Assessing the suitability of urban-oriented land cover products for mapping rural settlements

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ABSTRACT

In recent years, new settlement mapping products have become available at the global and continental scale. Although accuracy assessments have indicated the high quality of these products, assessments were performed mainly on urban areas. However, there is also a need to monitor rural settlement development, as it is often located in proximity to biodiversity hotspots. In this paper, we verified the suitability of three settlement products (i.e., Global Urban Footprint – GUF, European Settlement Map – ESM and Open Street Map – OSM) to detect rural settlements in the Carpathian ecoregion. Two independent accuracy assessments indicated that the GUF captures rural settlements most effectively (overall accuracy – OA – 65.4\% and 92.5\% depending on the procedure). In contrast, the ESM overestimated settlements (OA – 49.5\% and 90.8\%), while the OSM (OA – 61.2\% and 90.2\%) was the most inconsistent source of settlement data. A regional comparison indicated some deviations from these accuracies, reflecting the variability of settlement structures within the study area. This study highlights that although the GUF was the best-performing product in mapping rural settlements across the whole study area, the settlement information it provided was rather conservative, and rural settlements are still insufficiently represented in all tested datasets.

1. Introduction

One of the most profound and long-lasting land change processes is the expansion of settlement areas, which is likely to continue since global forecasts show clear tendencies for population increase in the 21st century (Gerland \textit{et al.} 2014, Jiang and O’Neill...
settlement development and its footprint on the global environment is expected to be most prevalent in the hinterland of cities, it may be also visible in a form of urban sprawl (Jaeger and Schwick 2014) or sprinkling settlements (Romano et al. 2017). Settlement increase will contribute to the development of micro-urbanization (Chai and Seto 2019) and will significantly affect rural areas (Güneralp and Seto 2013, Mcdonald et al. 2009).

In this paper, we will focus on the latter type of development, respectively the rural settlements. Within built-up mapping endeavors, much less attention is paid to rural development than to mega-cities (Fahmi et al. 2014, Chai and Seto 2019, van Vliet 2019). That is because large urban areas are of high economic interest and have a greater impact on the landscape as a whole system (Paz et al. 2017). However, settlement development in rural areas should not be neglected as it could have a high impact on the nearby natural areas. The impact is well documented, e.g., in the processes happening at the interface with natural areas and wildlife (Konig et al. 2020). Areas where settlements are located relatively far from urban centers and meet wildland vegetation are often defined as the wildland–urban interface (Radelhoff et al. 2005).

So far, the wildlife–urban interface has been most often analyzed in terms of wildfires (Lampin-Maillet et al. 2011, Conedera et al. 2015, Argainaraz et al. 2017, Radelhoff et al. 2018), but studies often overlook other environmental processes driving interactions between high biodiversity and high threat in those areas. For instance, the abundance of invasive species is much higher in the wildlife-urban interface than in other regions (Sullivan et al. 2005; Gavier-Pizarro et al. 2010). Housing located in remote areas often requires longer access roads, which create noise and light pollution (Ibisch et al. 2016), trigger landscape fragmentation (Bar-Massada et al. 2014), enhance human-wildlife conflicts (Evans et al. 2017) and may act as an important barrier for animal movement (Ziólkowska et al. 2016, Tucker et al. 2018). Domestic animals living in rural areas negatively affect wildlife species, killing them and altering food webs (Loss et al. 2013, Bar-Massada et al. 2014, Wierzbowska et al. 2016, Krauze-Gryz et al. 2019). Settlements also have a substantial impact on animal behavior and stress levels (Wang et al. 2017) in areas far from urban centres (Zbyryt et al. 2017). The above-mentioned processes happen very often in low-density settlement areas. Proper mapping of such zones requires high quality information on settlements located along the rural-urban gradient (Amato et al. 2018). Therefore, it is of high importance to detect and monitor settlement spread, especially in rural areas in close proximity to biodiversity hotspots.

