The use of LiDAR in reconstructing the pre-World War II landscapes of abandoned mountain villages in southern Poland

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Abstract
The cessation of most human activities resulting from post-World War II expulsions and forced displacements in Central Europe triggered massive land cover transformation in mountainous areas. However, many pre-War traces of past landscapes have survived—imprinted in microtopography—in permanently abandoned villages. Currently, they constitute unique cultural heritage of communities no longer in existence. Our main goal was therefore to reconstruct a lost cultural landscape of mountain villages abandoned after World War II (WWII). The case study area comprised three such villages located in southern Poland, two in the Carpathians and one in the Sudetes. We used the national airborne light detection and ranging (LiDAR) dataset combined with archival cadastral maps and field survey to detect man-made microtopographic features related to past boundaries, road network, agriculture and buildings and to interpret them in the landscape context. We demonstrated that the pre-War human footprint left in relief was shaped largely by past landownership divisions, land use and environmental constraints (related to lithology, soils and topography). Our secondary goal was to assess the value and application opportunities of LiDAR in reconstructing past landscapes. We showed that 38–70% of non-natural parcel boundaries and 65–79% of roads marked on mid-19th-century cadastral maps are still detectable using LiDAR. Therefore, we argue that the past landscape pattern, originating in late Middle Ages and subsequently transformed prior to WWII, remains well preserved in the relief and that LiDAR is an effective tool to reconstruct a past landscape of mountain villages abandoned after WWII. We also confirmed that customized LiDAR visualizations are more informative than ready-to-use shaded digital elevation models (DEMs), in particular when integrated with cadastral and field-based data. We conclude that the greatest advantage of LiDAR is the capacity to provide a landscape context for isolated traces of past human activity, allowing for the reconstruction of entire spatial patterns and interrelationships developed by past societies.

KEYWORDS
airborne laser scanning, cadastral maps, deserted villages, landscape archaeology, the Carpathians, the Sudetes

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The reconstruction of past landscapes provides a basis for understanding and predicting human–environment interactions in wider spatial contexts (Bürgi et al., 2017; MacDonald et al., 2000; Plieninger et al., 2016). According to European Landscape Convention, landscapes require understanding, protection and sustainable management as they constitute ubiquitous and primary context of shared heritage (Council of Europe, 2000; Millican et al., 2017). Because present-day landscapes are a legacy of past land use activities, the recognition of historical landscape patterns is a matter of both scientific and policy interest (Bürgi et al., 2007; Marcucci, 2000; Stabbertorp et al., 2007).

However, as settlement history is studied and past landscapes in various ways reconstructed, the challenge is to uncover scattered traces of past land use and to tie them together. Successive episodes of human activity leave marks in the landscape that are superimposed on present-day landscapes as a legacy of past land use activities, the recognition of historical landscape patterns is a matter of both scientific and policy interest (Bürgi et al., 2007; Marcucci, 2000; Stabbertorp et al., 2007).

A fairly accurate and precise reconstruction of the historical landscape can be obtained by analysing multitemporal cartographic sources, especially when georeferenced, digitized and analysed using geographic information system (GIS) tools (Kienast, 1993). Maps based on mathematical foundations and geodetic measurements have been available since the turn of the 18th and 19th centuries. Archival cadastral maps and associated protocols are among the most valuable sources of spatial data. They have been commonly used for the detailed analyses of landscape transformations (Oláh & Boltziar, 2009; Petek & Urbanc, 2004), delimitation of parcels (Forejt et al., 2018), and reconstructions of past tillage patterns (Domaas, 2007) and terrace fields (Rendu et al., 2015).

In turn, large-scale landscape reconstructions are often based on country-wide topographic and military surveys (Eremiášová & Skokanová, 2009; Schneeberger et al., 2007; Stäuble et al., 2008). Since the early 1930s, aerial photographs have been systematically collected (Pinto et al., 2019), whereas civilian and commercial satellite images with increasingly higher resolution are available since the 1970s (Belward & Skøien, 2015). Both of these data sources have been extensively used to approach past cultural landscapes in mountainous regions (Jabs-Sobocińska et al., 2021; Malek et al., 2014; Millican et al., 2017).

Available spatial data have usually been combined with non-cartographic sources, for example, census data (Affek et al., 2021), livestock tax registers (Dahlström, 2008), forestry inventories (Saito et al., 2007), national records of sites and monuments (Millican et al., 2017), ground-based repeat photography (Dethier et al., 2018; Kaim, 2017) and also memories of the local people (Bürgi et al., 2007). An invaluable complement to the proper identification of remnants of historical landscapes is provided by detailed geomorphic (Kirchner et al., 2020; Latocha, 2015b) and botanical (Latocha et al., 2019; Majewska, 2019) field-based data and mapping (Wolski, 2007). By integrating different data, a more accurate picture of the entire spatial patterns can be obtained (Pelorosso et al., 2009; Petit & Lambin, 2002).

Over the last decade, the most spectacular LiDAR-based reconstructions have been associated with UNESCO World Heritage Sites (Masini & Lasaponara, 2013; Megarry et al., 2016). One of the pioneering studies was conducted at Stonehenge, where new archaeological sites, hitherto concealed beneath vegetation, were revealed (Bewley et al., 2005). Yet the most extensive research of this kind has concerned pre-Columbian human settlement (especially the Maya civilization). The application of LiDAR made it possible to trace the spatiotemporal evolution of the cityscape with complex and highly structured systems of water management (canals and causeways), agriculture (terraces) and defence in Belize (Chase et al., 2014, 2011), Guatemala (Canuto et al., 2018) and Honduras (Fisher et al., 2016), as well as outside Mesoamerica, for example, in Lower Amazon in Brazil (Stenborg et al., 2018). Similar research has also been carried out in Cambodia, where the capitals of Khmer Empire at Angkor—the largest settlement complex of the preindustrial world—were located (Chevance et al., 2019; Evans et al., 2013). Furthermore, in the Caribbean, it proved possible to reveal historic-era landscapes impacted by volcanic disaster, so far concealed in Neotropical forest (Opitz et al., 2015).

