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Wall-to-Wall Parcel-Level Mapping of Agricultural Land Abandonment in the Polish Carpathians

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Abstract: Accurate estimations of the extent of agricultural land abandonment (ALA) are critical to the sustainable management of agricultural resources and forestry, the understanding of ALA determinants, and the development of future agricultural policies. Although ALA is widespread in Europe, mapping it over large areas using remote sensing data is difficult as a result of the complexity of this phenomenon. This study aims to develop methods for a detailed wall-to-wall regional-scale mapping of ALA using vegetation height and secondary forest succession indicators. The rates and distribution of ALA were analyzed at the parcel and communal level in the Polish Carpathians using a high-resolution vegetation height model (VHM) derived from Light Detection and Ranging (LiDAR) point clouds and topographic data. Depending on the parcel-level secondary forest succession threshold (10, 20, and 50%), the regional ALA rates were 18.8, 9.0, and 2.1%, respectively. Regardless of the threshold, abandoned grasslands covered about three times more area than abandoned croplands. The highest ALA rates were observed in communes located in the western part of the study area, as well as east and south of Rzeszów. We found that areas receiving European Union Common Agricultural Policy payments very rarely showed signs of secondary forest succession and land abandonment. The developed method proved to be effective for detailed ALA mapping at various spatial scales.

Keywords: Agricultural land abandonment; secondary forest succession; vegetation height; land use; parcels; LiDAR; Carpathians

1. Introduction

Agricultural land abandonment (ALA) represents one of the major land use and land cover changes across Europe, and marginal mountainous areas are particularly affected [1–3]. Estimation of ALA is critical to the sustainable management of agricultural resources and forestry, the understanding of its determinants, and the development of future agricultural policies [4,5], as well as for the ecosystems-related problems, such as soil erosion, biological changes, and landscape modifications [6].

ALA is defined as the complete withdrawal of agricultural management followed by natural succession processes [7] that continue for a minimum of 2–5 years [8]. The development of successional vegetation in temperate climates is relatively slow. First, annual and biennial plant species and grasses encroach on the abandoned land. Between 3 and 4 years later, perennial herbs and shrubs follow [9]. Five years after abandonment, nearly 30% of trees germinate [10]. The distribution of secondary forest succession is strongly influenced by seed dispersal, so the reforestation rates are higher in areas that are nearer to old trees and shrubs. Soon after the withdrawal of agricultural activity, the height and density of successional vegetation are rather uniform. Over time, however, the differences become visible, as various species grow at different rates [10]. Thus, an abandoned parcel may show an irregular vegetation pattern or only part of it may be overgrown, so secondary succession cannot be immediately interpreted as ALA.

In the Polish Carpathians, a gradual decline in agriculture has occurred since at least World War II [11,12], and it was accelerated by two breakthrough events. First, the collapse of socialism and the introduction of the open-market economy, which replaced the centrally planned economy in 1989 [12,13], and second, the accession of Poland to the European Union (EU) and the implementation of the Common Agricultural Policy (CAP) in 2004 [14]. The recent Polish agricultural census [15,16] reported a notable decrease in agricultural land area between 2002 and 2010 in the Carpathian provinces of Małopolska and Podkarpacie (by 16.5% and 14.9%, respectively). Also, previous research has revealed widespread forest succession on abandoned agricultural land in the region. Kolecka et al. [17] reported that the average forest succession that developed in recent decades in the Polish Carpathians was 14%, but locally the rates exceeded 30%. Ostafin [18] noted that between 14.9% and 46.6% of abandoned agricultural land was found to have signs of secondary forest succession in nine communes in the Beskid Średni Mountains.

The implementation of the CAP aimed to limit agricultural land abandonment and restore farming activities by creating opportunities to improve the profitability of agriculture. For example, prices of some agricultural products (cereals, potato, starch, sugar, dried fodder, tobacco, fruits, vegetables, meat, and milk) have risen, guaranteeing minimum sale prices to farmers [14]. The policy supports farmers' income by a system of direct payments from the European Union budget [14]. The subsidies can be paid only to farmers who, among other things, keep their land in good agricultural and environmental conditions, and hence do not stop managing the land [14]. Also, sustainable and competitive agriculture in less favored areas (for example, mountain areas characterized by a short growing season because of a high altitude, or by steep slopes [6]) has been subsidized by the European Union for many years. Nevertheless, some authors have claimed that the CAP has had little effect on traditional small-scale farming and has prioritized large-scale intensive farming [13], which occurs mainly outside mountainous regions. The mountainous regions have, thus, continuously been hotspots of agricultural land abandonment [17,19]. In southeastern Poland, the number of CAP applicants decreased by 13% between 2005 and 2012 [20].

The nature of ALA is complex. On one hand, it is a widespread phenomenon, but on the other, it is rather dispersed, very subtle, and therefore difficult to measure and quantify over large areas using remote sensing data. Several authors have mapped land abandonment at scales that range from regional to continental by using satellite imagery, particularly from Landsat [4,21,22] or the Moderate Resolution Imaging Spectroradiometer (MODIS) [19,23]. Kuemmerle et al. [21] used Landsat Thematic Mapper (TM) and Landsat Enhanced Thematic Mapper Plus (ETM+) images from 1988 and 2000 to map farmland use change at the border of Poland, Slovakia, and Ukraine. Yin et al. [4] and Dara et al. [22] aggregated Landsat TM/ETM+ and Operational Land Imager (OLI) dense time series to annual normalized difference vegetation index (NDVI) composites for all years between 1984 and 2016 and between 1985 and 2015, respectively, in order to detect both long-term gradual and short-term drastic changes in agricultural land use. Estel et al. [19] and Alcantara et al. [23] analyzed phenological metrics using 16-day MODIS NDVI composites in order to map abandoned agriculture over eastern Europe and Europe, respectively. All the authors achieved high overall classification accuracies that ranged from 87% to 97%, except for Alcantara et al. [23], who achieved an accuracy of 65%. Nevertheless, a significant drawback to approaching land abandonment mapping with satellite data is the low ability to map small patches of succession because the imagery has a coarse spatial resolution (30 and 250 m).

