Using remote sensing materials to assess the effects of peat extraction on the morphology and vegetation cover of a raised bog (Ludźmierz near Nowy Targ, Southern Poland)

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SUMMARY

The Orawa - Nowy Targ Basin is one of only a few areas in the Polish Carpathians with high relative cover of peatlands (12 %). This fraction is declining progressively due to several centuries of peat exploitation for fuel, gardening and balneology. The peatland at Ludźmierz near Nowy Targ is regionally important for its high biodiversity but has been scarred by historical and contemporary peat extraction. The current area and fragmentation of peat domes on Ludźmierz Bog were assessed, along with the characteristics and condition of the vegetation. Also, topographical changes across areas of peat extraction were analysed using a combination of remote sensing and field study methods in order to identify the locations of modern peat extraction and natural mass movements. The condition of the raised bog and changes in its boundaries were thus deduced, paying attention to the bog's exceptional environmental and landscape values. The area covered by the bog is currently 39 ha and it is divided into three separate domes which are drained by a network of ditches and through discontinuities of the water table at peat extraction areas. The vegetation on extraction areas currently has a higher biomass growth rate than the plant cover on the domes, and is in better condition on the basis of NDVI assessment.

KEY WORDS: human impact, Ludźmierz Bog, NDVI, plant cover, Western Carpathians

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INTRODUCTION

Peatlands are unique ecosystems whose biodiversity and geodiversity should be preserved for future generations (Tobolski 2012). Many research studies have highlighted the need for their effective management and restoration if this is to be achieved (Mauquoy & Yeloff 2008, Słowiński *et al.* 2019, Swindles *et al.* 2019). Raised bogs are peatlands that are completely dependent on rainwater. In Central Europe the presence of raised bogs is determined by climate and they have usually developed after terrestralisation of a water body and a minerotrophic stage rather than originating by paludification of mineral ground or bedrock (Lamentowicz *et al.* 2010, Marcisz *et al.* 2020). Extensive raised bogs are rare in the Polish mountains where their development is limited by geomorphological conditions, especially erosion and denudation in valleys, the scarcity of appropriately sized concave landforms (Żurek 1987) and climate conditions (Hrynowiecka-Czmielewska 2009). One of the few areas in the Carpathians with relatively high occurrence of peatlands is the Orawa - Nowy Targ Basin, which hosts a complex of more than thirty raised bogs characterised by exceptional floristic richness and specificity (Łajczak 2006, Koczur 2008, Malec 2012). Raised bogs cover 5 % of the basin and mires of all types (raised bogs, poor fens and fens) occupy 12 %, which Żurek (1987) calculates to be three times the average rate of peatland occurrence in Poland. The area covered by peatlands was much greater in the past and has been reduced significantly by drainage and peat extraction (Łajczak 2006). Previous studies assessing changes in peatland area within the Orawa - Nowy Targ Basin have used maps from various historical periods (Korczyńska 1952, Mirska 1956, Jostowa 1963, Łajczak 2006), while those investigating peatland development and assessing state and condition have used the results of detailed research on vegetation (Obidowicz 1988; Koczur 1996, 2004, 2008; Malec 2011, Korzeń 2012) or on various hydrological aspects (Łajczak 2014).

The study reported here employed remote sensing materials to assess the current area of the raised bog remnant in Ludźmierz near Nowy Targ; to determine the degree of dome fragmentation; to assess the basic character and stature/condition of vegetation on its remnant domes and the surrounding belt of peat extraction areas; and to characterise topographical changes at the edges of the domes, which arise from recent peat extraction and natural mass movements.