Traces of past human activity are reflected particularly well in the relief of areas with complex natural topography—in the uplands and mountains. Such areas are usually highly forested now and often difficult to penetrate from the ground; therefore, airborne LiDAR is seen
as the technique of choice to document the cultural remains in landscapes of this type. LiDAR has been used in the reconstruction of mediaeval fortified settlements in the Apeninines in Italy (Masini et al., 2018), German field fortifications from World War II (WWII) in the Polish Carpathians (Juchta et al., 2020), and historical reservoirs in the mountains of Moldova (Márgárint et al., 2021) and Czechia (Langhammer et al., 2018). On the other hand, the technique has also been used to map hollow ways and barrow cemeteries in selected sites in Slovenia (Kokalj & Hesse, 2017), as well as earthworks in the Harz Mountains in Germany (Swieder, 2021).

Apart from discovering the hidden ancient sites or structures, LiDAR technology has also offered unique possibilities to add spatial landscape context to historical reconstructions. However, despite the well-established position of LiDAR as a tool in archaeological studies, LiDAR-based reconstructions still rarely capture entire landscape patterns (Affek, 2016; Johnson & Ouimet, 2014; van der Schriek & Beex, 2017). Research has been usually focused on selected types of relic man-made features, for example, linear: hollow ways (Kirchner et al., 2020); agricultural terraces (Tarolli et al., 2014); ditch networks (Bailly et al., 2008); point: ancient shell mounds (Randall, 2014); protohistoric semi-subterranean caches (Krasinski et al., 2016); and pattern based: ridge-and-furrow topography (Sittler et al., 2007). Among the very few examples of LiDAR use in landscape-scale archaeological studies are the large-scale mapping programmes mounted in Germany (Hesse, 2013) and also in Scotland (Historic Environment Scotland—Banaszek et al., 2018) and England (Historic England Aerial Investigation and Mapping—Evans, 2019).

An area that was once populated, and permanently abandoned at some point, is perfect for the LiDAR-based reconstruction of former landscape patterns. The relic man-made features may indeed persist in a landscape provided that they are sufficiently resilient to processes of natural decay. However, it is not the fact of abandonment as such, but rather later land use, that shapes the survival pattern of earlier landscape features, with either good or poor conditions offered for the effort to reconstruct past landscapes. Mountain villages permanently abandoned after World War II in Central and Eastern Europe (see, e.g., Kucéra & Chromy, 2012; Latocha, 2012; Mares et al., 2013; Palang et al., 2006) provide a unique opportunity for contextual reconstruction of earthworks characteristic for the pre-War rural landscape. Moreover, as pre-War communities no longer exist in the areas concerned, traces of past activities imprinted in the topography down the centuries now constitute the only in situ heritage of former inhabitants, worth recognizing and protecting (Affek, 2016).

The main goal of our study was therefore to reconstruct the lost landscape of abandoned mountain villages in southern Poland using national airborne LiDAR dataset combined with archival and field-based data sources. Our specific objectives were, first, to characterize the landscape pattern of selected villages before abandonment and, second, to assess the value and application opportunities of LiDAR in reconstructing the past landscapes of such villages. Our case study samples a phenomenon observable throughout Central and Eastern Europe, that is, permanent abandonment of settlement in the aftermath of widespread post-WWII displacements of population. The case study approach applied allowed for an extraction of more generalized rules shaping past landscapes in now-deserted mountainous or upland areas, while helping augment existing knowledge on particular types of landscape features, to the benefit of both our understanding of mountain regions in Central and Eastern Europe, and future comparative studies and syntheses.

2 | STUDY AREA

Expulsions and forced displacements during and after World War II took place across most of Central and Eastern Europe. They were a consequence of border shifts and a policy of ethnically homogeneous nation states (Prausser & Rees, 2004; Ther & Siljak, 2001). As a result, vast areas of mountain borderslands least suitable for agriculture became permanently depopulated and abandoned (Blick & Štepánek, 1994; Kucéra & Chromy, 2012; Soja, 2012). Three rural mountain regions located within the present borders of Poland belong to those depopulated to the greatest extent: the Śnieżnik Massif (in the Sudetes), the Przemysł Foothills and the Bieszczady Mountains (both in the Carpathians) (Affek et al., 2020; Latocha, 2012; Wolski, 2007). The land of deserted villages usually underwent nationalization and afforestation, though natural secondary succession also ensued. This ensures a situation in which extensive areas are now covered by postagricultural forests with many man-made topographic forms hidden beneath the tree canopy (Affek, 2016; Latocha, 2015b). Concomitantly, the area of open landscape has shrunk considerably, remaining mostly in places where large-scale grazing was brought in during the post-War period (Wolski, 2007).

For the purposes of our study, each of the regions referred to above is represented by the single fully deserted village considered to have been least impacted by humans since the time of abandonment, that is, over the last 70 years. The villages meeting these criteria are Rogóżka, Borysławka and Caryńska (Table 1 and Figure 1). Soon after the War, Borysławka was subjected to almost total afforestation. In contrast, Caryńska and Rogóżka have retained substantial shares of open land, mostly grassland, until present.

3 | MATERIALS AND METHODS

3.1 | LiDAR data

We used classified point clouds (LAS 1.2 format), generated within the framework of the Polish national project entitled ‘Information System for Protecting the Country against Extraordinary Threats’ (ISOK; Table 2). Working with 3D classified point clouds instead of end products available online (shaded digital elevation model [DEM]) allowed us to manipulate and set the optimal DEM resolution (0.5 m, compared with the default 1 m). Increasing the resolution further was not recommended, given the rule of thumb that the number of pixels per m² should not exceed the point density in a single strip (in our
case—4 points/m², which translates into 0.5 × 0.5-m pixel size). Equally, the ground point densities measured at each study site (Rogóźka—4.22, Borysławka—5.37 and Caryńskie—3.00) do justify use of the higher than default DEM resolution. The increased resolution performed much better, particularly when it came to the detection of discrete linear features such as road ruts and ploughing traces (Figure 2).