Although many global urban maps exist (Florczyk et al. 2019), fine-scale settlement mapping and analysis has become possible only recently by using high-resolution products, e.g., the Global Urban Footprint (GUF) (Esch et al. 2013) or the Global Human Settlement Layer (GHSL) (Pesaresi et al. 2013). Furthermore, the European Commission adjusted the GHSL methodology to the European context and produced the European Settlement Map (ESM), which is so far the continental settlement product with the highest resolution (Florczyk et al. 2016). The adjustment of the GHSL methodology to produce the ESM included, for instance, image classification at the
very high resolution of 2.5 m and inclusion of a vegetated surface detector to generate urban green layers (Florczyk et al. 2016). Additionally, the validation procedure differed, as the Land Use and Coverage Area Frame Survey (LUCAS) dataset available for the European Union countries was used as a reference dataset (Florczyk et al. 2016). Previous studies have shown that the GUF and the GHSL are able to capture built-up structures much better than other global remote sensing products, such as MODIS 500 or GlobeCover v.2 (Klotz et al. 2016). However, an assessment of the accuracy conducted in Germany and Italy showed that the accuracy of the GUF and GHSL is higher for urban than rural areas (Klotz et al. 2016). A similar pattern was found for the GHSL in the United States (Leyk et al. 2018). Additionally, tests conducted in conditions of small-scale and fragmented settlement structures dominating the landscape of Burkina Faso also showed GUF advantage over GHSL in rural conditions (Mück et al. 2017). To the best of our knowledge, similar accuracy assessments of the GUF and ESM in rural and peri-urban areas have not yet been conducted.

Apart from remote-sensing-derived products, crowdsourced data such as the Open Street Map (OSM) is another important source of spatial information on settlements (Hecht et al. 2013, Fan et al. 2014, Brovelli et al. 2018). However, crowdsourced spatial data tend to focus more on urban than rural areas (Haklay 2010, Hecht et al. 2013), partially as a result of contributors’ availability or density (Girres and Touya 2010, Senaratne et al. 2017). While the examples of European metropolitan areas show that the OSM is a valuable alternative to other land use data (Jokar Arsanjani and Vaz 2015), little is known about its usefulness in rural conditions. It is likely that the precision of the rural settlement allocation according to crowdsourced spatial data has much lower accuracy than in urban-related mapping products.

The implementation of urban-oriented mapping products to assess the rural settlements has so far been limited to relatively densely populated areas (Klotz et al. 2016), or to the conditions of a single country (Mück et al. 2017). Local discrepancies among countries that are a result of, for example, spatial planning policies, were only partly taken into consideration (van Vliet et al. 2019). Differences in settlement structure resulting from local environmental conditions or planning regulations may also play an important role for the accurate capture of rural areas by remote sensing. Being aware of the limitations of different settlement products, the user must decide which one to choose. So far, such comparison for rural areas is not available.

The aim of this study was to verify to what extent are the existing settlement mapping products able to accurately capture rural settlements. To answer this question, we tested three existing urban-oriented mapping products (GUF, ESM and OSM) in the rural, mountainous conditions of the Carpathian ecoregion, located in Central Europe. We decided to focus on mountainous rural areas of the Carpathians as they are an important biodiversity hotspot in Europe, key for ecosystem services and nature conservation initiatives continentally (Hughes 2017). The settlement development in the ecoregion, even the scattered type, can have profound implications on biodiversity in general, through, for example, enlargement of potential conflict areas of the wildlife-urban interface, increasing number of movement barriers for species and bottleneck areas within wildlife corridors (Kaim et al. 2019). More broadly, by focusing on the mountainous rural areas, as opposed to rural regions located in lowlands, we can
verify the mapping products in more difficult conditions, which may result in relatively low accuracy. In addition, the study area covers five countries with development taking place in remote areas, in various types of patterns. That is why, we assume, that our accuracy assessment results can be considered as the ‘most difficult’ scenario.

2. Methods

2.1. Study area

The Carpathians are Europe’s largest mountain range, stretching in an arc across Austria, Slovakia, Czechia, Hungary, Poland, Ukraine, Romania and Serbia (Figure 1). The area hosts a large biodiversity but also experiences intense local land use change dynamics with important implications for nature conservation and the depletion of many ecosystem services (lojá et al. 2010, Kozak et al. 2013). The rural settlement

![Figure 1. Study area map and location of verification points of the settlement. Please note that only rural areas were taken into account (see: section 2.1 Study area for further explanation). Country name acronyms for the countries assessed in this study: Czechia (CZ), Hungary (HU), Poland (PL), Romania (RO) and Slovakia (SK).]
structure within the study area is highly heterogeneous, which is the consequence of the variety of cultural and political history across the countries and regions. Rural settlements can range from dispersed structures, as in the Apuseni region in Romania or in many regions in the Polish Carpathians, to compact villages in Czechia or Slovakia. To account for this variety of rural settlement structures, we tested the mapping products in the Carpathian conditions of five countries: Czechia (CZ), Hungary (HU), Poland (PL), Romania (RO) and Slovakia (SK) (Figure 1).