HISTORY OF PEATLANDS IN THE ORAWA - NOWY TARG BASIN

The Orawa - Nowy Targ Basin is a mountain depression bounded by the Western Beskids Mountains to the north and the Tatra Mountains to the south. The climatic conditions are characterised by frequent temperature inversions caused by influxes of cold air from the surrounding mountains, high incidence of clouds, frequent fog, long duration of snow cover, average annual precipitation of about 860 mm and an excess of precipitation over evaporation between May and October (Kowanetz 1998, Staszkiewicz & Szeląg 2003). In addition to the cool, humid climate, the main reasons for development of peatlands in this region are low soil permeability and the occurrence of large areas with shallow slopes (Obidowicz 1990, Lipka & Zając 2014, Pawełczyk *et al.* 2019). Despite the high humidity, bogs in the Orawa - Nowy Targ Basin have developed preferentially on glaciofluvial cones and postglacial terraces rising 5–40 m above riverbeds, at an altitude of 590–770 m above sea level (Łajczak 2014). This indicates the important role of local hydrogeological conditions and terrain in the peat-forming process.

The autochthonous accumulation of organic matter began at different times in different locations. The oldest radiocarbon dates reported for bottom deposits are around 10,000 BP for the Puścizna Rękowiańska bog (Obidowicz 1988), whereas the youngest are 6,100 BP (Korzeń 2012) and 4,450 BP (Krąpiec *et al.* 2014) for Puścizna Wielka and 5,100 BP (Pawełczyk *et al.* 2018) for Otrębowskie Brzegi. The average rate of peat accumulation in the Polish part of the Carpathians is usually between 0.4 and 0.6 mm year^{-1} (Żurek 1987). This rate is similar to the values calculated by this author for raised bogs in Europe, and local differences may be caused by composition of vegetation and the dominant species, moisture content and water table depth (Hájek 2009, Stivrins *et al.* 2017, Lipka & Zając 2018).

It is estimated that about 70 % of the Orawa - Nowy Targ Basin was covered by peatlands in the period leading up to agricultural colonisation (Łajczak 2006). The first indications of settlement date back to the fourteenth century AD, when local people avoided the peatlands due to numerous preconceptions. Peat was used initially as an organic fertiliser and later as fuel, which led to intensive exploitation of peatlands starting in 1850–1880 (Jostowa 1963). The next phase of exploitation in Podhale and Orawa was during World War II and the post-war years (Mirska 1956). From 1967 onwards, industrial-scale peat extraction commenced across a total area of about 165 hectares on bogs such as Puścizna Rękowiańska, Bór za Lasem and Puścizna Wielka (Żurek 1983, Koczur 1996). Surface extraction of peat was preceded by the construction of deep ditches to drain the deposit. A dense network of bands of ditches running perpendicular to the edge of the peat dome and cut down to the bedrock locally lowered the water table in the peat by four metres (Cichocki 2004). In the vicinity of Ludźmierz, on the other hand, peat was mined on a domestic basis, mainly for subsistence needs (fuel and fertiliser) by residents of the nearby villages of Wróblówka, Długopole, Krauszów, Ludźmierz and Rogoźnik (Koczur 1996). As a result of peat extraction, the area of the peat dome in Ludźmierz has decreased by about 100 ha since the end of the 19th century (Figure 1).