In addition to resolution, the interpolation algorithm used had a substantial effect on the accuracy and scope of image interpretation (Kokalj & Hesse, 2017). We tested two popular interpolation methods called inverse distance weighting (IDW) and triangulated irregular network (TIN). When we applied IDW, the image was blurred, the details located within the flat bottoms of valleys were undistinguishable, the road ruts and ploughing traces become barely visible, and interpolation artefacts appeared in areas with lower point densities. In contrast, the TIN interpolation, which we finally used, performed much better (Figure 3). The conversion from point cloud to DEM (only ‘ground’ class points, resolution 0.5 m, TIN interpolation, natural neighbour sampling and no thinning) was then conducted using LP360 Advanced software.

Next, we tested various visualization techniques, for example, shaded relief, openness, local dominance, sky-view factor (SVF) and composite images that were the combinations of the above (Kokalj & Hesse, 2017). Ultimately, we decided to use SVF because the comparative analysis carried out revealed SVF as the most informative technique and easiest to interpret in the context of our study areas and research purposes. Furthermore, SVF is recommended for areas of moderate to steep topography, given the way in which this highlights surface depressions (e.g., hollow ways and ploughing patterns) and features on slopes (e.g., agricultural terraces) (Kokalj & Hesse, 2017).

Based on diffuse illumination, SVF is a geophysical parameter that represents the portion of the sky visible from a certain point. In

### Table 1: Characteristics of the study sites

| Village       | Region                  | Coordinates (WGS-84) | Area (km²) | Elevation range (m a.s.l.) | Foundation century/abandonment period | Number of inhabitants/farms 1930s | Displaced population |
|---------------|-------------------------|----------------------|------------|---------------------------|--------------------------------------|----------------------------------|---------------------|
| Rogóźka       | Śnieżnik Massif          | 50°17′17″N 16°48′38″E | 3.6        | 560–820                   | 14th/1960s                           | 124/31                           | Germans             |
| Borysławka    | Przemyśl Foothills       | 49°38′41″N 22°36′43″E | 7.9        | 315–555                   | 15th/1945                            | 810/140                          | Carpatho-Ruthenians |
| Caryńskie     | Bieszczady Mountains     | 49°09′59″N 22°37′06″E | 17.0       | 615–1295                  | 16th/1946                            | 503/65                           | Carpatho-Ruthenians (Boykos) |

### Table 2: Metadata for the ISOK airborne LiDAR data used in this study

| Parameter                          | Value               |
|------------------------------------|---------------------|
| Scan angle                         | ≤±25°               |
| Strip overlap                      | 20–30%              |
| Laser beam footprint               | ≤0.50 m             |
| Point density in a single strip    | ≥4 points/m²        |
| Altitude accuracy                  | ≤0.15 m             |
| Horizontal accuracy                | ≤0.50 m             |
| Registration of multiple reflections (full waveform) | Yes |

Source: Riegl (2012) and Wężyk (2014) modified.

FIGURE 1 The location of the abandoned villages selected for detailed analysis ([1] Rogóźka, [2] Borysławka and [3] Caryńskie) [Colour figure can be viewed at wileyonlinelibrary.com]
practice, points on a ridge are brighter than those at the bottom of a valley because larger part of the sky can be seen from there (Kokalj et al., 2011). Our SVF visualization (16 directions, 5-m range, without noise reduction) was generated using the Relief Visualization Toolbox 1.3 (Zakšek et al., 2011). For the interpretation and measurement purposes, we additionally used cross-sections of point clouds and 3D views and animations performed on the fly. The on-screen detection and mapping of landscape features were performed using ArcGIS 10.2.

3.2 | Cadastral archival maps

To reconstruct relic cultural landscape patterns in the three villages selected for study, we used the following high-resolution spatial data as reference: (1) 1:2880 Austrian Empire cadastral maps dating back to 1852–1854 and (2) 1:2500 Prussian Empire cadastral maps from 1863. As both map series were developed for fiscal (land tax) and judicial purposes, they pay much attention to details relating to ownership structure and land use, and hence, the boundaries of individual plots, buildings and tax-free land (e.g., roads) were marked in great detail. Scans of the required maps were obtained from the Polish State Archives in Przemyśl, Rzeszów and Wrocław.

Processing of spatial data comprised two main stages: georeferencing and vectorization. We georeferenced all sheets in line with the procedure described by Affek (2015). In the case of the Austrian maps, we used the map datum and projection parameters for the Second Military Survey of Galicia and Bukovina (Affek, 2013), whereas for the Prussian maps, we used bilinear interpolation based on 30–40 ground control points per sheet. Then, we digitized manually selected information from the scanned maps (see Section 3.4), in line with the map legends (where possible verified with original mapping instructions and definitions of map symbols).

3.3 | Field work

We had conducted detailed field survey at all the selected test sites as part of our prior research (Affek, 2016; Latocha, 2015b; Wolski, 2007). Our non-invasive field prospection encompassed, among others: (1) morphometric measurements of old roads and agricultural terraces, (2) GPS location and mapping of settlement remnants and selected man-made features (mounds, stone walls, cellars and wells), and biotic components (secondary succession, postgrazing beech trees, old fruit trees, orchard remains, etc.).
(3) on-site evaluation of states and assessment of processes contributing to either degradation or preservation, and (4) interviews with senior members of the local community as well as employees of the State Forests National Forest Holding. Empirical knowledge of the research areas served as additional help in the reconstruction of the pre-War cultural landscape on the basis of LiDAR and cadastral maps.