As our study focuses on rural areas, we excluded from the analysis administrative areas that belong to cities of over 50,000 inhabitants as delimited by the European Urban Atlas 2012 (Montero et al. 2014). These were centers of the so-called Functional Urban Areas, that is, cities with commuting zones (see Supplementary Material 1 for the complete list and a map).

### 2.2. Settlement products

To capture rural structures, we used three freely available, high-resolution datasets with substantially different definitions of settlements: the GUF, ESM and OSM. Although the GUF and OSM have global coverage, the ESM dataset is restricted to countries which are members of the European Union. Therefore, to assure the consistency of our assessment, we excluded the Ukrainian and Serbian part of the Carpathian ecoregion from the analysis (Figure 1).

The analyzed datasets differ in terms of their origin and the format in which they are distributed. The GUF is a raster, binary dataset produced by the Earth Observation Center in the German Aerospace Center DLR, which primarily uses 2011 TerraSAR-X and TanDEM-X radar imagery (Esch et al. 2017). The GUF is available with approximately 12-m pixel resolution. As a radar-based product, it is more able to capture vertical structures but is not influenced by atmospheric effects (clouds or aerosols). The quality of the GUF has been proven for urban areas globally (Esch et al. 2017), while the tests conducted in Germany and Italy showed its lower accuracy for capturing rural settlements (Klotz et al. 2016).

The 2016 edition of the ESM is available in a raster format in two different resolutions, 10 m and 100 m (which is an aggregated 10 m product). In this study, we used the 10 m version. The ESM was generated using classification of SPOT 5 and SPOT 6 satellite images (mainly from 2011) and partly improved further by benchmarking with population data and building footprints of the OSM and Italian official settlement data. Accuracy tests resulted in a value higher than 95% for the built-up classes of LUCAS 2012 (Florczyk et al. 2016). In contrast to the GUF and OSM products, which contain binary information on settlements, the ESM shows the percentage of built-up area coverage per pixel. Although the ESM 2017 edition is already available with 2.5 m resolution, we decided to use the 10 m resolution product due to the higher level of comparability to other tested products.

The OSM dataset is a global vector layer of building footprints based on crowdsourced data, which implies differences in availability among countries and regions. European areas are mapped, however, by the vast majority of the global initiative users (Neis and Zipf 2012). Typically, in crowdsourced data, the urban areas are
characterised by higher accuracy than rural areas (Hecht et al. 2013). For the analysis conducted in this study, we used the OSM version available on January 2017.

All of the settlement products were transformed into a binary raster format (with settlement areas coded with 1 and no-settlement areas coded with 0) with a 12 m spatial resolution. Before transformation, each of the three products went through a pre-processing step which involved data aggregation and rasterization (Figure 2). The GUF mask was finally used in original form of 12 m resolution binary raster, while the ESM was resampled from 10 m to 12 m resolution and changed into binary format using minimum share of 5% built-up area (following the approach by van Vliet et al. 2017). The OSM data presenting individual buildings as polygons was first generalised using aggregation with a 50 m threshold to obtain ‘built-up area’ patches, and then converted to raster (following a sensitivity analysis). Detailed information on pre-processing of each product, as well as the sensitivity analysis which guided the selection of the aggregation threshold for OSM are presented in the Supplementary Material 2.

Additionally, we compared the settlement structure, as shown on the products and tested the impact of each of the settlements’ mask on the results of the spatial analysis, i.e., least-cost path, where the settlements were treated as a barrier. The description of the comparison and the results are presented in Supplementary Material 3.

2.3. Accuracy assessment

The accuracy assessment was conducted with two independent approaches regarding the selection of verification points. In the first approach, a set of verification points was defined through the stratified random selection of 500 points per country (2500 points in total) within the area of any of the three analysed settlement datasets combined, hereafter called the ‘total settlement mask’. In the second approach, a set of
verification points was defined through the stratified random selection of 500 independent points per country (2500 points in total) within the ‘total settlement mask’ (i.e., the sum of all the masks tested) buffered by 100 m, hereafter called the ‘buffer mask’. Testing the influence of the 100 m buffer around the settlement aimed to cope with the so-called ‘true negatives’ in the accuracy assessment, which might artificially improve the overall accuracy results. We decided to use a 100 m buffer, as it is a relatively high value in rural areas (Figure 3). Using 100 m buffer in rural, very often scattered, mountain settlement resulted in having substantially more area treated as buffer than the area of any type of settlements (‘total settlement mask’). Overall, the area of the total settlement mask was 7608 km², while the area of the buffer mask area was 36232 km².

