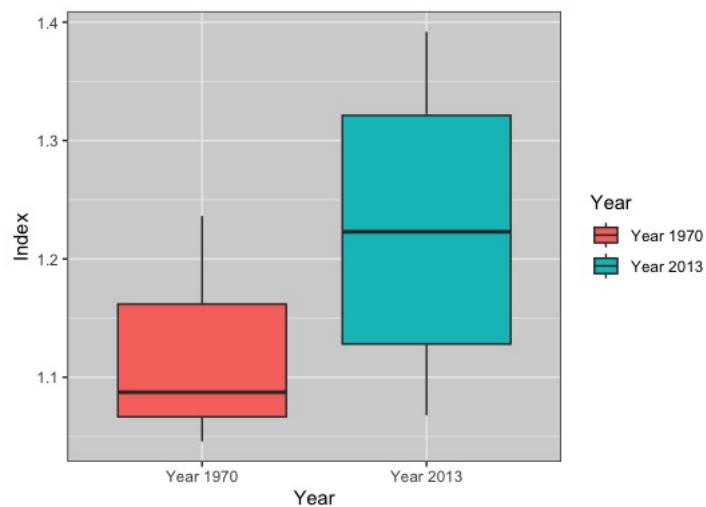


Table 13. Path Tortuosity and Cost of Optimal Paths in Polish Carpathians - 1970 and 2013

1970				2013			
ID1	ID2	Cost of Optimal Paths	Path tortuosity index	ID1	ID2	Cost of Optimal Paths	Path tortuosity index
1	2	235,192.42	1.31	1	2	63,676.75	1.35
4	5	10,477.42	1.04	4	5	4,262.61	1.14
5	6	87,266.90	1.08	5	6	54,386.65	1.06
10	11	1,442,704.75	1.08	9	10	835.69	1.5
9	10	266,334.09	1.09	8	9	8,811.64	1.14
3	4	677,456.00	1.19	2	4	280,907.53	1.17
7	8	2,667,875.25	1.1	6	10	88,307.20	1.18
8	9	2,124.90	1.54	7	1	305,949.31	1.24
7	6	354,977.47	1.23	7	2	12,666.22	1.11
7	11	1,286,713.25	1.13	7	4	962,848.00	1.2
11	8	6,507.69	1.18	8	10	4,430.77	1.16
				5	3	701,547.31	1.29

The Table 13 presents the values of cost of optimal paths and path tortuosity index for all the paths in 1970 and 2013, where the highlighted values represent the paths that existed in 1970 along their counterparts in 2013. Upon examining the data presented in the previous table a clear trend emerges, indicating that the paths existing in 1970 have become considerably more traversable in 2013. This conclusion is based on a comparison of the cost of optimal paths for each route, which consistently display lower values than those recorded in 1970. Nevertheless, the comparison of tortuosity index for these paths does not give the same conclusion: five from seven paths paths show higher values in 2013 than in 1970, meaning these despite the paths are shorter, they became more complicated to traverse due these are less direct paths than before.

Moreover, a closer look at the costs of optimal roads and tortuosity index for sub-areas reveals divergences between these values. Table 14 provides a comprehensive overview of these findings, with highlighted values representing again the paths that existed in 1970 and that can be compared with their 2013 counterparts. For instance, in the Eastern zone, habitats 10 and 11 (1970) display an increase in their tortuosity index, suggesting that the directness of the path between the two patches has diminished in 2013. However, it is noteworthy that the cost of the optimal path has decreased significantly, from 1,442,704.75 to 835.69, implying that traversing this path is now less challenging.

Similar results can be observed with patches 9 and 10 in 1970. These connectivity outcomes raise interesting questions about their relationship with the forest transition process and the expansion of WUI (Wildland-Urban Interface) areas. Overall, the data presents a compelling case for the improved ease of travel along existing paths in 2013, highlighting the importance of considering these findings within the context of forest transition and the evolving WUI landscape.

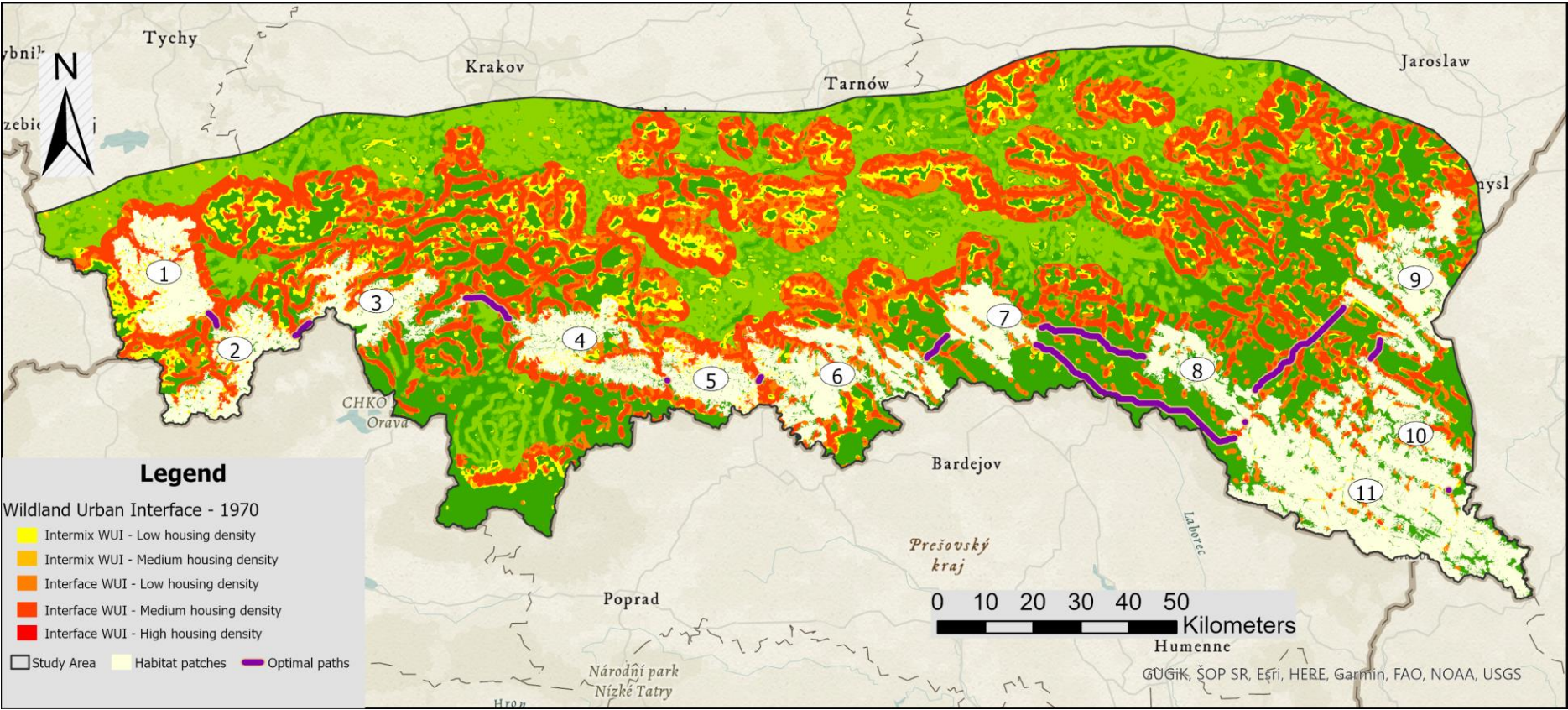
Table 14. Path Tortuosity and Cost of Optimal Paths in Polish Carpathians by sub areas- 1970 and 2013

	1970				2013			
	Habitat Patches		Cost of Optimal Paths	Tortuosity Index	Habitat Patches		Cost of Optimal Paths	Tortuosity Index
Eastern area	10	11	1,442,704.75	1.08	9	10	835.69	1.50
	9	10	266,334.09	1.09	8	9	8,811.64	1.14
	8	9	2,124.90	1.54	8	10	4,430.77	1.16
	11	8	6,507.69	1.18				
Central area	4	5	10,477.42	1.04	4	5	4,262.61	1.14
	5	6	87,266.90	1.08	5	6	54,386.65	1.06
	7	6	354,977.47	1.23	3	4	494,894.78	1.39
					5	3	701,547.31	1.29
Western area	1	2	235,192.42	1.31	1	2	63,676.75	1.35
	2	3	194,547.30	1.44	7	1	305,949.31	1.24
					7	2	12,666.22	1.11