Some authors have incorporated airborne laser scanning data (ALS) based on light detection and ranging (LiDAR) technology to map forest succession in more detail at local scales. In [24–26], LiDAR data were demonstrated as able to characterize successional vegetation and distinguish its multiple stages across spatial extents of ca. 8000–30,000 ha. In Szostak et al. [27], an even smaller area of 70 ha was analyzed, and results showed that LiDAR data and orthophotomaps could provide very precise information on secondary forest succession. To the best of our knowledge, the only attempt to use LiDAR data in a regional-scale study is in [17], in which stratified sampling of LiDAR point clouds (one sample tile of 2 × 2 km per commune) was applied to estimate secondary forest succession and land abandonment over the entire Polish Carpathians. All the authors indicated the high importance of the LiDAR-derived height of vegetation in forest succession mapping.

As LiDAR data processing is computationally demanding, it is difficult to fully use all LiDAR capabilities of detecting vegetation patterns for large areas. However, LiDAR-derived products, such as digital terrain models (DTMs) and digital surface models (DSMs), reduce data volume yet retain at least some properties of the original LiDAR point clouds. In this study, we attempted to develop methods for conducting detailed wall-to-wall mapping of ALA across a large area (the Polish Carpathians) using secondary forest succession indicators derived from a high-resolution LiDAR vegetation height model (VHM). Wall-to-wall ALA mapping was then investigated in the context of land eligibility for direct payments within the EU CAP.

2. Materials and Methods

2.1. Study Area

We studied 194 communes falling entirely within the boundaries of the Polish Carpathians (18,275 km^2) (Figure 1). The Polish Carpathians cover the northernmost part of the Carpathian arc, ranging from approximately 300 m above sea level (a.s.l.) (foothill zones) to 2500 m a.s.l. in the Polish part of the Tatra Mountains (Balon et al., 1995). The typical landscape consists of a mosaic of agricultural lands and forests, with most settlements located in the valleys. Several large urban centers are located in or near the mountains (e.g., Kraków, Rzeszów, Bielsko-Biała). In 2013, forests covered 47% of the Polish Carpathians [28], following a long period of a gradual forest cover expansion that started in this part of Europe around the mid-19th century [11,12].

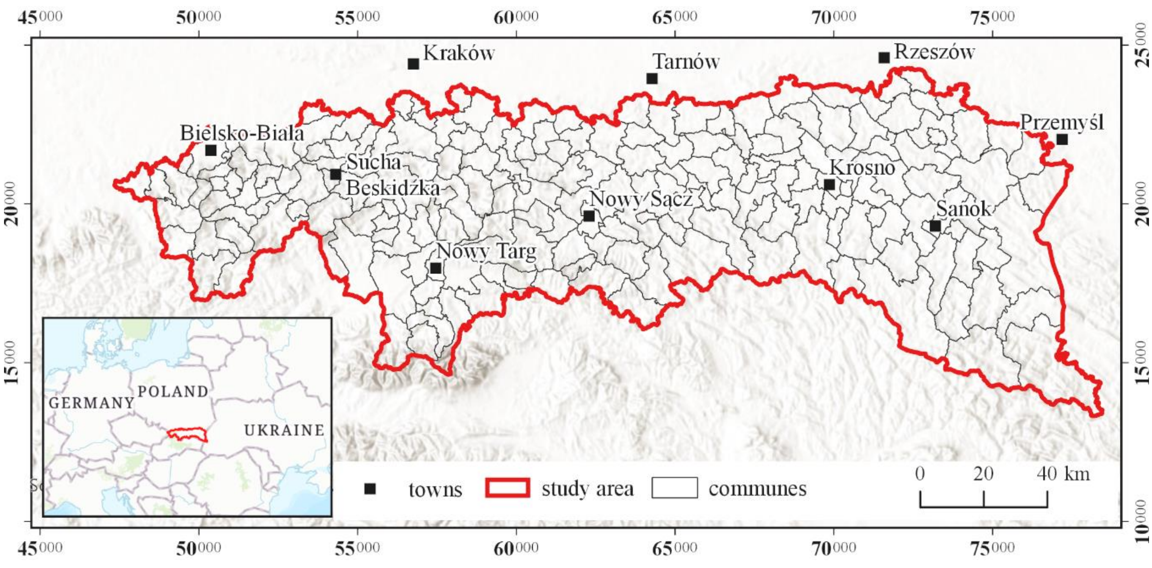


Figure 1. Study area with the Carpathian communal boundaries and the main cities across the region.

2.2. Data

The main data sources were the digital terrain model (DTM) and digital surface model (DSM), with a ground sampling distance (GSD) of 1.0 m and a vertical root-mean-square error lower than 0.2 m. The data were produced from ALS point clouds acquired in the Information System of National Protection Against Extraordinary Risks (ISOK) project [29] between 2011 and 2014. The elevation models were received from Główny Urząd Geodezji i Kartografii (GUGiK; the Head Office of Geodesy and Cartography in Poland) in a series of files (text format) corresponding to the standard topographic map sheet with a scale of 1:5000.

The auxiliary spatial data in this study were The National Database of Topographic Objects at a 1:10,000 scale (Baza Danych Obiektów Topograficznych, BDOT10k) and data collected in the land parcel identification system (LPIS). BDOT10k data were received from the central archive for cartographic data in Poland (Centralny Ośrodek Dokumentacji Geodezyjnej i Kartograficznej (CODGiK)). It represents accurate and up-to-date topographic information in Poland in vector format [30] and was completed in 2013 with a level of detail corresponding to topographic maps with a 1:10,000 scale. BDOT10k includes a continuous-coverage land cover layer consisting of twelve land cover categories: water bodies, residential land, forest and woodland, shrubland, permanent crops, grassland and cropland, transport units, wasteland, open spaces, mine sites, waste dumps, and other industrial areas. Additionally, a land use layer stores the boundaries of sports and recreational facilities, such as parks, botanical gardens, zoos, sports centers, and summer houses.