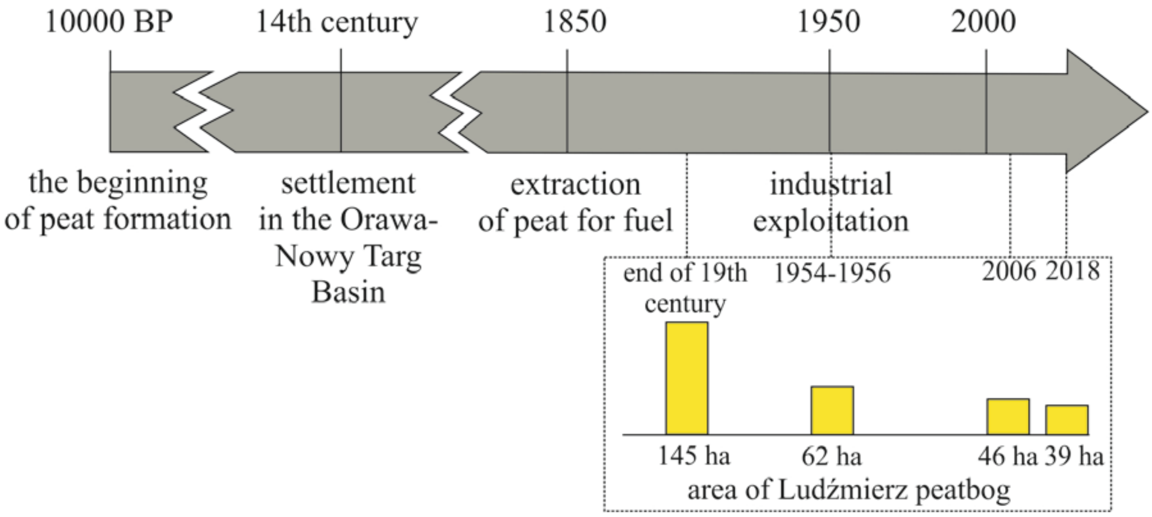


Figure 1. Key stages of peat-forming processes and anthropogenic changes in peatlands of the Orawa-Nowotarska Basin (Lubicz-Niezabitowski 1922, Jostowa 1963, Obidowicz 1988, Łajczak 2002).

Despite many projects to protect the peatlands of Orawa - Nowy Targ Basin (Lubicz-Niezabitowski 1922, Obidowicz 1977, Denisiuk & Pioterek 1990), the "Bór na Czerwonem" bog is the only one where a nature reserve has been established. The other raised bogs, which are often much richer in terms of flora, are still not subject to any form of protection except for inclusion in the planned Natura 2000 Orawa-Podhale Peatlands PLH120016. As of the end of December 2019, the protected area has not yet been approved and peat is still being extracted in many places, both for domestic purposes by local residents and on an industrial scale.

METHODS

Study site

Ludźmierz Bog (also known as Ludźmierskie, Rękowiańska Puścizna, Młaka Brzeżek, Torfy, Grel, Do Grela and Przymiarki) developed between two tributary streams of the Czarny Dunajec river, namely the Wielki Rogoźnik to the south and the Czerwony Potok to the north (Figure 2). The bog's many names result from the gradual fragmentation of a larger bog dome that, at one time, also encompassed the Przymiarki and Puścizna Rękowiańska Bogs listed in the previous section ("History of peat bogs