5.2.3. Optimal paths for potential habitat patches considering WUI areas

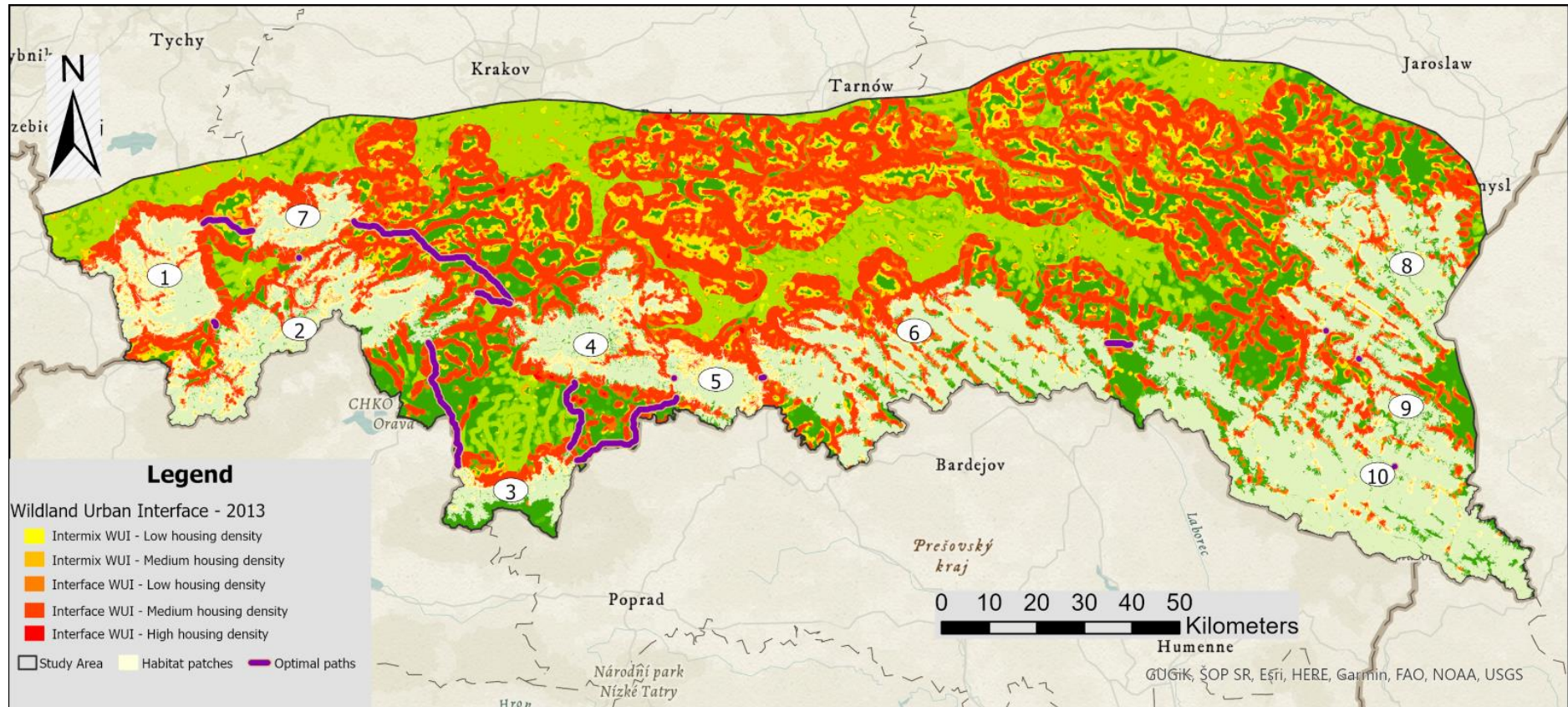
This section presents the optimal pathways from the previous section, but this time considering the WUI areas. The objective is to visualize how the above information can be better understood from the areas most exposed to human infrastructure development.

Fig. 19. Potential hábitat patches connected by optimal paths according to WUI areas – 1970



Source: Own Elaboration. Dataset from Kaim D., Szubert P., Shahbandeh M., Kozak J., Ostafin K., Radeloff V.C., in preparation, Growth of the Wildland-Urban Interface and its Spatial Determinants in the Polish Carpathians

Fig. 20. Potential hábitat patches connected by optimal paths according to WUI areas – 2013}



Source: Own Elaboration. Dataset from Kaim D., Szubert P., Shahbandeh M., Kozak J., Ostafin K., Radeloff V.C., in preparation, Growth of the Wildland-Urban Interface and its Spatial Determinants in the Polish Carpathians

When comparing the changes between the 1970 (Fig. 20) and 2013 (Fig. 21) maps, it is observed that the Eastern zone (already defined in the previous section) presents the least expansion of WUI areas compared to other areas within the study territory. This expansion helps to understand why the levels of the tortuosity index in the same zone (Fig. 19b) have increased slightly, despite the fact that the distance of the optimal paths are much shorter (Fig. 18a). A similar situation occurs in the Central zone, where the expansion of the WUI areas also helps to understand the increase in the tortuosity indexes (Fig. 19d), in addition to the fact that in this area the optimal paths, and therefore the corridors, are much longer, which would mean greater challenges in the Central zone (Fig. 18d) for the establishment of adequate corridors compared to the Eastern area. Also, it is worth to mention, that the Central area presents an outstanding increase of the WUI areas as can be observed in Fig. 13b.

Finally, in the Western zone there is also an expansion of WUI areas, which is less marked than in the central zone. However, here we do observe a slight decrease in the tortuosity indexes (Fig. 19c) and a much lower median number of optimal paths for 2013. This would indicate that although the Western zone shows an expansion of WUI areas, it has also experienced a process of growth of potential optimal paths that at least seems to indicate less difficulties for mobilization than in the central zone. It is worth to pose the question whether these favorable changes in the Central zone are due to the fact that the effects of forest expansion in this area were much greater than the expansion of the WUI areas.

On the other hand, when evaluating the percentage of optimal paths intersecting with WUI areas in both 1970 and 2013, the following results were obtained:

Table 15. Length of Optimal Paths intersected with WUI areas - 1970 and 2013

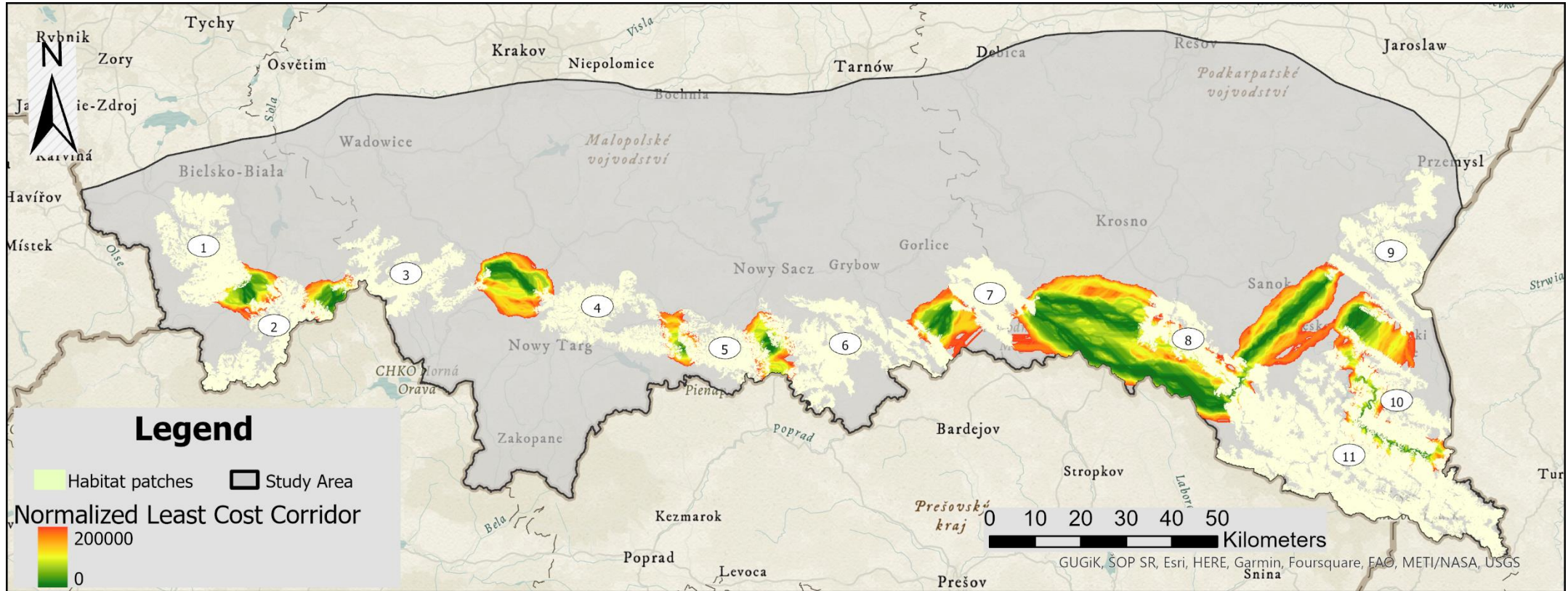
1970		2013	
Lenght of paths	Percentage	Lenght of paths	Percentage
60,050.60 m	44.28%	31,095.14 m	20.34%