The data collected in the LPIS, provided by the Agency for Restructuring and Modernization of Agriculture (ARMA), contained reference parcels and the reference-eligible area (REA), valid as of 2015. A reference parcel is a geographically delimited area with a unique identification code under which it is registered in the member state's identification system [31]. In Poland, a reference parcel is a cadastral parcel that is manually updated according to land cover patterns visible on current orthophotomaps [32]. A parcel may contain various land uses, e.g., agriculture, forest, and residential. REA constitutes the land considered eligible for annual payments of European Union CAP subsidies to farmers, and it is delineated by visual interpretation and vectorization of high-resolution orthophotomaps that include cultivated field plots larger than 0.10 ha.

2.3. Methods

In this study, we considered two spatial scales of ALA. First, the rates and distribution of ALA were investigated at the parcel level in relation to land use and eligibility for payments. Second, the general rates and distribution of ALA were studied in relation to administrative units (communes).

2.3.1. Parcel Stratification

All parcels within the study area were grouped according to land use and eligibility for CAP payments. According to land use, as defined by the BDOT10k topographic data, we distinguished three basic types of parcels: fully agricultural (95% or more cropland or grasslands), partly agricultural (between 5% and 95% cropland or grasslands), and non-agricultural (5% or less cropland or grasslands). Non-agricultural parcels were excluded from the analysis. Using the same thresholds of 5% and 95% REA, fully or partly agricultural parcels were classified as fully (>95%), partly (5–95%), and not eligible (<5%) for CAP payments. As a result, parcels for analysis were stratified into six categories.

2.3.2. Agricultural Land Abandonment Mapping

The prerequisite to investigate ALA was the mapping of secondary forest succession on agricultural land.

To map secondary forest succession, the following steps were taken (Figure 2):

1. The normalized DSM (nDSM) was calculated as the difference between the DSM and the DTM.
2. Buildings (including residential and office buildings and backyard gardens) were eliminated from the nDSM by assigning them a "0" value, resulting in a vegetation height model (VHM).
3. A vegetation height threshold of 0.5 m was introduced to eliminate crops, herbaceous vegetation, grass, and very small trees and shrubs, and to create a raw vegetation mask [33].
4. Morphological filtering [34] was applied in order to remove noise from the raw vegetation mask (single pixels, gaps, and artifacts) without loss of important details; the resulting layer is referred to as the vegetation mask.

5. Secondary forest succession on agricultural land was mapped by overlaying the vegetation mask on agricultural land (according to BDOT10k topographic data) and applying an additional 5 m buffer around forests to exclude forest tree crowns and branches overhanging agricultural fields. Forest and woodland boundaries from BDOT10k were previously updated using available spatial data from other national agencies, such as the forest numerical map (eLMapa), the Forest Data Bank, the Polish Topographic Map for the 1970s (1:25,000; available at http://mapy.geoportal.gov.pl/), and aerial and satellite imagery from 2009–2015 (available at http://mapy.geoportal.gov.pl/) [28].

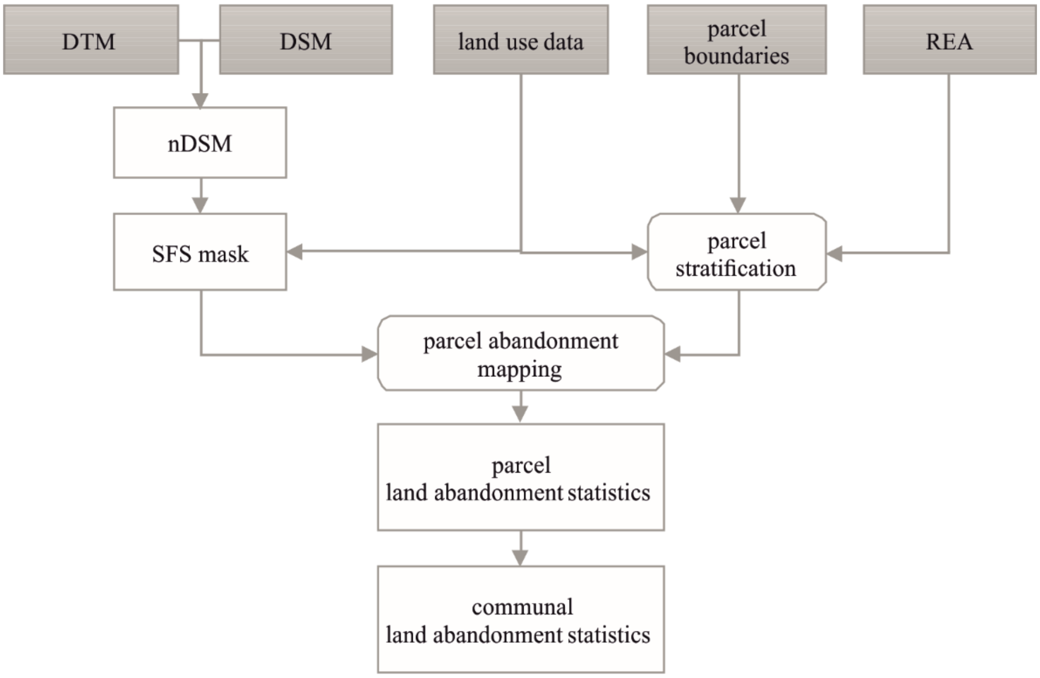


Figure 2. Workflow of agricultural land abandonment mapping. Note: SFS = secondary forest succession.

The secondary forest succession rates were determined at two spatial scales: per parcel and per commune. The secondary forest succession rate per parcel or per commune was calculated as the ratio of the identified area covered by successional vegetation to the total available agricultural land area in the areal unit, which is either a parcel or a commune (Figure 3).