### 3.4 Data integration and analysis

Scanned archival cadastral maps and LiDAR-derived DEM visualizations (SVF), along with vector layers generated on their basis, were brought to a common coordinate system (Poland CS92; EPSG:2180). The project was then further augmented by vector layers with data collected in the field, together with geolocalized photographs. Cadastral data and field survey served as a support in identification of earthworks with pre-WWII origin reflected in LiDAR-based DEM visualizations (in relation to dating, and the determination of origins and functions). We characterized the physical attributes (quantity, course, shape, visibility, etc.) of village boundaries, strips of fields, agricultural terraces, ploughing patterns, mounds, roads, remnants of buildings and mining-related earthworks (Table 3).

As our second objective was to assess the effectiveness/usefulness of LiDAR in reconstructing the past landscapes of the abandoned villages, we performed comparative visibility analysis. We sought to determine how much of the landscape pattern recorded on the mid-19th-century cadastral maps is still detectable by LiDAR in each studied village. To this end, we analysed three anthropogenic landscape elements, that is, the boundaries of agricultural parcels

| Table 3 Pre-world War II landscape features detectable by LiDAR (identification supported by cadastral maps and field survey) |
|--------------------------------------------------|
| Landscape features | Physical attributes | Rogoźka (Śnieżnik Massif) | Borysławka (Przemysł Foothills) | Carynskie (Bieszczady Mountains) |
| Village boundaries | Easily recognizable, mostly delineated on ground, usually in form of escarpment up to 2.5 m high or stone wall up to 1 m high, often along field roads | Ditch up to 2 m wide and 0.6 m deep separating former crown lands, other segments moderately visible | Moderately visible, usually along natural landforms and roads, no dedicated border marks |
| Strips of land (lans) | 20 parallel strips of land, on average 100 m wide, perpendicular to settlement axis, with earth escarpments up to 3 m high and stone walls/mounds | 50 mostly parallel strips of minor land, on average 40 m wide, perpendicular to settlement axis, on slopes with escarpments up to 3 m high, on flat—visible through different ploughing pattern | 45 mostly parallel strips of minor land, on average 55 m wide, perpendicular to settlement axis, with plenty of small stone mounds on boundaries and some earth escarpments up to 1 m high |
| Agricultural terraces | 2.3 km, 0.6 km/km², just a few and quite gentle up to 1.5 m high | 32.2 km; 4.8 km/km² on cadastral arable fields (additionally 5.6 km beyond fields), earth escarpments up to 2.5 m high | 29.1 km, 8.1 km/km² on cadastral arable fields (additionally 0.9 km beyond fields), low (up to 1 m high) earth escarpments |
| Ploughing pattern | Almost invisible | Easily recognizable, ridges up to 5.5 m wide and 0.4 m high | Moderately visible, ridges 3–4 m wide and up to 0.2 m high |
| Mounds | 473 stone mounds (clearance cairns) (131/m²), up to 15 m and 4 m high, with flat top, both on and within parcel boundaries | Single earth mounds on village border tripoints, 4.5 m and 0.8 m high | 640 conical stone mounds (clearance cairns) (38 mounds/km²; 170 mounds/km² on cadastral arable fields), up to 3 m and 0.5 m high, mostly on parcel boundaries |
| Roads | 19.5 km of pre-War roads (5.4 km/km²), both perpendicular and parallel to slope, with undercuts/escarpments up to 3 m high and 2–3 m wide, rarely hollow ways, only up to 1 m deep | 24.0 km of pre-War roads (3.0 km/km²), often V-shaped classic hollow ways parallel to slope, up to 3 m deep, often only 1.5 m wide | 53.2 km of pre-War roads (3.2 km/km²), often V-shaped classic hollow ways up to 4 m deep and 1–2 m wide |
| Remnants of buildings | Hard to recognize, 14 remnants of farmsteads | Easily recognizable, ~150 stone foundations, residential buildings on average 15 × 7 m | Hard to recognize, 5 stone foundations, ~30 remnants of farmsteads (mainly indirect traces, e.g., cellars) |
| Mining-related earthworks | Several marble quarries, largest 4.5 ha and 55 m deep | Small limestone quarry 18 m and 4 m deep | – |

Note: Physical attributes measured as presented in LiDAR derivatives.
(excluding natural boundaries), cadastral roads and the remnants of farmsteads (Table 4). We generated three vector layers showing the respective elements as they were presented on cadastral maps. Then, we compared them with SVF DEM visualization and assigned the binary visibility category (visible/invisible) to each line section (roads and boundaries) and polygon object (farmsteads). Those sections of old roads that were rebuilt completely after WWII (hardened, profiled, widened, with corrected course and geometry) were not considered part of past landscape and were therefore classified as ‘invisible’ (covered by a new layer). In the case of remnants of farmsteads, we considered these visible even when it was possible to detect only a minor man-made disturbance to the natural relief indicative of historical settlement (e.g., a cellar, a well and an unambiguous settlement terrace).

4 | RESULTS

4.1 | The past rural landscape in abandoned mountain villages as reflected in LiDAR data

The past landscape of the three mountain villages abandoned after World War II was still reflected in the topography (Figure 4) and therefore well visible in LiDAR data. The field survey and the analysis of archival cadastral maps allowed for the interpretation of microtopographic features reflected in LiDAR derivatives and for the reconstruction of the pre-WWII landscape (Figures 5 and 6). We described quantitatively several man-made landscape features (earthworks) detected by LiDAR (Table 3) and grouped them into the following four major categories: boundaries, the road network, agriculture and buildings.