As depicted in the table above, there was a significant decrease in the percentage of path lengths intersected with WUI areas, dropping from 44.28% to 20.34%.

5.2.4. Ecological Corridors for potential habitat patches

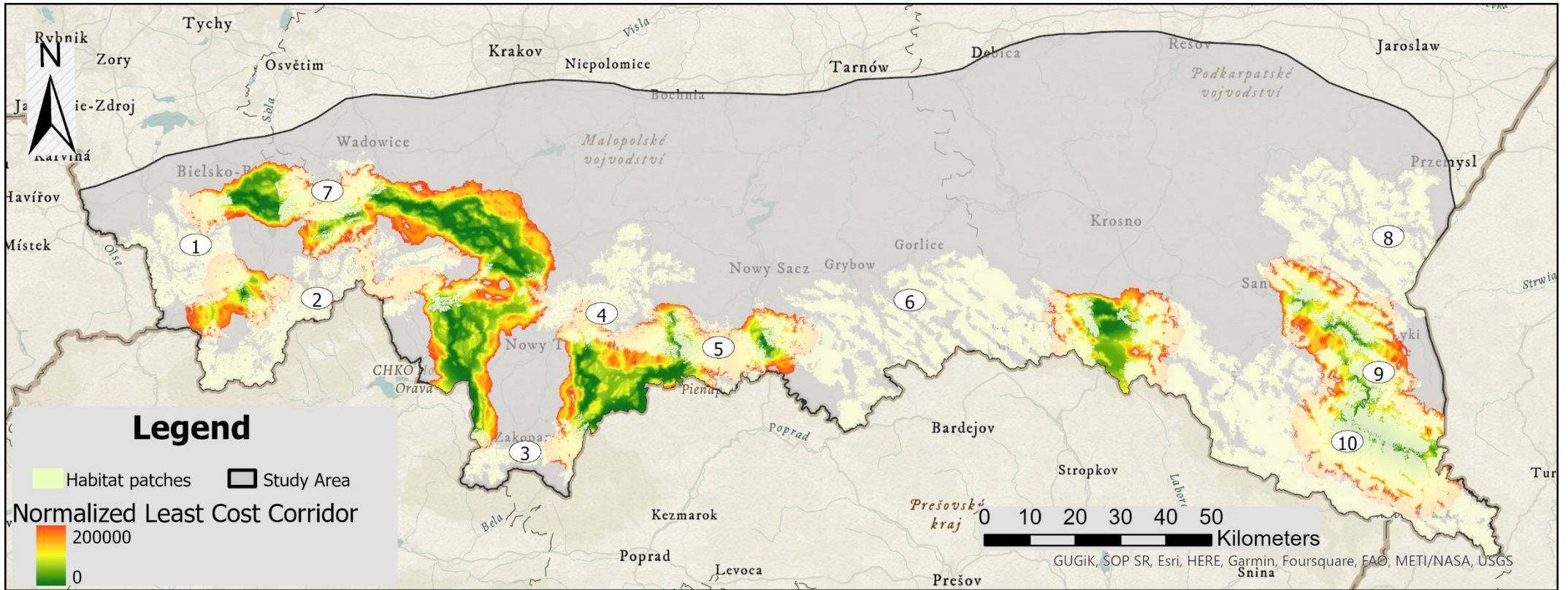
Finally, this section presents the corridors built from the optimal paths presented in the previous section.

Fig. 21. Connectivity between wolves' habitats patches using Corridor analysis – 1970



Source: Own Elaboration. Dataset from Kaim D., Szubert P., Shahbandeh M., Kozak J., Ostafin K., Radeloff V.C., in preparation, Growth of the Wildland-Urban Interface and its Spatial Determinants in the Polish Carpathians

Fig. 22. Connectivity between wolves' habitats patches using Corridor analysis – 2013



Source: Own Elaboration. Dataset from Kaim D., Szubert P., Shahbandeh M., Kozak J., Ostafin K., Radeloff V.C., in preparation, Growth of the Wildland-Urban Interface and its Spatial Determinants in the Polish Carpathians

In 1970, the largest corridors were found mainly in the Eastern zone (Fig. 22). While the Western zone contained the smaller corridors, which limited the potential for wolf transit between forest patches in that time. But for the same area in 2013 (Fig.23) the corridors have increased in size, perhaps this is one of the most striking changes given the situation in 1970. In the case of the corridors in the Central and Eastern area, increases in corridor size are also observed.

Therefore, a first observation is that by 2013 there are a greater number of potential corridors for wolves among the habitat patches considered for this work. However, the maps indicate that the level of expansion of the WUI areas plays a role in the complexity of traversing these corridors depending on whether they are in the East, West or Central areas as already mentioned in the previous section.

6. Discussion

This dissertation seeks to study how potential habitat patches for wolves were affected by changes in forest cover and WUI areas in the Polish Carpathians. The initial premise of this work was to see if increases in forest cover, as well as a greater presence of housing density had indeed benefited connectivity between potential habitat patches, thus creating quality habitat for wolves. This issue is relevant since the expansion of forest cover may be accompanied by forest fragmentation processes due to land ownership and land use dynamics (Kozak et al., 2018). The present discussion focuses on four aspects that seek to address the issues proposed in the research questions of this paper:

1. The impact of the forest transition process and the changes of WUI areas on the connectivity of habitat patches.
2. Based on the overlap between the changes in forest cover intersected with the WUI areas shown in section 5.1, it is proposed a discussion about the opportunities and limitations for habitat patches provided by changes in forest cover.
3. On the possible consequences on human-wildlife dynamics as there are several corridors and habitat patches that are "surrounded" or very closed by WUI areas.
4. Limitations about the datasets and method for determining forest habitat patches for fragmentation analysis.

First, the forest transition process is accompanied by a clear increase of habitat patches from 150 km² onwards for wolves. The corridor maps indicate that the process of forest expansion has been accompanied by a process of reduced fragmentation of forest patches specially in the Eastern area, leading to a more continuous forest cover. An example of this decrease in fragmentation would be habitat patches N° 8, 9 and 10 where the increase in forest has been sufficient to reduce the gaps between these habitats. Thus, the expansion of forest in the Polish Carpathians has had a positive impact on increasing the connectivity for wolves' habitats (Kaim et al., 2019). As mentioned before, for the case study of this work, the type of forest transition was driven by economic development (Wilson et al., 2017), this case fits into the categorization of Wilson about the drivers for forest transition and its positive impacts for ecosystem.

If we return to the proposal of Wilson et al. (2017) that the results of a forest transition by economic development generates restoration of nature, and this is reflected in the fact that by 2013 there are lower values for the cost of optimal roads between patches 10 and 11; and 9 and 10. And at the same time, the increase in the tortuosity index suggests that despite the lower difficulty in transit cost, the roads between these patches have become less direct over time, and all this occurs in a context of expansion of WUI areas that has already been shown in the results section. As areas of human infrastructure have grown, wolves may have to travel less direct paths in order to avoid these areas. As mentioned by Bar-Massada et al. (2014), WUI areas also play a role in their impacts on neighboring ecosystems due to their proximity to them.