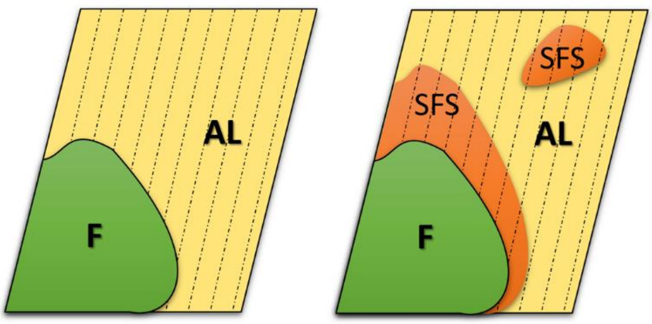


Figure 3. The concept of agricultural land abandonment mapping. On the left, the formal land use in a parcel is shown. It includes forest (F, green) and agricultural land (AL, dotted yellow). On the right, the real land cover is presented, which shows successional vegetation on cropland or grassland (SFS, orange). The secondary forest succession rate is calculated as SFS/AL. Using 10, 20, and 50% thresholds of secondary forest succession rate, a parcel may be classified as abandoned or not.

The relationship between the extent of secondary vegetation and land abandonment is not straightforward. Janus and Bozek [35] tested three thresholds in a case study located in the Polish Carpathians: 10%, 20%, and 50%. For further calculations, we used the same three secondary forest succession threshold values (10%, 20%, and 50%) to determine whether the parcel was abandoned. Then, we determined the area and percentage of the agricultural land within the abandoned parcels, the number of abandoned parcels, and the area of overgrown parcels that were part of the REA. The outputs were then summarized to estimate agricultural land abandonment at the communal and regional levels.

3. Results

3.1. Parcel-Level Statistics

All analyzed parcels (4,590,920) occupied 1,827,127 ha, with agricultural land constituting 38.0% of the entire area (695,000 ha), approximately half cropland and half grasslands, according to BDOT10k topographic data. Fully, partly, and non-agricultural parcels constituted 55.4% (385,170 ha), 44.2% (306,948 ha), and 0.4% (2882 ha) of the overall agricultural land, respectively. In total, 497,773 ha was eligible for payments in the region, including 92.2% of agricultural parcels. Parcels that were fully, partly, and not eligible for payments constituted 48.2% (239,879 ha), 51.5% (256,251 ha), and 0.3% (1643 ha) of the total REA, respectively (Table 1).

Table 1. Characteristics of parcels in relation to land use and eligibility for the Common Agricultural Policy (CAP) payments. Headings used in the table: AGR (agricultural) and REA (reference-eligible area) indicate the proportions in which parcels are covered by agricultural land and the areas eligible for CAP payments, respectively. Agr. = Agricultural.

		REA			
	AGR	**Fully**	**Partly**	**No**	**Sum**
Agr. land area (ha)	**Fully**	209,114.18	50,086.95	125,968.90	385,170.03
REA (ha)		208,400.58	41,555.33	45.37	250,001.27
Number of parcels		677,766	141,843	1,021,030	1,840,639
Agr. land area (ha)	**Partly**	14,770.53	179,692.68	112,485.09	306,948.30
REA (ha)		19,357.52	189,600.40	168.67	209,126.58
Number of parcels		50,018	318,857	906,103	1,274,978
Agr. land area (ha)	**No**	39.76	581.69	2260.63	2882.09
REA (ha)		12,121.07	25,094.95	1428.86	38,644.88
Number of parcels		22,520	50,246	1,402,537	1,475,303
Agr. land area (ha)	**Sum**	223,924.47	230,361.32	240,714.62	
REA (ha)		239,879.16	256,250.68	1642.89	
Number of parcels		75,0304	510,946	332,9670	

3.2. Intensity and Patterns of Agricultural Land Abandonment

In the Carpathian region, 9.0% of agricultural land was overgrown with successional vegetation, and ALA was widespread (Figure 4, Figure S1 in Supplementary Materials). Depending on the parcel-level secondary forest succession threshold (10, 20, or 50%), the proportion of abandoned agricultural parcels in the Polish Carpathians was estimated to be 18.8% (779,543 parcels, 130,915 ha), 9.0% (460,467 parcels, 62,275 ha), and 2.1% (151,096 parcels, 14,277 ha), respectively. Abandoned grasslands covered about three times more area than abandoned croplands.

Parcels not eligible for CAP payments were abandoned more frequently than parcels fully or partly eligible for payments (Figure 5), and they also contained the largest area of abandoned agricultural land. The ALA rates for those parcels were 33.1%, 18.5%, and 4.7% for the three secondary forest succession thresholds (10%, 20%, and 50%, respectively), approximately twice as high as the ALA rates for all of the agricultural parcels in the Polish Carpathians.