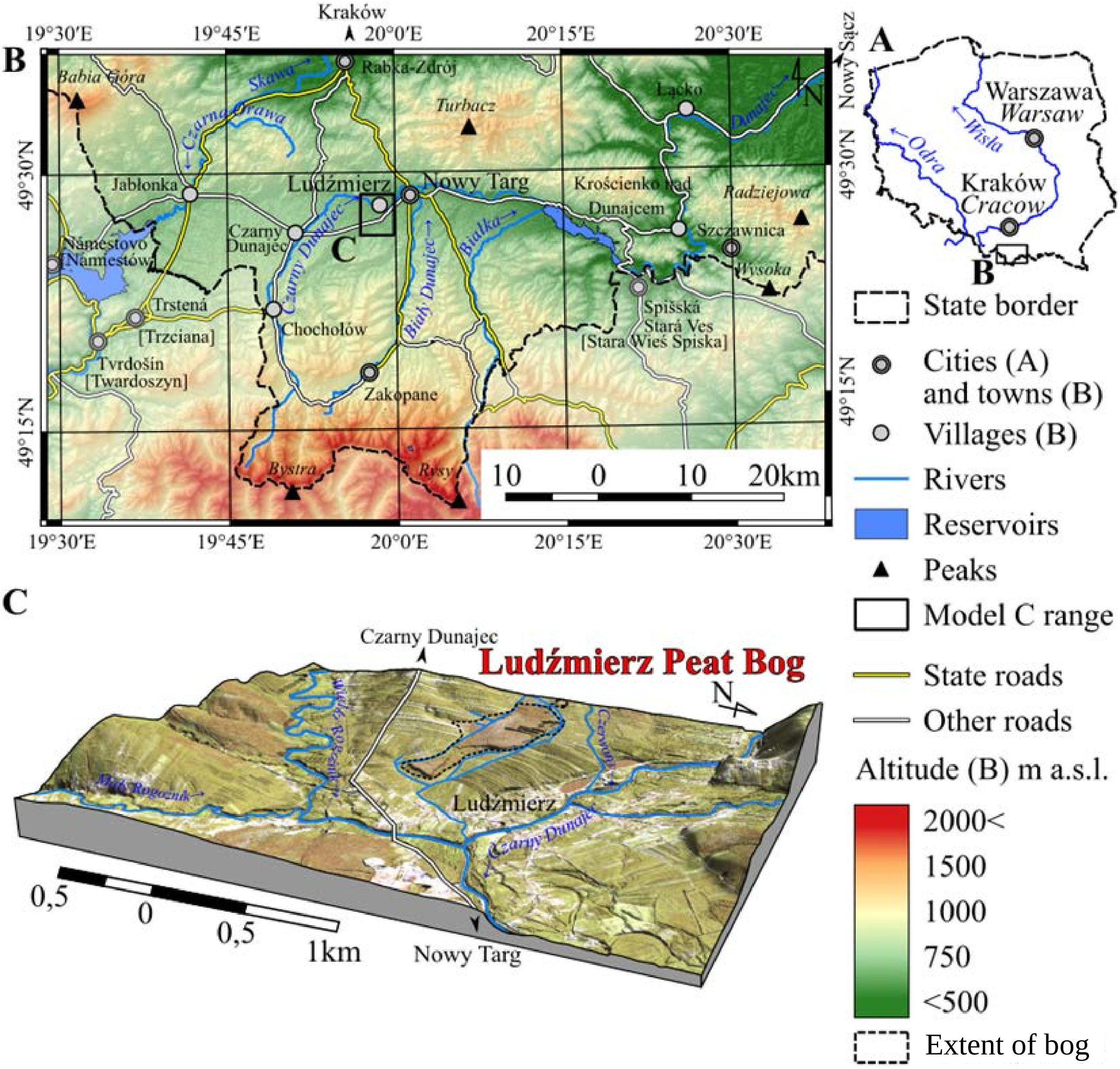


Figure 2. Location of the study area in Poland (A), in the Orawa - Nowy Targ Basin (B) and near the village of Ludźmierz (C).

in the Orawa - Nowy Targ Basin”) of this article (Łajczak 2002, Lipka & Zając 2014). Here we adopt the name of the closest village to the area of peatland that we examined. The extent of the bog was reported in 2006 as 105 ha with dome remnants covering 46.25 ha (Łajczak 2006). Peat thickness is 1.21 m on average, and 4.0 m at maximum. The dominant peat type is *Eriophoro-Sphagneti* (Lipka 2000, Łajczak 2006, Lipka & Zając 2014).

The bog is surrounded by highly fragmented arable fields. The road from Nowy Targ to Czarny Dunajec passes 500 m south of the bog, and the village of Ludźmierz lies within 1 km to the east. Ludźmierz Bog is associated with a mediaeval legend about the miraculous rescue of an errant traveller by the Virgin Mary, commemorated by the Marian Sanctuary in the village (Sanktuarium MBL 2019).

Early reports on the Ludźmierz peatland by Lubicz-Niezabitowski (1922) and Korczyńska (1952) indicate that it was floristically rich and did not display significant changes in water relations caused by human activity. Its size has now decreased substantially, and the peat body has been fragmented (Koczur 1996). As a result of the associated changes in water relations, the first plant species and communities to disappear are those of the wettest habitats (primarily *Caricetum limosae*), which give way to *Molinio-Arrhenatheretea, Nardo-Callunetea* and *Epilobietea angustifolia* (Koczur 2004, Malec 2011). There are also potential repercussions for the role of the peatland in shaping the water level regimes of rivers (Lipka 2000) and for the balance of the natural habitat (Malec *et al.* 2016, Chlost & Cieśliński 2018).