However, in general, it can be affirmed with the information in Table 14 that for the patches that already existed since 1970, the cost of the paths connecting them is lower for all areas. While the tortuosity index values of these same patches are higher in 2013, with the exception of the paths between patches 5 and 6 of the central area (See Table 14). In summary the analysis suggests that the landscapes changes in the Polish Carpathians due to WUI areas and forest cover expansion have had both positive and negative impacts: transformed into one the most extensive wilderness areas in Central Europe, at the same time the Polish Carpathians also was place for the increasing of human settlements (Affek et al., 2021).

It is worth mentioning, the reduction in the value of path cost is quite significant, while the increase in tortuosity index values is slightly higher in some cases and much higher in others. Thus, while the cost values show that there has been a noticeable improvement in connectivity for all areas, at the same time the tortuosity index values show less direct paths, reflecting potential obstacles on the same paths.

The data on the greater presence of the WUI area (see Figures 20 and 21) helps to explain why tortuosity index values are higher in 2013. A question to be raised about connectivity in the Polish Carpathians is what other variables are critical in determining good connectivity between wolf patch habitats in the study area. This work has focused on the role of the habitat patches in 2013 regarding 1970 and also in the new WUI areas, and from this data it was found that connectivity levels between habitat patches show complex trends: while the WUI expansion can contribute to more indirect paths, the overall increase of forest cover facilitates better transit of the optimal paths.

Secondly, this work accounts for the changes occurred over a period of almost 45 years, most of them triggered by socialism collapse (Affek et al., 2021). In the section results there is a clear overlap between WUI areas and forest cover for the years 1970 and 2013. And the expansion of WUI areas shown in Table 11 shows that the process of forest transition in the Polish Carpathians has been accompanied by an expansion of human infrastructure. How this happened? the legal aspect helps to understand this phenomena, since there was a need of better planning decisions to define the define the location of new infrastructure, as a consequence human infrastructure was authorized in a way that continuity of landscapes was not considered as critical variable (Ćwik & Hrehorowicz-Gaber, 2021). Hence, to attain ecological sustainability and sustainable cities as proposed by Baumgartner (2019) for this process, it is imperative to take into account various scales for conservation management and planning in the study area. These should encompass, at a minimum, the dynamics of urban expansion, land use, and land cover.

As is well known, the presence and expansion of WUI areas brings with it a series of impacts on wildlife population such as habitat fragmentation and the likelihood of increased human-wildlife conflicts (Kaim et al., 2018). Considering the results from the previous section, a first answer to the research questions in this paper would point out that the effects of forest expansion for the creation of suitable habitats for wolves within the territory of the Polish Carpathians need to consider the different dynamics of WUI expansion when the moment comes to take decisions about the spatial management of the area. It is clear that there are challenges to overcome for guarantee the connectivity of habitat patches in the central and Western area.

This first part of the results are relevant since the study area is considered to offer highly suitable habitats for wolves (Jędrzejewski et al., 2005). Nevertheless, these results also raise critical questions concerning the current challenges and opportunities related to spatial management in Poland, and indeed, in other regions of Europe, where mountain areas are undergoing rewilding alongside expanding human presence (Kaim et al., 2019). The evidence in this work stresses the importance of identifying and addressing the problems related to connectivity of habitat patches, especially considering the expansion of WUI areas. As our understanding of the extent of WUI expansion remains

limited, it becomes crucial to assess and monitor its impact on wildlife habitats and movement corridors. By doing so, we can develop effective spatial management policies aimed at promoting sustainable land use practices within the Polish Carpathians

To ensure the long-term success of rewilding efforts and the preservation of viable habitats not only for wolves but also for other species within the region, comprehensive tools for better spatial management is essential (Ćwik & Hrehorowicz-Gaber, 2021). Such policies should focus on maintaining ecological connectivity, preventing habitat fragmentation, and reconciling the needs of human development with conservation objectives (Papp et al., 2022). Through these measures, we can strive to foster coexistence between nature and human activities, safeguarding the ecological integrity of these valuable mountain ecosystems in the face of ongoing changes. therefore, spatial management policies should aim at a sustainable management of land uses in the area if we want to guarantee the increase of suitable habitats for wolves and also other species within the Polish Carpathians.

Thirdly, it should be mentioned that the corridors shown in this work, especially those located to the West and Center, are surrounded by extensive WUI areas. While on the one hand it is positive that there are more habitat patches for wolves, it is also clear that there are larger WUI areas in 2013, which represents also potential scenarios of conflict between wildlife and humans (Olson et al., 2019). This situation raises the question of what are the particular challenges in each sub area regarding the expansion of habitats and corridors in order for them to be sustainable in the long term? For a sustainable development of the area, it is important to involve population in an adaptive way in relation to the return of wildlife(König et al., 2021). Otherwise, the occurrence of these conflicts ends up threatening the sustainability of the rewilding process within the study area. Overall, this is also one of the greatest challenges to be taken up if the sustainability of the rewilding process is to be promoted not only in Poland, but also in other rewilding hotspots within Europe.

By 2013 it was observed that the value of tortuosity index in the Eastern area is the lowest in relation to the other areas, which would mean that the corridors in the Eastern area are with better possibilities to facilitate the movement of species, as well as a better genetic exchange compared to the Western and Central areas. The rate of expansion of the WUI areas may help to explain these different levels of difficulty in the transit of corridors, since, as was observed, the Eastern zone is the one that has experienced the least growth of WUI areas. Likewise, the maps in this work show a process of reduction of forest fragmentation in this area, which also favors transit.

The corridors in the Central and Western zones present different levels of complexity. On one hand, it is evident that the forest expansion in 2013 has significantly increased the availability of potential habitats for wolves, offering improved corridor opportunities compared to the situation in 1970. And on the one hand, the greater expansion of the WUI areas in the central zone may explain the presence of additional challenges to cross the corridors compared to those located in the Western part of the study area (see the median values of the tortuosity indexes in Figure.19c and Figure.19d). Therefore, the expansion of WUI areas in the Central zone presents more challenges in terms of possible smoother connectivity. All these results highlight the need to implement differentiated conservation and landscape management strategies if wolf mobility and genetic exchange are to be maintained and promoted within the study area.

On the other hand, the values of the tortuosity index in Figure 19 indicate higher values in 2013 than in 1970 for the central and Eastern areas, in addition to the fact that this implies greater complexity in potential mobility dynamics, it could also imply scenarios of potential human-wildlife conflict since the deviations of the paths reflected in the indexes were constructed from land use variables and WUI types according to the housing density criterion, which would imply that such deviations would be due to anthropogenic causes. To what extent and in which specific areas within the Central and Eastern part of the Polish Carpathians mobility between habitats would be more limited by these factors is a

question to be further explored in future work or when conservation policies within the area need to be designed.

Finally, a paragraph about limitations of the datasets used for this work. In this particular area there were another patches which were neighboring the selected ones for this dissertation: these habitat patches were a little below the threshold of 150Km² determined here. Therefore, if these neighboring habitat patches with areas little below of 150Km² would have considered, this work would have been able to show even more forest cover and therefore less fragmentation in Polish Carpathians. This a limitation generated from the methodology selected for the treatment of datasets.

7. Conclusions

Rewilding in Polish Carpathians poses several challenges for the process to be sustainable in the long term. The aim of this dissertation was to understand to what extent changes in forest cover and WUI areas have had an impact on the connectivity of habitat patches for wolves. This analysis is relevant because forest expansion processes do not necessarily imply that the negative effects of forest decline prior to forest transition such as reduced connectivity between habitat patches or forest fragmentation have been reversed (Kozak et al., 2018). In other words, the expansion of forest cover does not automatically imply the restoration of connectivity between habitat patches.