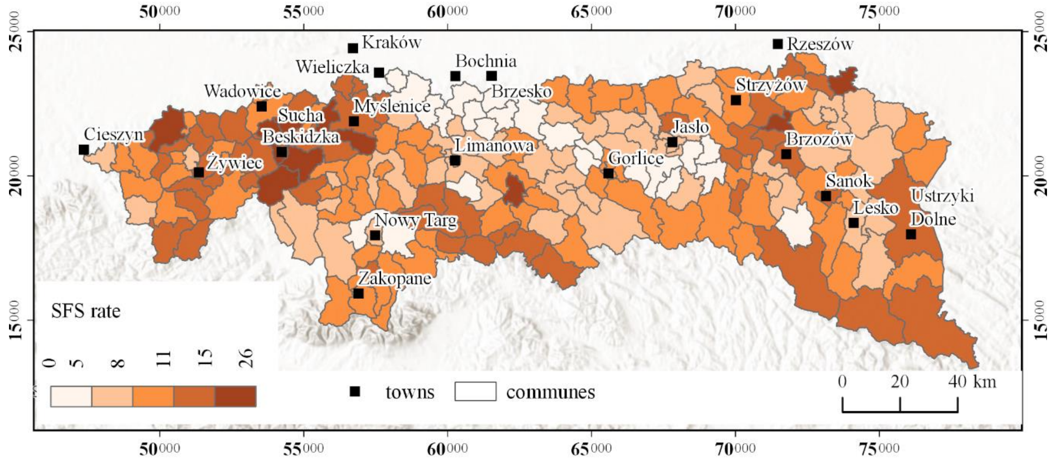
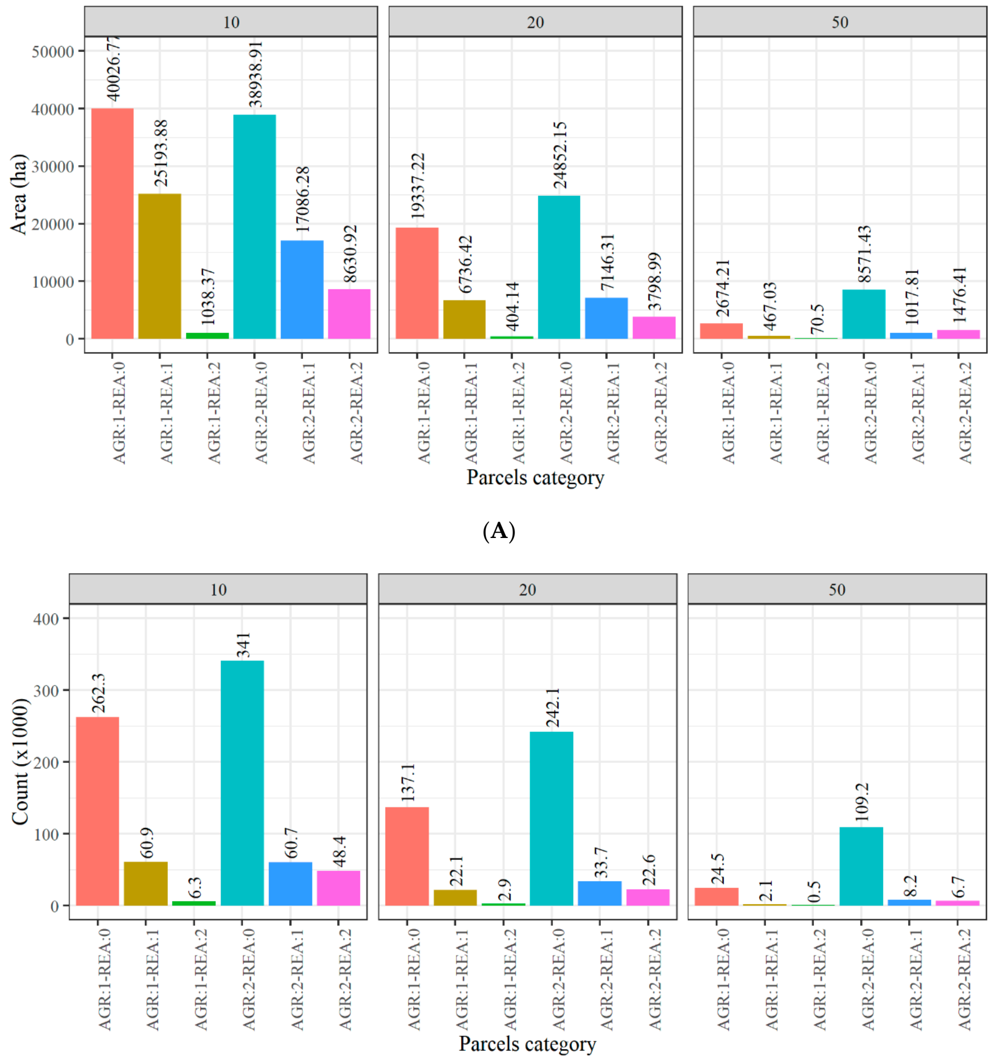


Figure 4. Rates of secondary forest succession (SFS) in communes in the Polish Carpathians.



(**A**)

(**B**)

Figure 5. Area (**A**) of agricultural land on abandoned parcels and the number of abandoned parcels (**B**) for three secondary forest succession thresholds (10, 20, and 50%). AGR:2 and AGR:1 refer to parcels that are fully and partly agricultural, and REA:2, REA:1, and REA:0 refer to parcels that are fully, partly, and not eligible for CAP payments.

Communes with the highest ALA rates were located in the western part of the study area, as well as in the area south of Rzeszów (Figure 6). The highest ALA rate for the 10% threshold was observed in the Sucha Beskidzka commune (53.3%), and the highest rate for the 20 and 50% thresholds was in the Nowy Sącz commune (37.8 and 11.5%, respectively). The lowest ALA rates were found in Nowy Wiśnicz (1.9, 0.5, and 0.0%). The Nowy Sacz commune showed high ALA rates because most of its area was categorized as built-up in BDOT10k, and the remaining parcel sample was small and might have been unrepresentative. Regardless of the threshold, the spatial patterns of ALA were consistent for the entire analyzed region.