4.1.1 | Boundaries

The various types of old boundaries clearly visible on LiDAR-based DEM visualizations include village administrative boundaries, ownership boundaries and land use boundaries. It was possible to track the old village boundary of Rogóżka at its complete length and to a large extent also those of Borysławka and Caryżyskie. They either ran along natural landforms (ridges and streams—in that case, additional cartographic materials were needed for boundary identification), or were marked by man by way of a stone wall (in Rogóżka most often along the road), an escarpment or a ditch (in Borysławka). Administrative boundaries also ran partially along old tracks (especially ridge paths used by cattle herders at Caryżyskie). In Borysławka, village tripoints were additionally marked using groups of three earth mounds.

The former ownership boundaries dating back to the colonization period (14–16th centuries) were also clearly visible in LiDAR derivatives. Field strips perpendicular to the main axis of settlements were only slightly adapted to the terrain and were bordered by escarpments (up to 3 m high in Borysławka and Rogóżka) or by stone walls and mounds (in Rogóżka and Caryżyskie). They also in part ran along secondary streams or rock outcrops (in Rogóżka). In some places, the only evidence of the ownership boundary was a field road or preserved diverse patterns of ploughing between neighbouring pre-War parcels. Originally, in accordance with the Wallachian or German law by virtue of which the villages were founded, each strip of land belonged to a different owner. However, in some strips, it was possible to see inner divisions marked by anthropogenic escarpments perpendicular to the slope. Our analyses showed that the divisions and ownership changes taking place from the time of foundation of villages through to the period of population displacement modified only slightly an original pattern of fields that is still perfectly visible.

4.1.2 | Road network

Roads are the elements of the past landscape that usually leave visible marks in the topography and therefore are very well reflected in LiDAR data. In all three studied villages, the main communication route, partially paved with small stones, ran along the bottom of the valley forming an axis of settlement typical for late mediaeval mountain villages. In Caryżyskie and Rogóżka, the original course of the main road has been blurred due to the construction of a new paved road after the War. The former road network also included numerous unpaved tracks (access to fields, transhumance) leading usually in a direction perpendicular to the main settlement axis. Those tracks often took the form of hollow ways and led along natural gorges and bottoms of streams (mainly in Borysławka and Caryżyskie), or were accompanied by distinct escarpments (Rogóżka). We also detected local farm roads not reaching main roads, but ending behind

| TABLE 4 | Proportions of past landscape features detectable in LiDAR derivatives, from among those marked on mid-19th-century cadastral maps |
| --- | --- | --- | --- |
| Landscape features | Village | Borysławka | Rogóżka |
| Boundaries of agricultural parcels | 38.4% (70.9 km out of 184.9 km), excluding 23.6 km of natural boundaries | 48.9% (99.0 km out of 202.3 km), excluding 10.7 km of natural boundaries | 70.3% (50.6 km out of 72.0 km), excluding 4.2 km of natural boundaries |
| Roads | 64.5% (24.2 km out of 37.5 km) | 78.9% (11.7 km out of 14.8 km) | 75.5% (14.0 km out of 18.5 km) |
| Farmsteads | 42% (21 out of 50) | 71.4% (65 out of 91) | 42.4% (14 out of 33) |
farmsteads, as well as old forest roads used in timber extraction that go unmarked on cadastral maps. This network was complemented by long-distance ‘transit’ routes leading mainly along ridges (Borysławka) or administrative boundaries (Rogóżka).

4.1.3 | Agriculture

The most characteristic elements of relief related to mountain agriculture are the embankments of agricultural terraces. These earthworks perpendicular to the slope were located at field margins, and they made the ploughing easier and limited erosion. Some coincided with ownership boundaries, whereas others were perpendicular to strips of land and located within one parcel, depending on the topography. Ploughing pattern was another agriculture-related pre-War feature visible in LiDAR derivatives, but only in Borysławka and Caryńskie. They are best preserved/most visible in former arable fields located further away from the valley bottom, which were completely abandoned and underwent succession processes directly after displacements, and now are covered by mature forest. In Borysławka, we identified ancient ridge-and-furrow pattern of ploughing, evidence of decades of ploughing with the primitive, non-reversible ploughs used back in the Middle Ages, but apparently also as recently as in the 1940s in this case (Affek, 2016). The ridges reached up to 4.5 m wide and 0.5 m high. In turn, we detected stone mounds related to agriculture (clearance cairns) in Caryńskie and Rogóżka only. Stones were lifted and removed from the fields nearby to make agriculture more effective. Their presence on the surface in large numbers was a side effect of the ploughing of very stony and shallow soils, as combined with needle ice activity and selective surface wash.

FIGURE 4  Examples of pre-World War II earthworks in the abandoned villages: (a) remnants of a house, (b) a stone wall, (c) an agricultural terrace, (d) a hollow way, (e) a clearance cairn, (f) a well and (g) a cellar [Colour figure can be viewed at wileyonlinelibrary.com]
The remains of former farmsteads and residential buildings were clearly visible in LiDAR derivatives in the case of Borysławka. However, they were hardly detectable at all in Caryńskie and Rogóżka. In all villages, buildings were located along valleys, on both sides of the main water course. They were usually built on artificial settlement terraces, which are often the only traces of former farmsteads detectable using LiDAR. The original buildings were represented mainly by a simple type of a single, elongated building with a residential and a utility part under a single roof. Such were present in all three of the studied villages. However, only Rogóżka featured larger farmsteads, on which separate residential and utility buildings were built into a quadrangle around an inner courtyard.

There are also minor traces of former elements of dwellings, which can be detected (at least partially) by LiDAR. Examples include cellars, wells and earth pits (e.g., for storing potatoes). They were found in all the analysed areas. We also identified free-standing...
granaries (at Caryńskie) and the foundation of an Orthodox church (at Borysławka). In turn, larger remnants of buildings protruding significantly above the ground (e.g., of the church in Rogóżka) are not visible in LiDAR-derived DEM, because in the 3D point cloud, they were classified as buildings, not ground. The status of buildings as serving different various functions (historical documents, for example, refer to water mill, brewery, forge, inn, school and guest house) appears to have no discernible influence on the visibility of remains on LiDAR-based DEM visualizations, as well as on the state of preservation in the field.