This study demonstrates that the processes of forest expansion have also been accompanied by dynamics of urban expansion that have transformed the landscape, and therefore the way in which the WUI areas can be visualized within the study area. The most striking aspect is that in this work at least two different dynamics are observed:

- The Western and Eastern zones exhibit dynamics of WUI area expansion, which are comparatively less intense in relation to the Central zone. In the Eastern zone, the increase in WUI areas appears to be the most modest among the studied regions (Figure 21); however, it is noteworthy that navigating these road networks has become more challenging compared to the conditions in 1970. But on the other side the cost of traversing the roads of the Eastern area are the lowest ones compared to other zones.
- This phenomenon may be attributed to heightened vulnerability of corridors to the expanding WUI areas. Conversely, in the Western zone, despite the presence of WUI area expansion, there is a noticeable reduction in tortuosity index (Figure 19) for the year 2013, which can be partially attributed to a decrease in forest fragmentation within this region and the limited expansion of WUI areas.
- On the other hand, the Central zone presents a distinctive scenario characterized by a pronounced expansion of WUI areas alongside the presence of optimal paths for wolves, which consequently constitute potential corridors that are more challenging to traverse (Figure 19) and lengthier (Figure 18). These factors would significantly impact the efficiency of potential corridors within this region.

Therefore, this suggests the design and implementation of multi-scale strategies for the management and conservation of forests and their ecosystems. It is worth mentioning that in these strategies, it is essential to incorporate a social dimension on the reasons that led to the dynamics of forest and urban expansion in each of the mentioned areas as a way for the designing of policies more accurate to the social and environmental context.

On the other hand, this study shows that there is indeed an increase in the areas of forest patches with the 150Km² threshold, and that the corridors of the 2013 period offer more displacement alternatives than those of 1970. However, the path tortuosity index also indicates that the mobility offered by the 2013' corridors in some cases would not be good as it was 1970. But it is also true, that the optimal

paths that conform corridors have less presence within WUI areas (Table 15), which can be considered as a positive impact for corridors in 2013.

Finally, as mentioned above, the corridors shown in this work, such as those in the Western zone, are surrounded or traversed by WUI areas. This scenario poses challenges not only in terms of ensuring that connectivity between habitat patches is sustainable, but also in terms of managing potential conflicts between wildlife and humans. Regarding the latter, the importance of including the local population in adaptation measures in the face of rewilding processes is highlighted. Therefore, it is critical to develop policies that address a socioecological approach to the management and conservation of habitat patch connectivity and rewilding processes. By adequately addressing the challenges related to connectivity, rewilding and human-wildlife conflict, we can move towards a more sustainable future, where ecosystems are strengthened, and local communities can enjoy the benefits that nature provides without compromising their welfare.

8. References

- Affek, A. N., Wolski, J., Zachwatowicz, M., Ostafin, K., & Radeloff, V. C. (2021). Effects of post-WWII forced displacements on long-term landscape dynamics in the Polish Carpathians. *Landscape and Urban Planning*, 214, 104164. <https://doi.org/10.1016/j.landurbplan.2021.104164>
- Bar-Massada, A., Radeloff, V. C., & Stewart, S. I. (2014). Biotic and Abiotic Effects of Human Settlements in the Wildland–Urban Interface. *BioScience*, 64(5), 429-437. <https://doi.org/10.1093/biosci/biu039>
- Bar-Massada, A., Stewart, S. I., Hammer, R. B., Mockrin, M. H., & Radeloff, V. C. (2013). Using structure locations as a basis for mapping the wildland urban interface. *Journal of Environmental Management*, 128, 540-547. <https://doi.org/10.1016/j.jenvman.2013.06.021>
- Bauer, N., Wallner, A., & Hunziker, M. (2009). The change of European landscapes: Human-nature relationships, public attitudes towards rewilding, and the implications for landscape management in Switzerland. *Journal of Environmental Management*, 90(9), 2910-2920. <https://doi.org/10.1016/j.jenvman.2008.01.021>
- Baumgartner, R. J. (2019). Sustainable Development Goals and the Forest Sector—A Complex Relationship. *Forests*, 10(2), 152. <https://doi.org/10.3390/f10020152>
- Bucala, A. (2014). The impact of human activities on land use and land cover changes and environmental processes in the Gorce Mountains (Western Polish Carpathians) in the past 50 years. *Journal of Environmental Management*, 138, 4-14. <https://doi.org/10.1016/j.jenvman.2014.01.036>
- Carlson, A. R., Helmers, D. P., Hawbaker, T. J., Mockrin, M. H., & Radeloff, V. C. (2022). The wildland–urban interface in the United States based on 125 million building locations. *Ecological Applications*, 32(5). <https://doi.org/10.1002/eap.2597>
- Csaki, C., & Lerman, Z. (2002). Land and Farm Structure in Transition: The Case of Poland. *Eurasian Geography and Economics*, 43(4), 305-322. <https://doi.org/10.2747/1538-7216.43.4.305>
- Ćwik, A., & Hrehorowicz-Gaber, H. (2021). Causes and Effects of Spatial Chaos in the Polish Carpathians – A Difficult Way to Sustainable Development. *European Countryside*, 13(1), 153-174. <https://doi.org/10.2478/euco-2021-0009>
- De Jong, W. (2010). Forest Rehabilitation and Its Implication for Forest Transition Theory: Forest Rehabilitation and Forest Transition. *Biotropica*, 42(1), 3-9. <https://doi.org/10.1111/j.1744-7429.2009.00568.x>
- Diserens, T. A., Borowik, T., Nowak, S., Szewczyk, M., Niedźwiecka, N., & Mysłajek, R. W. (2017). Deficiencies in Natura 2000 for protecting recovering large carnivores: A spotlight on the wolf *Canis lupus* in Poland. *PLOS ONE*, 12(9), e0184144. <https://doi.org/10.1371/journal.pone.0184144>
- Dobosz, M., Kozak, J., & Kolecka, N. (2019). Integrating contemporary spatial forest cover data in the Polish Carpathians: Does abundance of data increase knowledge or uncertainty? *Geoinformatica Polonica*, 18, 31-43. <https://doi.org/10.4467/21995923GP.19.002.10886>
- Dunn-Capper, R., Quaas, M., Sandom, C. J., Svenning, J., & Pereira, H. M. (2023). Applying conventional funding mechanisms to rewilding: The opportunities and challenges for funding rewilding in Europe. *Restoration Ecology*, 31(4), e13884. <https://doi.org/10.1111/rec.13884>
- FAO. (2011). *State of the World's Forests 2011*. FAO. <https://www.fao.org/3/i2000e/i2000e01.pdf>