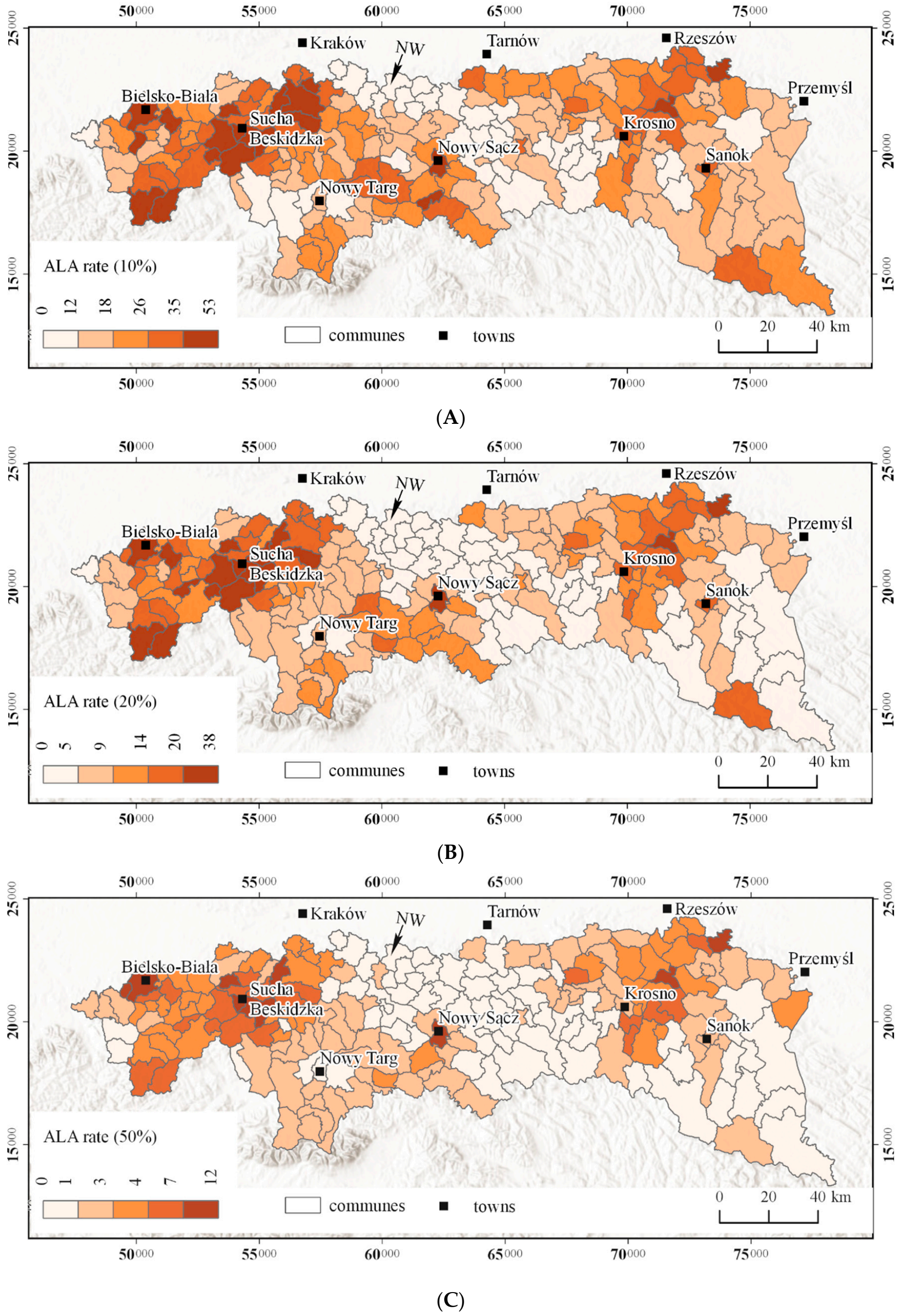


Figure 6. Rates of agricultural land abandonment in communes in the Polish Carpathian in the three secondary forest succession thresholds of 10 (**A**), 20 (**B**), and 50% (**C**), respectively. Note: SP = Siepraw; NW = Nowy Wiśnicz.

The average secondary forest succession rate within the agricultural parcels that are not eligible for payments was 11.8% (34,925 ha). Moreover, 2.9% (14,290 ha) of the REA (including the REA on non-agricultural parcels) is currently overgrown with successional vegetation. The highest rate of overgrown REA on agricultural parcels was found in Siepraw (8.4%), and the lowest was found in the Nowy Wiśnicz (0.4%) communes (Figure 7).

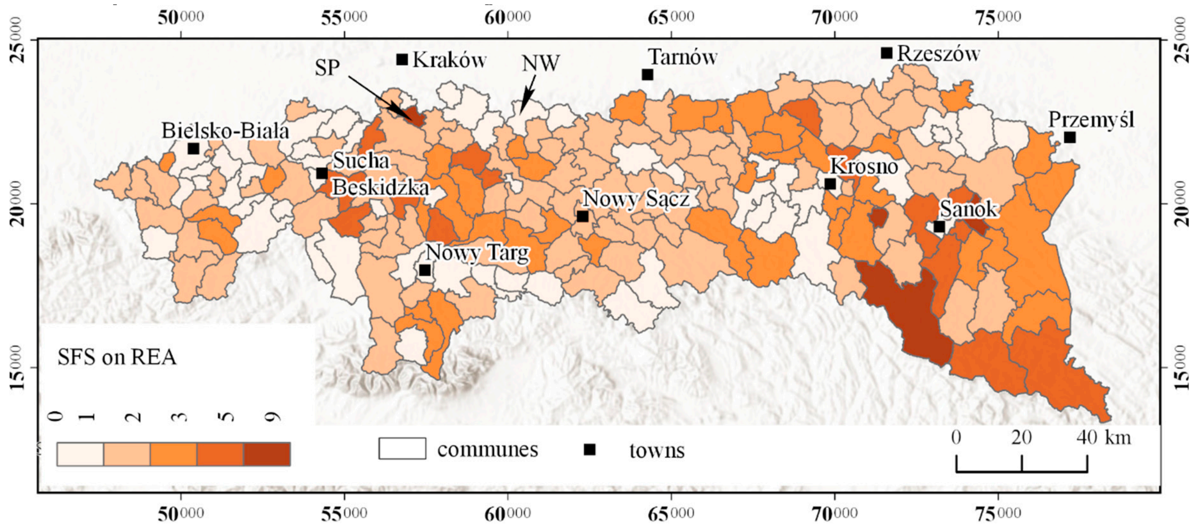


Figure 7. Rates of REA with secondary forest succession (SFS) in communes in the Polish Carpathians. Note: SP = Siepraw; NW = Nowy Wiśnicz.