4.2 The effectiveness of LiDAR in detecting past landscape features of abandoned villages

The capacity of LiDAR derivatives to detect past landscape features marked on mid-19th-century cadastral maps varied among features and locations (Table 4). We noted the highest proportion of visible features in regard to old roads (73% on average) and considerably lower in regard to farmsteads and the boundaries of agricultural parcels (52% on average). Borysławka stands out in terms of the visibility of farmstead remnants (71%), whereas Rogóżka for the high visibility of its old field boundaries (70%).

| Features          | LiDAR | Cadastral map | Field survey |
|-------------------|-------|---------------|--------------|
| Parcel boundaries | ++    | +             | +            |
| Agricultural terraces | +    | -             | +            |
| Clearance cairns  | +     | -             | +            |
| Ploughing pattern | +     | -             | -            |
| Logging roads     | +     | -             | +            |
| Public roads      | +     | +             | +            |
| Buildings         | -     | +             | +            |
| Farmsteads        | +     | +             | +            |
| Quarries          | +     | +             | -            |

Note: ‘+’ means identifiable/detectable without additional data sources. ‘+’ means identifiable/detectable with additional data sources or only partially (not all features in the study area). ‘-’ means unidentifiable/undetectable.

We compared the usefulness of LiDAR with the two other data sources (archival cadastral maps and field survey), when it came to the detection of past landscape features in the villages studied (Table 5). Our qualitative evaluation confirms LiDAR as definitely the best.
choice in detecting ancient ploughing patterns, concealed under both tree canopy and turf. In the vast majority of cases, the identification of agricultural terraces and old quarries can be achieved using LiDAR data alone, whereas detection of old roads, clearance cairns and especially remnants of old farmsteads can be done most effectively through the integration of data sources. LiDAR had the capacity to detect to some extent all of the earthworks and land use analysed, yet for the complete reconstruction of past landscape pattern, the additional information from other sources was often needed, in particular in terms of the features’ ages and functions.

5 | DISCUSSION

5.1 | Lost landscapes—Past land use reflected in relief

The use of LiDAR in combination with archival cartographic sources and field survey allowed us to precisely (unambiguously) locate old landscape elements, to reconstruct spatial patterns of the pre-War landscape and describe quantitatively several man-made landscape features. We found both similarities and differences among the three investigated villages as regards reconstructed pre-War landscapes. The similarities stem from the generally similar foundation period (the Late Middle Ages), as well as a location within the common European cultural area associated with the feudal system at that time. These circumstances ensured comparable spatial arrangement of parcels. The long and narrow strips of land stretching upslope behind each farmstead were characteristic for mediaeval rural settlements established in areas of forest clearing in Central Europe (Ger. Waldhufendorf and Pol. wieś lasuchowa). The reported variation in strip widths related to density of population, number of farmsteads and specific rules in respect of the locating of villages in each region (Wallachian or German law).

In turn, the differences between the investigated sites can be explained mainly by reference to local environmental constraints, involving topography, elevation and lithology. The very shallow and stony soils developed in crystalline bedrock (at Rogóżka) contributed to a far greater number of stone embankments located along roads and field boundaries, as well as to sizes of clearance cairns larger than those at the sites in SE Poland, where thicker soil overlays the sedimentary rocks (Carpathian flysch in Borysławka and Caryńska). This fact ensured that farmers in the latter villages were less affected than their counterparts in the Sudetes by the need to remove stones to facilitate or even allow for ploughing.

In turn, the much greater density of agricultural terraces in the Carpathian villages can be explained by the need to make greater efforts to limit surface wash from highly erodible flysch soils. In general, such terraces are among the commonest features of past agricultural landscapes detectable using LiDAR derivatives in the uplands and mountains (Chase et al., 2011; Crow, 2009; Migoni & Latocha, 2018). The flysch structure also favoured the formation of hollow ways. They proved to be much more common and deeper at the two sites in SE Poland than in the Sudetes where development was much hampered by the hard, crystalline bedrock or coarse-grained weathering slope covers.

It also emerges that the old ploughing pattern that might be very persistent in an abandoned landscape (Domaas, 2007; Latocha, 2015b) is actually visible solely where there is sedimentary bedrock. However, we also observed differences between Borysławka and Caryńska, and they may be attributed to both topography and altitude. Many more stony features (mounds, walls etc.) and agricultural terraces were recorded in the mountainous locations and on steep slopes (at Caryńska) than in the foothills (at Borysławka). In this aspect, Caryńska is more similar to Rogóżka, despite substantial differences in lithology. Such differences between LiDAR-detectable features in areas with more and less complex topography resemble those in other regions, regardless of the climatic zone (Canuto et al., 2018; Millican et al., 2017). This shows how knowledge of the local environmental conditions is vital for proper interpretation of LiDAR data and for comparative analysis between sites as regards the potential to preserve (or not) man-made features from the past. Moreover, the wider environmental context provides a wider landscape perspective from which to interpret the isolated traces of past human activities.

Our results can be related to observations made by other researchers in different European mountain regions and landscape types characterized by complex topography (Jucha et al., 2020; Kokalj & Hesse, 2017; Märgärint et al., 2021; Masini et al., 2018; Seitsonen & Ikäheimo, 2021). At the same time, we recognized a scarcity of studies applying LiDAR to the contemporary archaeology of deserted mountain areas (compare: Affek, 2016; Affek et al., 2017; Duma et al., 2020; Latocha, 2015b). Case studies should therefore be continued to allow for the development of comparative analysis and syntheses in regard to the visibility of landscape features, as well as to the utility of open-access LiDAR datasets for various European regions and mountainous landscapes.