- Ganteaume, A., Barbero, R., Jappiot, M., & Maillé, E. (2021). Understanding future changes to fires in southern Europe and their impacts on the wildland-urban interface. *Journal of Safety Science and Resilience*, 2(1), 20-29. <https://doi.org/10.1016/j.jnlssr.2021.01.001>
- Gillson, L., Ladle, R. J., & Araújo, M. B. (2011). Baselines, Patterns and Process. En R. J. Ladle & R. J. Whittaker (Eds.), *Conservation Biogeography* (1.^a ed., pp. 31-44). Wiley. <https://doi.org/10.1002/9781444390001.ch3>
- Gong, Z., Gu, L., Yao, S., & Deng, Y. (2020). Effects of bio-physical, economic and ecological policy on forest transition for sustainability of resource and socioeconomics development. *Journal of Cleaner Production*, 243, 118571. <https://doi.org/10.1016/j.jclepro.2019.118571>
- González-Moreno, P., Pino, J., Carreras, D., Basnou, C., Fernández-Rebollar, I., & Vilà, M. (2013). Quantifying the landscape influence on plant invasions in Mediterranean coastal habitats. *Landscape Ecology*, 28(5), 891-903. <https://doi.org/10.1007/s10980-013-9857-1>
- Gratzer, G., & Keeton, W. S. (2017). Mountain Forests and Sustainable Development: The Potential for Achieving the United Nations' 2030 Agenda. *Mountain Research and Development*, 37(3), 246-253. <https://doi.org/10.1659/MRD-JOURNAL-D-17-00093.1>
- Grau, H. R., Aráoz, E., Navarro, C. J., Nanni, A. S., & Malizia, A. (2020). Pathways of megaherbivore rewilding transitions: Typologies from an Andean gradient. *Elementa: Science of the Anthropocene*, 8, 19. <https://doi.org/10.1525/elementa.415>
- Gula, R., Bojarska, K., Theuerkauf, J., Król, W., & Okarma, H. (2020). Re-evaluation of the wolf population management units in central Europe. *Wildlife Biology*, 2020(2). <https://doi.org/10.2981/wlb.00505>
- Gurung, A. B., Bokwa, A., Chelwicki, W., Elbakidze, M., Hirschmugl, M., Hostert, P., Ibisch, P., Kozak, J., Kuemmerle, T., Matei, E., Ostapowicz, K., Pociask-Karteczka, J., Schmidt, L., van der Linden, S., & Zebisch, M. (2009). Global Change Research in the Carpathian Mountain Region. *Mountain Research and Development*, 29(3), 282-288. <https://doi.org/10.1659/mrd.1105>
- Helmer, W., Saavedra, D., Sylvén, M., & Schepers, F. (2015). Rewilding Europe: A New Strategy for an Old Continent. En H. M. Pereira & L. M. Navarro (Eds.), *Rewilding European Landscapes*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-12039-3>
- Huck, M., Jędrzejewski, W., Borowik, T., Miłosz-Cielma, M., Schmidt, K., Jędrzejewska, B., Nowak, S., & Mysłajek, R. W. (2010). Habitat suitability, corridors and dispersal barriers for large carnivores in Poland. *Acta Theriologica*, 55(2), 177-192. <https://doi.org/10.4098/j.at.0001-7051.114.2009>
- Ibisch, P. L., Hoffmann, M. T., Kreft, S., Pe'er, G., Kati, V., Biber-Freudenberger, L., DellaSala, D. A., Vale, M. M., Hobson, P. R., & Selva, N. (2016). A global map of roadless areas and their conservation status. *Science*, 354(6318), 1423-1427. <https://doi.org/10.1126/science.aaf7166>
- Jędrzejewski, W., Niedzialkowska, M., Mysłajek, R. W., Nowak, S., & Jędrzejewska, B. (2005). Habitat selection by wolves *Canis lupus* in the uplands and mountains of southern Poland. *Acta Theriologica*, 50(3), 417-428. <https://doi.org/10.1007/BF03192636>
- Johnston, L., Blanchi, R., & Jappiot, M. (2019). Wildland-Urban Interface. En S. L. Manzello (Ed.), *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires* (pp. 1-13). Springer International Publishing. https://doi.org/10.1007/978-3-319-51727-8_130-1
- Kaim, D., Helmers, D. P., Jakiel, M., Pavlačka, D., & Radeloff, V. C. (2023). The wildland-urban interface in Poland reflects legacies of historical national borders. *Landscape Ecology*.

<https://doi.org/10.1007/s10980-023-01722-x>

Kaim, D., Radeloff, V., Szwagrzyk, M., Dobosz, M., & Ostafin, K. (2018). Long-Term Changes of the Wildland–Urban Interface in the Polish Carpathians. *ISPRS International Journal of Geo-Information*, 7(4), 137. <https://doi.org/10.3390/ijgi7040137>

Kaim, D., Ziólkowska, E., Szwagrzyk, M., Price, B., & Kozak, J. (2019). Impact of Future Land Use Change on Large Carnivores Connectivity in the Polish Carpathians. *Land*, 8(1), 8. <https://doi.org/10.3390/land8010008>

Karlsson, J., Brøseth, H., Sand, H., & Andrén, H. (2007). Predicting occurrence of wolf territories in Scandinavia. *Journal of Zoology*, 272(3), 276–283. <https://doi.org/10.1111/j.1469-7998.2006.00267.x>

Kiffner, C., Bond, M. L., & Lee, D. E. (Eds.). (2022). *Tarangire: Human-Wildlife Coexistence in a Fragmented Ecosystem* (Vol. 243). Springer International Publishing. <https://doi.org/10.1007/978-3-030-93604-4>

Kolecka, N., Kozak, J., Kaim, D., Dobosz, M., Ostafin, K., Ostapowicz, K., Wężyk, P., & Price, B. (2017). Understanding farmland abandonment in the Polish Carpathians. *Applied Geography*, 88, 62–72. <https://doi.org/10.1016/j.apgeog.2017.09.002>

König, H. J., Ceaușu, S., Reed, M., Kendall, H., Hemminger, K., Reinke, H., Ostermann-Miyashita, E., Wenz, E., Eufemia, L., Hermanns, T., Klose, M., Spyra, M., Kuemmerle, T., & Ford, A. T. (2021). Integrated framework for stakeholder participation: Methods and tools for identifying and addressing human–wildlife conflicts. *Conservation Science and Practice*, 3(3). <https://doi.org/10.1111/csp2.399>

Kozak, J., Ziólkowska, E., Vogt, P., Dobosz, M., Kaim, D., Kolecka, N., & Ostafin, K. (2018). Forest-Cover Increase Does Not Trigger Forest-Fragmentation Decrease: Case Study from the Polish Carpathians. *Sustainability*, 10(5), 1472. <https://doi.org/10.3390/su10051472>

Lambin, E. F., & Meyfroidt, P. (2010). Land use transitions: Socio-ecological feedback versus socio-economic change. *Land Use Policy*, 27(2), 108–118. <https://doi.org/10.1016/j.landusepol.2009.09.003>

Lasanta, T., Nadal-Romero, E., & Arnáez, J. (2015). Managing abandoned farmland to control the impact of re-vegetation on the environment. The state of the art in Europe. *Environmental Science & Policy*, 52, 99–109. <https://doi.org/10.1016/j.envsci.2015.05.012>

Marull, J., Otero, I., Stefanescu, C., Tello, E., Miralles, M., Coll, F., Pons, M., & Diana, G. L. (2015). Exploring the links between forest transition and landscape changes in the Mediterranean. Does forest recovery really lead to better landscape quality? *Agroforestry Systems*, 89(4), 705–719. <https://doi.org/10.1007/s10457-015-9808-8>

Mather, A. S. (1992). The Forest Transition. *The Royal Geographical Society*, 24(4), 367–379.

Mather, A. S., Fairbairn, J., & Needle, C. L. (1999). The Course and Drivers of the Forest Transition: The case of France. *Journal of Rural Studies*, 15(1).

Niedziałkowski, K., & Putkowska-Smoter, R. (2020). What makes a major change of wildlife management policy possible? Institutional analysis of Polish wolf governance. *PLOS ONE*, 15(4), e0231601. <https://doi.org/10.1371/journal.pone.0231601>

Noga, T. (2019). Valuable habitats of protected areas in southern Poland – a source of rare and poorly known diatom species. *Acta Societatis Botanicorum Poloniae*, 88(1). <https://doi.org/10.5586/asbp.3595>

Nowak, S., Mysłajek, R. W., & Jędrzejewska, B. (2008). *Density and demography of wolf, Canis lupus*

population in the Western-most part of the Polish Carpathian Mountains, 1996–2003.

Olson, E. R., Van Deelen, T. R., Wydeven, A. P., Ruid, D. B., MacFarland, D. M., & Ventura, S. J. (2019). A landscape of overlapping risks for wolf-human conflict in Wisconsin, USA. *Journal of Environmental Management*, 248, 109307. <https://doi.org/10.1016/j.jenvman.2019.109307>

Ortyl, B., & Kasprzyk, I. (2022). Land abandonment and restoration in the Polish Carpathians after accession to the European Union. *Environmental Science & Policy*, 132, 160-170. <https://doi.org/10.1016/j.envsci.2022.02.026>

Ostafin, K., Iwanowski, M., Kozak, J., Cacko, A., Gimmi, U., Kaim, D., Psomas, A., Ginzler, C., & Ostapowicz, K. (2017). Forest cover mask from historical topographic maps based on image processing. *Geoscience Data Journal*, 4(1), 29-39. <https://doi.org/10.1002/gdj3.46>

Papp, C.-R., Dostál, I., Hlaváč, V., Berchi, G. M., & Romportl, D. (2022). Rapid linear transport infrastructure development in the Carpathians: A major threat to the integrity of ecological connectivity for large carnivores. *Nature Conservation*, 47, 35-63. <https://doi.org/10.3897/natureconservation.47.71807>

Pereira, H. M., & Navarro, L. M. (Eds.). (2015). *Rewilding European Landscapes*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-12039-3>