4. Discussion

This study provides a unique dataset resulting from the wall-to-wall mapping of agricultural land abandonment in the Polish Carpathians using high-resolution DSM and DTM data derived from ALS. ALA is nowadays widespread across the region; however, the intensity of the phenomenon varies in different parts of the mountains. If an intermediate ALA threshold of 20% is applied, as much as 620 km^2 of agricultural land has been abandoned in recent decades. The value reaches 1300 km^2 if the more liberal secondary forest succession threshold (10%) is adopted. Because much of the land is currently overgrown with successional vegetation, the area may convert to forestland in the next several decades and increase the forest cover in the Polish Carpathians from 47% in 2013 [28] to 50–54% in approximately 2050. Forest cover exceeding 50% was projected for approximately 2030–2040 by Kolecka et al. [17] on the basis of forest succession rates detected from LiDAR data, and it was projected for about 2060 by Price et al. [36] on the basis of future land use and land cover change modeling. The selection of the secondary forest succession threshold (that is, the percentage of overgrown agricultural land per parcel) is of high importance in ALA rate estimation, since the threshold significantly changes the estimates of ALA—from 2.1% (50% threshold) or 9.0% (20% threshold) to 18.8% (10% threshold). The values, however, may also be interpreted in terms of categorized probability, for example, "possibly abandoned", "likely abandoned", and "abandoned", respectively.

The spatial distribution of ALA hotspots shows that agricultural land located in the vicinity of large cities was more likely to be abandoned. This is consistent with the findings of Kolecka et al. [17], who observed higher rates of secondary forest succession in the western (more developed) part of the Polish Carpathians and closer to the major city of the region, Kraków, and former provincial capital cities, particularly Bielsko-Biała, Nowy Sącz, and Krosno. This fact emphasizes the importance of socioeconomic factors for farmers' decisions related to the cessation of land cultivation; a particular stimulus is the availability of better-paying jobs outside agricultural sectors and rural–urban migration. This is a common tendency that is present not only in the Polish Carpathians [6,11,17,37] but also in Albania [38], Romania [39], the Ukraine [40], Slovakia [41], Switzerland [42], and France [43]. The higher agricultural land abandonment rate in suburban areas may also be explained by the high demand for land for residential development around major cities, which is frequently obtained from agriculture [11,44].

Our study shows that grasslands were three times more likely to be abandoned than cropland. Almost the same proportion of overgrown land (78% of grasslands and 22% of cropland) was reported by previous authors [17], who attributed it to the decreasing demand for pastures and hay due to the significant decrease in cattle and sheep populations over the last two decades [45]. In addition, compared with croplands, grasslands are located on land that is less productive, less convenient for management, and less accessible. Various future land use and land cover change scenarios [36] suggest that forest succession by 2060 will occur mostly in abandoned pastures.

Crucially, agricultural parcels not eligible for payments were abandoned much more frequently than parcels that were eligible. This fact may indicate either that the CAP payments were a motivation for farmers to continue land cultivation or that payment control effectively rules out areas previously excluded from agricultural management. In most communes, parcels that were eligible for payments and identified as abandoned constituted only a small fraction of all agricultural parcels. For the 20% and 50% secondary forest succession thresholds, the size of this fraction for practically all communes was less than 5%; for the 10% threshold, this fraction was less than 5% in 93 out of 194 communes. The detection of secondary forest succession on parcels eligible for payments was therefore rare, and in many cases, this might be attributed to the uncertainty of the assessment and errors in delineating the vegetation height mask, especially since visual investigation confirmed the general agreement between the REA and the land cover interpreted from orthophotomaps. In such a scale of analysis, however, errors can result even from single trees or tree rows located at the boundaries of agricultural parcels, single trees growing in fields or pastures, or tree branches extending beyond the field boundaries. On the other hand, a visual assessment of some areas showed fields densely overgrown with trees and shrubs that were classified as cultivated in the REA map (Figure 8), confirming the partial reliability of our finding that a small fraction of parcels eligible for payments had signs of ALA.

The importance of financially supporting small-scale, traditional agriculture in mountainous areas, highlighted for instance in Slovakia by Lieskovský et al. [13], seems to fit the main CAP principle of bringing new opportunities to minimize abandonment and promote sustainable and competitive agriculture in less favored areas, mostly by means of payments. For Polish farmers whose farm size does not exceed one or two hectares, the direct payments may account for 90% of their average agricultural income [14]. In the Polish Carpathians, however, though the average agricultural parcel size is 0.5 ha, around half of the parcels are smaller than the minimum threshold size for CAP payments eligibility (0.1 ha), in this way excluding their owners from the relevant CAP schemes. These CAP limitations were also raised by Wojewodzic [20] and Lieskovský et al. [13], who reported that in practice CAP payments have had little effect in mountainous or highly fragmented landscapes with the prevalence of small, individual farms in the Polish Carpathians [20] and Slovakia [13]. Moreover, Kundera [14] argued that the CAP was ineffective in changing overall Polish agriculture into a more productive sector of the economy. Thus, the effective reduction in ALA on the smallest parcels may require the adaptation of the CAP to encourage farmers to continue or restart land cultivation.

To date, no other study has attempted to perform wall-to-wall forest succession and agricultural land abandonment mapping over large areas in such detail and at a spatial resolution of 1 m. This study covers the entire Polish Carpathians and was based on a vegetation height model derived from digital elevation and surface models with a 1 m spatial resolution. Our previous studies [17,46,47], which were based on LiDAR point clouds and covered one sample tile of 2 × 2 km per commune, showed 13.9% forest succession over the region, which exceeds the 9.0% estimate derived from this study. The previous studies, however, were performed using object-based analysis, which might have included non-vegetated pieces of land in the secondary forest succession class and thus overestimated the actual rate of overgrown land. In some communes, the differences between the two methods exceeded ±20%. We found, however, that the differences were much lower (reaching ±12.0%, an average of 2.3 ± 4.9%) if wall-to-wall mapping results were constrained to the extent of the tiles studied in [16], suggesting that both the VHM-based and the point cloud-based methods allow for the consistent detection of secondary forest succession over the same area, and we noted that commune-level discrepancies reflected differences between sample-based and wall-to-wall mapping. In conclusion, for the investigation of such a widespread but subtle, dispersed, and difficult-to-discriminate phenomenon, the developed method proved to be effective for ALA mapping on communal and regional levels.