5.2 | Landscape stability and the persistence and visibility of earthworks

The high level of consistency between the landscape patterns visible on mid-19th-century cadastral maps and in LiDAR derivatives points to the stability of landownership structure and land use prior to the post-WWII displacements. On the other hand, it also indicates the good state of preservation of these forms in the relief, despite the cessation of their maintenance and use by humans in the post-War period. The preserved pattern characteristic for the Middle Ages and the lack of visible traces of other older structures in the relief suggest that what we see on LiDAR-based DEM visualizations may at least partially reflect the original spatial pattern formed when the villages were founded on bare earth in the 14–16th centuries (Johnson & Quimet, 2014). Although we are aware that some of the features observed could have been modified in the early and late Modern period (e.g., by the rearrangement of ownership or with changes in population), the villages permanently abandoned after World War II
reconstruction of past landscapes

The observed inconsistencies between old cadastral maps and LiDAR data may result from several reasons, and it is not always easy to judge which is real. Errors can be present on old maps, and objects may have been distorted by subsequent land use or levelled spontaneously. Some landscape features may never have gained reflection in the relief, whereas others may indeed be reflected in relief, but not in LiDAR data. Therefore, we cannot speak with full confidence about the persistence of old earthworks in the landscape but rather about their visibility on LiDAR.

Nonetheless, the major disparities between villages as regards the visibility of past landscape features point to the impacts of certain objective factors. For instance, we assume that remnants of farmsteads are far better visible in Borysławka, because it is the only village in which farmsteads are now completely under tree canopy, and low and middle-height vegetation remains sparse (see also Section 5.3). In turn, past field boundaries are best visible in Rogóżka because they often took the form of embankments reinforced with stones.

5.3 | Added value and limitations of LiDAR-based reconstruction of past landscapes

With the advent of LiDAR, it became possible to reveal, at the landscape scale, traces of former land use hidden beneath vegetation (Mlekuź, 2013b). Thanks to LiDAR, we were able to contextualize single historical features (e.g., farmstead foundations, clearance cairns and hollow ways) and reconstruct entire cultural landscapes well reflected in the relief of abandoned villages. Images from a bird’s-eye view helped perceive and interpret organized wholes instead of collections of parts, in line with the Gestalt theory of perception (Farina, 2006). They offered deeper insight into the process by which a landscape could be understood. LiDAR allowed us to reconstruct linear objects with even small, 10- to 20-cm height differences and major discontinuities, for example, old roads and field boundaries now hidden beneath tree canopy. This proved to be particularly true in the case of old ploughing patterns in postagricultural forests, which were extremely hard to detect and map without LiDAR. By recording those patterns, laser scanning offered a unique chance to distinguish between ancient and postagricultural forests and to reconstruct past field mosaics and local agricultural practices.

As LiDAR has opened up new horizons for the visualization of the Earth’s surface, and provided highly detailed, precise and visually appealing images, it is tempting to forget that LiDAR-based visualization is only a model of reality, not reality itself. The value of LiDAR-based DEM visualizations is influenced—and may be biased—by multiple scanning-related factors, such as time of the year and day and weather conditions, as well as by sensor and acquisition parameters (including scanning patterns and angle, footprint size and beam divergence) (Montaghi, 2013; Pirotti et al., 2013).

However, the most important disruptive factor, especially when detecting subtle artefacts, is site-specific vegetation cover (Guan et al., 2014). When earthworks are covered by low and dense vegetation, there is no possibility of obtaining an accurate shape of the Earth’s surface due to scanner limitations manifested in the so-called multitarget resolution (MTR) (Ullrich & Pfennigbauer, 2011). In such cases, even if some of the pulses reach the ground, the nominal ranging accuracy of 2 cm (for single returns) increases up to 60 cm (Wagner et al., 2006). As a result, echoes separated by shorter distances within the same laser shot cannot be distinguished. Consequently, the measured range can only be estimated, and the resulting image is blurred (Di Salvo & Lo Brutto, 2014). This is particularly evident where vegetation porosity is very poor, for example, in the circumstances of a dense understorey with brambles and bracken fronds (Crow, 2009; Doneus et al., 2008), or else where there is thick blanket moss (Krasinski et al., 2016). Therefore, we argue that MTR limitations may constitute the main reason for the poor visibility of farmstead foundations in Caryńska and Rogóżka in LiDAR derivatives. This is also evidenced by the varied dates of acquisition: the most favourable for Borysławka (29 March 2014), much worse for Caryńska (17 October 2017) and definitely unfavourable for Rogóżka (18 August 2012). We are also aware that the LiDAR data used were acquired and processed to develop a protection system against natural hazards (mainly flooding). This means that the point cloud filtration and classification algorithms used are not dedicated to the identification of small linear and point objects on the ground (Klarszys & Szalast, 2014).

The effectiveness of LiDAR in detecting past landscape features imprinted in relief is also dependent on applied data processing techniques. In a long chain of transformations from electromagnetic echo to DEM visualization (light signal → electric signal → raw point cloud → classified point cloud → triangle grid → raster model → shading), every subsequent ‘chain link’ may be a source of error or uncertainty. For instance, at the stage of point classification, some relief points with untypical characteristics (in terms of location, or intensity value) may not be classified as ground points and therefore not used to create DEM. This may be true of stone foundations assigned to the class ‘building’, cellars and wells—to the class ‘low point’, and dugouts—to the class ‘low and medium vegetation’ (Affek, 2014; Norstedt et al., 2020). In our case, customizing the entire process of generating final DEM visualizations (selection of points, DEM resolution and visualization technique), instead of working on ready-to-use shaded DEM, allowed for the detection of far more man-made microporphographic features (e.g., road ruts and subtle old ploughing traces) and for dating them more accurately. The presence of road ruts, apart from the U-shape cross-section of hollow ways (Kirchner et al., 2020), was an important indication of current use of roads, so a possibility of detecting them improved the dating of road traces substantially.