Petriello, M. A., Edgeley, C. M., Chambers, C. L., & Lee, M. E. (2023). Factors influencing support for bat management and conservation in the wildland-urban interface. *Human Dimensions of Wildlife*, 28(2), 170-186. <https://doi.org/10.1080/10871209.2021.2018630>

Prishchepov, A. V., Radeloff, V. C., Baumann, M., Kuemmerle, T., & Müller, D. (2012). Effects of institutional changes on land use: Agricultural land abandonment during the transition from state-command to market-driven economies in post-Soviet Eastern Europe. *Environmental Research Letters*, 7(2), 024021. <https://doi.org/10.1088/1748-9326/7/2/024021>

Radeloff, V. C., Hammer, R. B., Stewart, S. I., Fried, J. S., Holcomb, S. S., & McKeefry, J. F. (2005). THE WILDLAND–URBAN INTERFACE IN THE UNITED STATES. *Ecological Applications*, 15(3), 799-805. <https://doi.org/10.1890/04-1413>

Rey Benayas, J. M., & Bullock, J. M. (2012). Restoration of Biodiversity and Ecosystem Services on Agricultural Land. *Ecosystems*, 15(6), 883-899. <https://doi.org/10.1007/s10021-012-9552-0>

Rudel, T. K., Coomes, O. T., Moran, E., Achard, F., Angelsen, A., Xu, J., & Lambin, E. (2005). Forest transitions: Towards a global understanding of land use change. *Global Environmental Change*, 15(1), 23-31. <https://doi.org/10.1016/j.gloenvcha.2004.11.001>

Rudel, T. K., Meyfroidt, P., Chazdon, R., Bongers, F., Sloan, S., Grau, H. R., Van Holt, T., & Schneider, L. (2020). Whither the forest transition? Climate change, policy responses, and redistributed forests in the twenty-first century. *Ambio*, 49(1), 74-84. <https://doi.org/10.1007/s13280-018-01143-0>

Schug, F., Bar-Massada, A., Carlson, A. R., Cox, H., Hawbaker, T. J., Helmers, D., Hostert, P., Kaim, D., Kasraee, N. K., Martinuzzi, S., Mockrin, M. H., Pfoch, K. A., & Radeloff, V. C. (2023). The global wildland–urban interface. *Nature*. <https://doi.org/10.1038/s41586-023-06320-0>

Selva, N., Switalski, A., Kreft, S., & Ibsch, P. L. (2015). Why Keep Areas Road-Free? The Importance of Roadless Areas. En R. Van Der Ree, D. J. Smith, & C. Grilo (Eds.), *Handbook of Road Ecology* (pp. 16-26). John Wiley & Sons, Ltd. <https://doi.org/10.1002/9781118568170.ch3>

Skrzecz, I., & Perlińska, A. (2018). Current Problems and Tasks of Forest Protection in Poland. *Folia*

Forestalia Polonica, 60(3), 161-172. <https://doi.org/10.2478/ffp-2018-0016>

Speed, J. D. M., Austrheim, G., Kolstad, A. L., & Solberg, E. J. (2019). Long-term changes in northern large-herbivore communities reveal differential rewilding rates in space and time. *PLOS ONE*, 14(5), e0217166. <https://doi.org/10.1371/journal.pone.0217166>

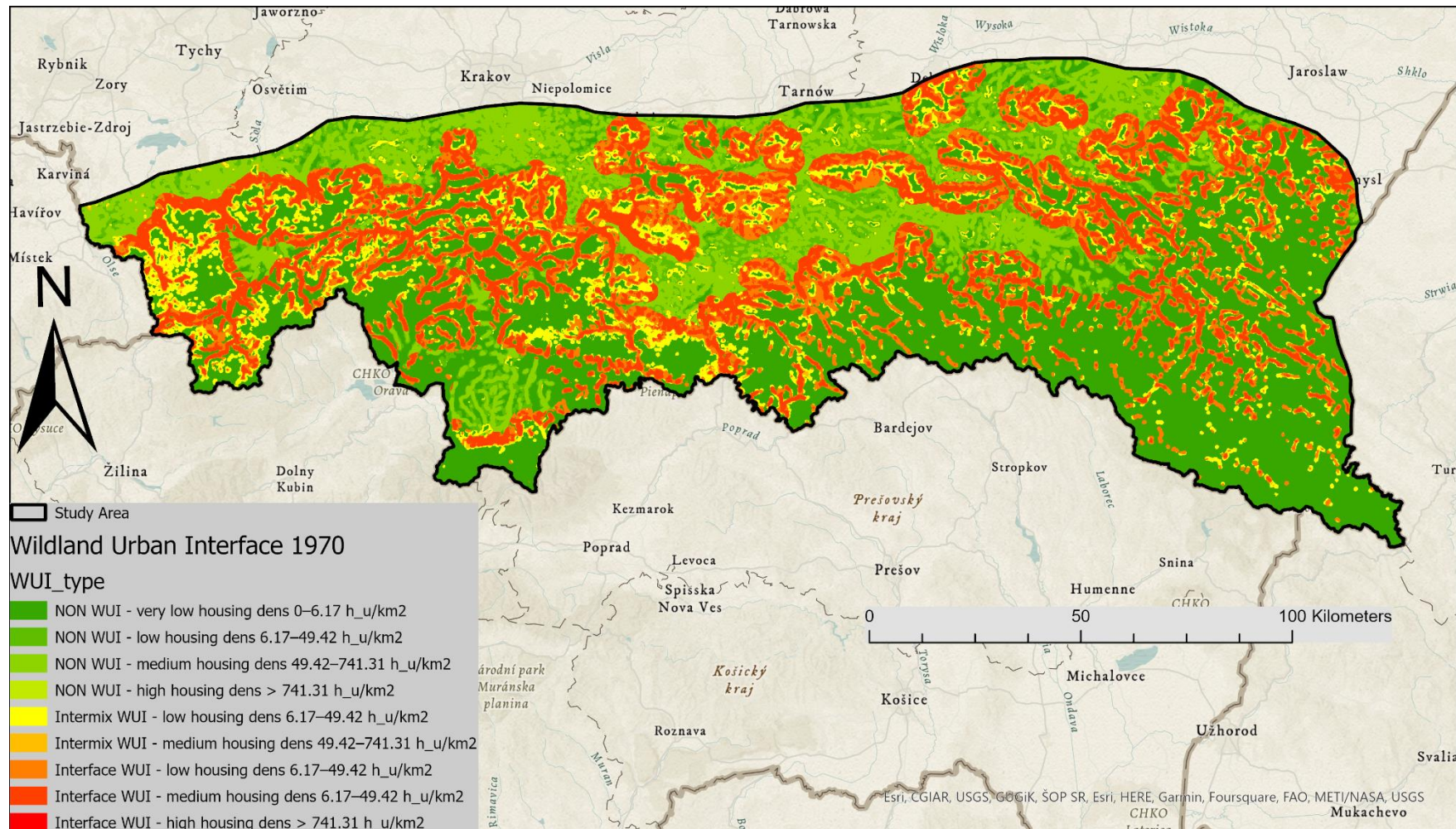
Stoner, D. C. (2011). Ecology and Conservation of Cougars in the Eastern Great Basin: Effects of Urbanization, Habitat Fragmentation, and Exploitation. *All Graduate Thesis and Dissertations*.

Sunderlin, W., Dewi, S., & Puntodewo, A. (2007). Poverty and forests: Multi-country analysis of spatial association and proposed policy solutions. *Multi-Country Analysis of Spatial Association*.