In both abovementioned approaches, at each verification point the agreement in settlement presence and absence between each of the three analyzed datasets and the reference high-resolution satellite imagery taken from online Bing maps (Bing Imagery referenced to a similar year as the settlement products) was assessed visually (Figure 3). To ensure consistency among the tested data sources, we decided to base the agreement on land use. Since the tested materials were showing settlements, not separate buildings, the spaces between the buildings, like gardens, parking spaces, terraces, driveways, gazebos were all understood as settlement. Other land uses located around, like agriculture, forests, water etc., were not considered settlement.

The results of the accuracy assessment were represented by a confusion matrix comparing the commission and omission errors of each of the analyzed products to the reference data. All accuracy measures were calculated for the entire study area as well as for each country independently.
3. Results

3.1. Accuracy assessment among settlement masks

The overall accuracy calculated for the entire study area using the total settlement mask approach indicated that the GUF is the most suitable settlement product (65.4% ± 3.3 (SE; all the values for the entire study area are presented in the Supplementary material 4), followed by the OSM (61.2% ± 1.7) and the ESM (49.5% ± 3.5). The GUF was also found to be the best settlement product in most of the country-specific overall accuracy assessments, except Poland (where the OSM was indicated as the best product) and Czechia (where the ESM was the best; Figure 4). On the other hand, the producer’s accuracy indicated that the ESM is the most effective both for the entire study area (73.8% ± 4.4) and for each of the countries, where it is lowest for Poland (58.6%) and highest for Czechia (81.3%; Figure 4). The highest user’s accuracy for the entire study area (90.3% ± 3.7) and for four out of five tested countries was found for the OSM. For Romania, the user’s accuracy was the highest for the GUF (79.4%). The user’s accuracy for the ESM was found to be the lowest out of the three analyzed products (Figure 4).

Although the overall accuracy values calculated using the buffer mask approach (Figure 5) were substantially higher than those measured using the total settlement mask approach, they showed similar tendencies, also indicating that the GUF is the most suitable settlement product for both the entire study area (92.5% ± 1.1) and specific countries (88.9–95.2%; Figure 5). The differences among settlement products were, however, much lower (only up to 8.1%) than those shown by the total settlement mask approach (Figures 4 and 5). According to the producer’s accuracy, the ESM was found to be the most accurate for the entire study area (48.6% ± 6.1) but, regionally, only for Slovakia (59.1%) and Romania (60.4%). For Czechia and Hungary, the GUF was indicated as the best product (with accuracies of 57.8% and 50.7%, respectively). In Poland, the ESM and the GUF performed similarly but were much worse than in other countries (with a producer’s accuracy of 27%). In all regional assessments, as well as for the whole ecoregion, the producer’s accuracies for the OSM were the
lowest (Figure 5). Similar to the total settlement mask approach, the user’s accuracy for the entire study area (86.6% ± 4.7) and for most of the analyzed countries was found to be highest with the OSM and lowest with the ESM (Figure 5).

4. Discussion

In this paper, we set out to assess and compare the accuracy of freely available products, the GUF, ESM, and OSM, in mapping settlements in rural areas using the example of the Carpathian ecoregion. We focused on rural settlement as it is often much harder to map with settlement products and, at the same time, the monitoring of its development at regional scale (especially if across countries) is important for many ecosystem services.

The accuracy assessments showed substantial, country-specific differences among the analyzed settlement products. Overall, the GUF was found to be the most effective, although conservative in detecting rural settlements over the entire study area, as well as for most of the countries. The overall accuracy results measured using the buffer mask approach were even higher (92.5%) than the similar GUF accuracy measures for 12 urban areas worldwide (mean of 85.04%) (Esch et al. 2017).