On the other hand, the most challenging was the dating of forest roads and minor field roads, as they were not marked on old cadastral maps. Some such roads were used after the War by foresters, but they may as well have been created in the pre- or inter-War periods.
which was also noticed by Johnson and Ouimet (2014). Sometimes
overgrown, nonhollow dirt roads (especially within a flat valley bot-
tom) simply cannot be fully discriminated from bare earth (Bujan
et al., 2013), though patterns of artefacts (i.e., sequences of pointless
or blurred areas) can also be a hint (Jucha et al., 2020). Still, in many
cases, it was possible to distinguish between pre- and post-WWII for-
est roads, mainly by analysing their course against the landscape pat-
tern. Old forest roads fit much better into the historical landscape
pattern and usually lead along ridges, whereas post-War forest roads
often cross the pre-War mosaic of fields, are less steep and almost
perpendicular to the slope and form a specific network in line with
post-War forestry guidelines (Affek et al., 2017). Moreover, modern
mechanized skidding with heavy logging equipment leaves visually dif-
ferent traces compared with the historical use of draught horses
(Affek et al., 2017), and the 0.5-m resolution DEM allowed us to
detect such indicative microtopographic details as the shape of the
ruts and overall road profile. But even when all these premises are
taken into account, some level of uncertainty in dating remains.

LiDAR has been confirmed as an extremely powerful reconnaiss-
ance tool. However, LiDAR alone, and despite optimization efforts,
does not suffice for the reliable dating of past landscape features and
for clear distinguishing between pre- and post-WWII origins. Joint
analysis with archival cadastral maps did much to facilitate the identi-
fication of old parcel boundaries, public roads and farmsteads. In turn,
field survey contributed to the verification of small cave and con-

evex objects (e.g., clearance cairns, wells and cellars) not marked on
any available source of spatial data, including cadastral maps.

In general, LiDAR-based identification is more problematic for
point features than linear features (Crow, 2009), though the interpre-
tation of the latter is also not obvious at times, where pedestrian sur-
vey data are lacking (Johnson & Ouimet, 2018; Quintus et al., 2017;
Risbøl et al., 2013). Firstly, point features can be easily obscured by
dense overlying vegetation or omitted where point density is too low.
Secondly, this category provides for many possible misinterpretations
with pseudoarchaeological features. Piles of decomposing branches
(effect of forest thinning) (Affek, 2014; Doneus et al., 2008;
Mlekuž, 2013b; Schindling & Gibbes, 2014), tree boles, stumps and
wood dump sites (Horňák & Zachar, 2017) can all be interpreted as
false clearance cairns or burial mounds, whereas depressions between
clumps of vegetation can be mistaken for remnants of storage or liv-

ing structures (Krasinski et al., 2016).

Moreover, field survey was necessary to create an image inter-
pretation key that linked real landscape features with their reflection
on LiDAR-based visualizations ( Randall, 2014). Due to the LiDAR limi-
tations referred to above, certain man-made features might only be
detected through field prospection, inter alia by reference to the pre-

cence of characteristic ruderal vegetation—a valuable indicator of past
human activities in abandoned areas (Latocha et al., 2019).

Last but not least, it is worth remembering that LiDAR itself does
not ensure archaeological interpretations (Kokalj et al., 2011). Rather,
it is the researcher’s expertise and personal experience of the local
landscape that underlies the process of appropriate reconstruction
(Banaszek, 2014; Johnson & Ouimet, 2018). And DEM visualization,
no matter how accurate, is still not a map. An interpretation key has
to be provided, because ‘interpreting means correlating trace with the
event that produced it, supplementing the trace with a mental image
of what is missing from it’ (Mlekuž, 2013b). Only then, by contextual-
izing the traces of past societies imprinted in the relief, may LiDAR
contribute vitally to the answering of anthropological questions
regarding interactions between humans and the surrounding land-
scape (Johnson & Ouimet, 2014).

6 | CONCLUSIONS

We demonstrated that the mountain villages in Poland abandoned
after World War II offer a unique opportunity for accurate reconstruc-
tion of past cultural landscapes dating back to the feudal period. The
spatial pattern visible on mid-19th-century cadastral maps is still well
conserved in the relief and detectable using LiDAR. We found that
the landscape pattern imprinted in that relief was largely shaped by
environmental conditions (lithology, soils and topography), the initial
landownership division and land use. As permanent abandonment fol-

dowing post-WWII displacements of population was observed in
mountains throughout Central and Eastern Europe, our case study can
be considered representative of a regionally relevant phenomenon.
The approach taken allowed for the analysis of a range of LiDAR-
derived landscape features, as further compared between study sites,
and relate our results to those from other mountainous regions and
landscapes. We provided new evidence regarding the visibility of past
landscape features that can help build international comparative stud-
ies and syntheses.

Although laser scanning proves to be a powerful tool in landscape
archaeology, it has its limitations like any science-based technology.
LiDAR’s eye looks deeply and penetratingly, but the stand-alone tool
does not understand what it perceives. Hence, accurate identification
and dating of microtopographic man-made features is possible only
when LiDAR data are integrated with data from other sources, includ-
ing field survey. It is often believed that the main added value of laser
scanning in archaeology is the possibility to reveal previously
unknown objects, and accurately and precisely determine their posi-
tion, size and shape, as well as evaluate their state of preservation or
degradation. Notwithstanding the foregoing, we argue that the
greatest advantage of LiDAR is its capacity to provide a landscape
context to isolated traces of past human activities and thus allowing
for the reconstruction of entire spatial patterns and interrelationships
developed by past societies.

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CONFLICT OF INTERESTS

The authors declare no conflicts of interest.
DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Geoportal Infrastructure Informacji Przestrzennej at https://www.geoportal.gov.pl/.

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