Wilson, S. J., Schelhas, J., Grau, R., Nanni, A. S., & Sloan, S. (2017). Forest ecosystem-service transitions: The ecological dimensions of the forest transition. *Ecology and Society*, 22(4), art38. <https://doi.org/10.5751/ES-09615-220438>

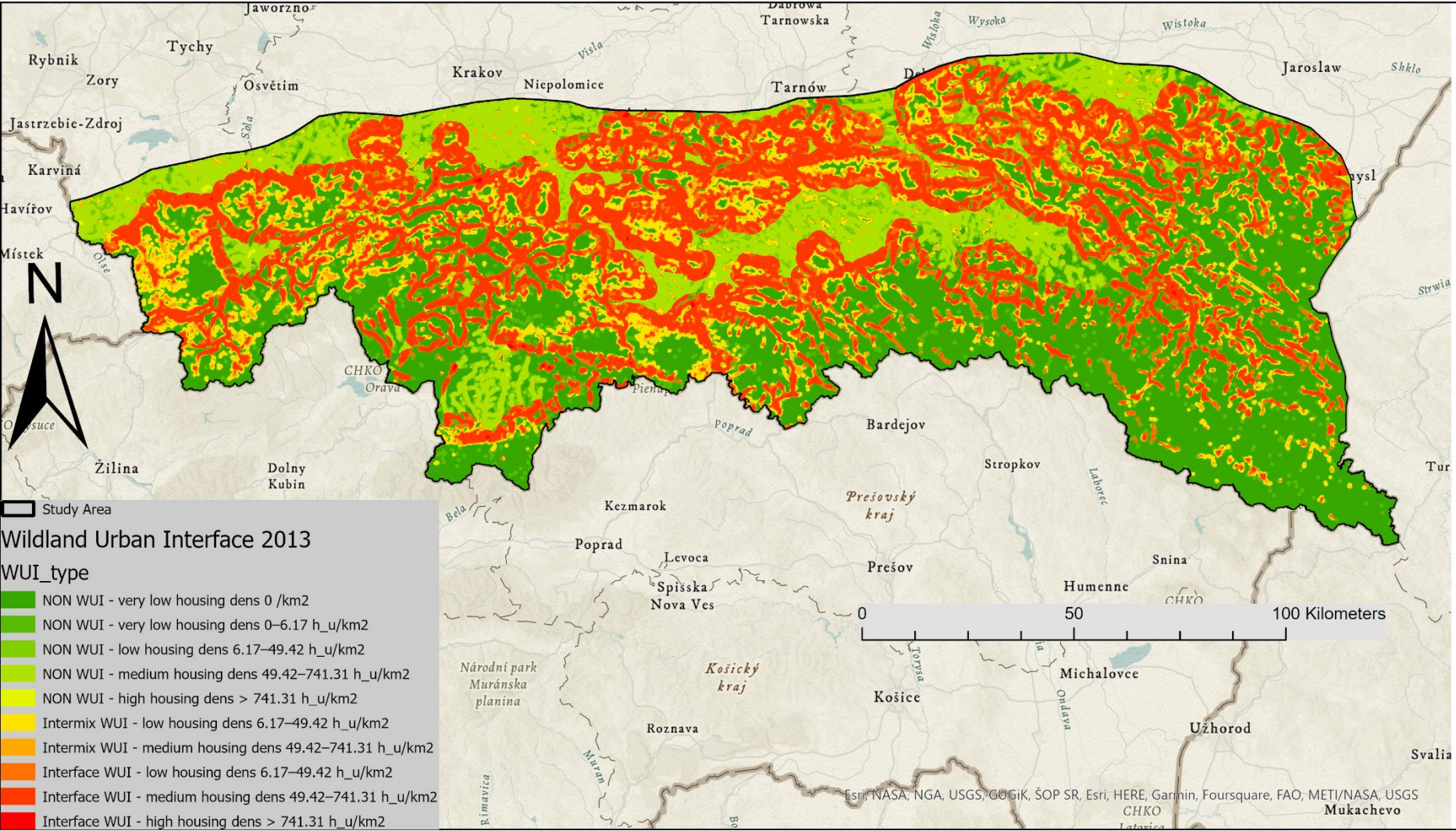
9. Annexes

Annex 1. Wildland Urban Interface Map for 1970



Source: Kaim D., Szubert P., Shahbandeh M., Kozak J., Ostafin K., Radeloff V.C., in preparation, Growth of the Wildland-Urban Interface and its Spatial Determinants in the Polish Carpathians

Annex 2. Wildand Urban Interface Map for 2013



Source: Kaim D., Szubert P., Shahbandeh M., Kozak J., Ostafin K., Radeloff V.C., in preparation, Growth of the Wildland-Urban Interface and its Spatial Determinants in the Polish Carpathians

Annex 2. INTERNSHIP REPORT: DIGITALIZATION OF HISTORICAL MAPS FOR CELSA PROJECT

Main Researcher: Van Rompaey, Anton – KU Leuven

PRESENTATION OF THE ORGANIZATION AND RESEARCH PROJECT

CELSA is the organization that is in charge of the project of my internship. It was founded in April 2016 by 7 old and famous universities in 4 European cities:

- Prague (Czech Republic)
- Budapest (Hungary)
- Leuven (Belgium)
- Ljubljana (Slovenia)

The Alliance aims at promoting collaboration between its members, to exchange practice at both policy and operational level, and together to find solutions for the major problems Europe is facing.

The project addresses the situation of rural abandonment as a dominant ongoing demographic process in Europe which have brought at least two consequences:

- Extremely intensified agriculture with monocultures on megaparcels that had a negative impact on the environment.
- Nature restoration leading to the recovery of degraded ecosystems services.

The theoretical frameworks to approach nature restoration trend to focus on the forest transition, which overlooks the inter- and intra-regional heterogeneity of land cover change processes and their impacts on ecosystem services. This makes them less suitable to develop policies about of land abandonment processes. Therefore, there is an urgent need for clear guidelines on how to manage their depopulating areas to restore key ecosystem services.

The project in which the internship was framed focused on the digitization of historical maps on land uses of the previous century in two areas:

Location	Research objective
Czech Republic – Prague	What is the impact of the observed land cover change on the hydrological regime and the corresponding sediment fluxes? To

	what extent are expected future extreme weather events buffered by the land cover change?
Poland - Krakow	What is the impact of the observed land cover change on potential habitats for large mammals such as bear, lynx and wolf. How fast are abandoned areas colonized by these species and what specific factors may slow down their reintroduction?

My participation in the project was the digitization of historical maps of interest for the project, which were provided by the partner researchers from the Czech Technical University in Prague and Jagiellonian University in Krakow. The task of the internship was to digitize different types of land cover and land uses of interest to assess changes in nature restoration at different times of the 20th century or 19th century according to the need of the partner researchers. The digitization process was carried out at the facilities of each of the partner universities for 6 weeks in total, here the responsible researchers were in charge of explaining the context of their respective areas of study, as well as providing training in the use of Arcgis software, which was used for the digitization of the maps.

PRESENTATION OF THE INTERNSHIP ACTIVITIES

	Week 1	Week 2	Week 3
Czech Technical University - Prague	<ul style="list-style-type: none"> - Session on the use of Arcgis software - Session on digitizing criteria 	<ul style="list-style-type: none"> - Digitalization of maps - Meeting on the progress of maps. 	<ul style="list-style-type: none"> - Participation in workshop to present the internship research - Meeting about final status of the digitalization of maps.
Jagiellonian University - Krakow	<ul style="list-style-type: none"> - Session on digitizing criteria - Meeting on the progress of maps. 	<ul style="list-style-type: none"> - Digitalization of maps - Meeting on the progress of maps. 	<ul style="list-style-type: none"> - Digitalization of maps - Meeting about final status of the digitalization of maps.

As a contribution of the internship activities, the digitized maps offer new inputs for the analysis of changes in land covers and land uses for the study areas. Another important aspect to point out is that the digitization of maps is a work that requires many hours, so the final result is a collection of maps whose information can be valuable for studies other than those of the CELSA project.

Self-evaluation of the internship activities

In general, the internship experience has been a very important element in my experience in the master's program since it has offered me the possibility of having a more interdisciplinary training. The digitization of maps during the internship, implied for me an approach with spatial analysis tools, which was very useful for my thesis work. I emphasize the theme of the experience in interdisciplinarity, because when I started my master's degree, I had the expectation of broadening my training in fields of formation that go beyond the Social Sciences.

On the other hand, what I learned during the internship was the basis that helped me to approach and develop my thesis topic with greater confidence, in other words, I feel that my experience in the internship has complemented quite well with the skills I needed in spatial analysis for the development of my thesis. In this sense, what I learned in the internship has allowed me to enjoy the thesis process and to have a more interdisciplinary training, which I repeat has been one of the greatest lessons learned during the master's program.

Annex 3. Skills Certificate

Certificate – Scientific integrity at the Faculty of ...

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Certificate



Certificate



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