In contrast, the producer’s accuracy generally indicated that the ESM was the best-performing product, while the user’s accuracy showed the strength of the OSM product. This finding indicates overestimation of settlement in the ESM in comparison to other tested products. However, similar results were found by Florczyk et al. (2016) in urban conditions. On the other hand, high user accuracy values for the OSM show high positional accuracy related to the relatively low coverage of the OSM building footprints in general. Although the completeness of the OSM is rather low and varies considerably among the regions, it will increase over time with contributors’ availability and effort (Hecht et al. 2013). The regional differences in OSM coverage are found not only in rural, but also in metropolitan areas (Jokar Arsanjani and Vaz 2015).
Although accuracy assessments conducted using two different approaches showed similar tendencies, they differed substantially in terms of the magnitude of reported values. The overall accuracies were in general rather low but all up to 20–30% higher according to the buffer mask approach. This difference between approaches was a result of the zero proportion of the true negative values, where the overall accuracy is artificially increased by the high agreement between assessed and reference data in areas outside the class under study. This problem with ‘true negatives’ is especially problematic in terms of the accuracy assessment of land cover/use classes which cover a relatively small fraction of the landscape, such as settlements (especially in rural conditions). Therefore, our results support the necessity of including class proportion-based measures in the accuracy assessments (Olofsson et al. 2014).

Results of accuracy assessment can be partly explained by the acquisition procedure of GUF and ESM products. The GUF product derived from radar interferometry is rather consistent due to its ability to correctly depict vertical structures that are not easily misinterpreted as other objects. On the other hand, the ESM is based on the classification of satellite images and therefore tends to overestimate settlements, as other objects (i.e., rocks or rocky riverbeds) with similar optical reflectance may be misclassified as settlements. We used a 5% share of built-up area threshold for transforming ESM to binary settlement/non-settlement map, following the work by van Vliet et al. (2017). This approach could also have impacted the overestimation tendency of ESM. For the OSM product a substantial regional differences in completeness play an important role. Nevertheless, the general accuracy of the OSM substantially exceeded the ESM in some countries, confirming its potential usefulnes (Haklay 2010, Jokar Arsanjani and Vaz 2015, Ibisch et al. 2016) if the spatial consistency of the data quality is properly addressed.

Our results clearly show that the choice of the most suitable settlement product should not be made *a priori* but needs to be preceded by some (at least simple) assessment of local environmental and socio-economic conditions that influence settlement structure (see: Supplementary Material 3). For example, the substantially lower accuracy of the satellite settlement products in Poland is very likely to be connected to the high rate of settlement dispersion in Polish rural areas. The scattered settlement patterns are specific for Poland, including mountainous regions (Kowalewski et al. 2013, Kaim 2017), in contrast to neighboring Carpathian countries, such as Slovakia. The settlement structure reflects not only the local environmental conditions but also the national spatial planning policy, governance or political legacies (van Vliet et al. 2019). For example, in the Polish part of the Carpathians, post-war collectivization of agricultural lands was conducted to a limited degree, leaving most of the land in private hands, while in Slovakia collectivization was widespread (Lieskovský et al. 2014). This phenomenon affected the Slovak settlement by strongly pursuing new settlement development towards the village center (Pazúr and Bolliger 2017), while in Poland it was much easier to build a house, even farther away from the village centre, on private land.

5. Conclusions

This study compared the quality of the existing, urban-oriented settlement products (the GUF, ESM and OSM) in rural landscapes on the example of the Carpathian
The mapping of settlements in rural areas is often challenging as they cover only a small fraction of a landscape and are rather scattered. On the other hand, products such as the GUF, ESM or OSM are often the only products available for large-scale and/or regional-scale analysis, and it is therefore important to assess their accuracy not only in urban but also in rural areas. Our study is unique as it is the first such broad-scale, cross-country assessment of urban-oriented settlement products focused on rural areas. Taking into account that the tested settlement products are available for all EU countries, our results can be informative to scholars studying rural settlements in many regions, as they were obtained in a heterogenous and diverse rural landscape.

The results showed that the GUF is the most consistent and most accurate settlement product for large-scale assessments. Although far from being perfect, it gives a conservative, but trustworthy image of rural settlements. The ESM product generally overestimate rural settlements, while the OSM proved to be the most spatially inconsistent. However, the relatively low values of accuracy indices suggest that rural settlements mapping is still a challenge, and there is a space for improvement. Potentially, newly developed products made available recently, like World Settlement Footprint (WSF; Marconcini et al. 2020) may help in solving this problem. Regional differences in product accuracy need to be considered as well, as one product may be more appropriate in a given region/country than in another as a result of environmental and socio-economic conditions influencing the local settlement structure.

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Data and code availability statement

The data and code that support the findings of this study are available at https://doi.org/10.6084/m9.figshare.19478984

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