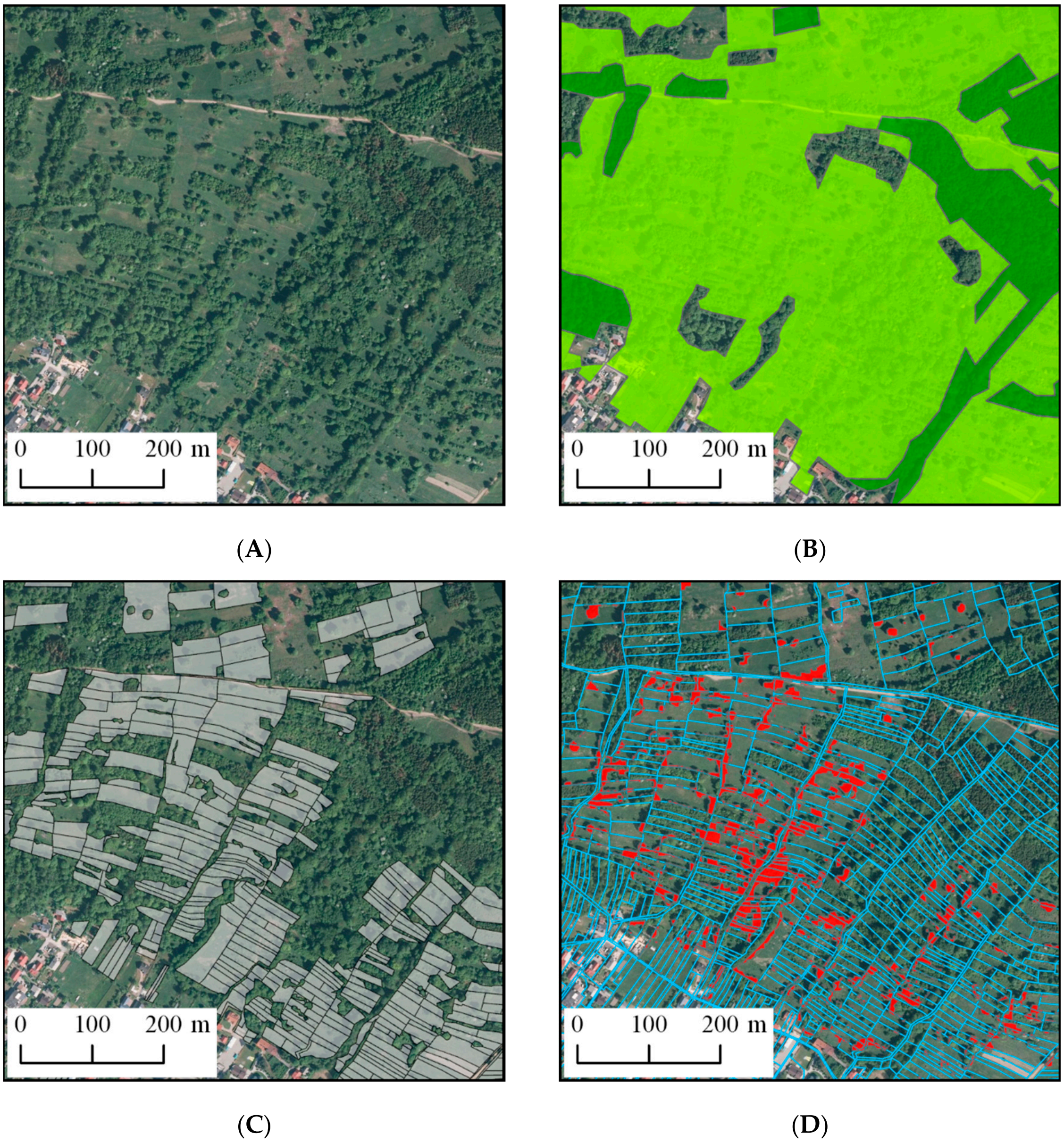


Figure 8. Relations of land cover, REA boundaries, and detected parcels with ALA in the Węgierska Górka commune: orthophotomap (**A**); grasslands (light green) and forest (dark green) from the Baza Danych Obiektów Topograficznych (BDOT10k) topographic data (**B**); REA from the land parcel identification system (LPIS) database (gray) (**C**); and patches delineated as abandoned (red) against the cadastral parcels (blue outlines) (**D**). The abandoned parcels are clearly visible (**D**) and confirm errors in topographic (**B**) and LPIS (**C**) data.

5. Conclusions

In this study, we successfully mapped agricultural land abandonment at the regional scale. We developed methods for the detailed wall-to-wall mapping of secondary forest succession with a high-resolution LiDAR-based vegetation height model and topographic data, which were used to derive the relationship between secondary forest succession and agricultural land parcels. The method is efficient, and its reliability was confirmed through visual assessment and comparison with the results of previous studies. The method is also transferable to agricultural land abandonment mapping in other areas at both regional and local scales. Though the study shows significant land abandonment in several parts of the region, our results also allow us to conclude that even in the highly fragmented mountainous regions the direct payments in the European Union CAP may motivate farmers to continue land cultivation, and to some extent are likely to prevent agricultural land abandonment.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-445X/8/9/129/s1. Figure S1: Distribution of agricultural parcels with various ranges of overgrown agricultural land in the Polish Carpathians.

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