Field survey

Characteristics of the edges of the peat domes were examined and mapped in the field on 10 November 2018, by using GPS devices to record coordinates. The devices used were hand-held Garmin GPS with maximum accuracy of 2 m, reached with averaging of measurement. Each section of the boundary between the domes and peat extraction areas was classified according to the description of peat-extraction scarp evolution described by Łajczak (2006), modified on the basis of field observations by adding two subtypes (for areas currently being exploited and scarps transformed by mass movements), to give a total of four classes:

1. Place of peat extraction (a: mechanical; b: domestic)
2. Steep slope at bog edge
3. Scarp transformed by mass movements (a: mass flow of peat; b: landslide)
4. Semi-natural border (poorly delineated or invisible boundary).

At poorly delineated or invisible edges, the extent of the bog was determined during the field study using an Instorf Russian pattern peat sampler (equipped with a 50 cm cylinder of 5 cm diameter), by making drillings on the semi-natural border with distance intervals of 10–20 m and a peat depth limit of 0.3 m (Miotk-Szpiganowicz *et al.* 2005).

Desk study

Spatial data on the courses of the dome boundaries was transferred to a Geographical Information System (GIS). During the work, both Quantum GIS and GRASS GIS software was used to compile a spatial database containing data collected in the field and three types of remote sensing source materials.

The first source material was the Airborne Laser Scanner (ALS) dataset from the Polish National ISOK Program (ISOK 2019). Data for the research area have been prepared to ISOK Standard I, i.e. with average point cloud density 4–6 m^{-2} and vertical accuracy up to 15 cm. The point clouds were used to generate two 1-m-resolution Digital Elevation Models (DEMs); the first based on bare terrain points only, and the second on bare terrain plus vegetation points (land cover DEM). The bare terrain DEM was used to derive Digital Terrain Models (DTMs) for slopes, aspect and shaded relief. On the basis of these models, a geometric correction and precise measurements of the dome remnants were made using ‘digitize’ and ‘vector attribute’ tools, then areas and shape index parameters for the mapped objects were derived. The shape index used here is the quotient of the object’s perimeter and the minimum possible perimeter of a geometric figure with the same area (Urbański 2011, Cybul *et. al.* 2018). Higher index values indicate a more complicated object shape, which may be the result of fragmentation caused by human impact. The extents of the peat extraction area and drainage channels were also mapped on the basis of the model. The channels are visible in the model as a network of roughly rectilinear interconnected ditches surrounding the bog and connected with adjacent watercourses. Then, by superposing the land cover DEM on the bare terrain DEM, a differential model of the height (stature) of the vegetation was produced. The distribution of vegetation height across the peat extraction area and peat domes was examined using raster analysis tools.

The second source material was the 2018 Orthophotomap of Poland (resolution 0.25 m), which we used as remote sensing data for photointerpretation of the vegetation cover on and around the bog. Data on vegetation types covering individual parts of the bog were obtained by photointerpretation (Barabach & Milecka 2013) combined with data from an investigation of the literature (Koczur 1996, 2004; Malec 2011) and field observations. In total, five types of vegetation were distinguished on the peatland:

1. Hummock-hollow complex
2. Wet grassland
3. Shrubs with juniper and *Pinus* spp.
4. Coniferous trees with *Pinus* spp.
5. Deciduous trees with *Betula* spp.

The third remote sensing source material was multispectral satellite imagery from the European Space Agency's Sentinel-2A mission (ESA 2019). The satellite scene was taken on 27 May 2018, at spatial resolution 10 m. Color Infrared composition (Sentinel's Bands 3,4,8) and Normalised Difference Vegetation Index (NDVI) were generated from these data, and used to assess vegetation condition (Prigent *et al*. 2001, Chen *et al*. 2002, Adam *et al*. 2010, Rastogi *et al*. 2018). NDVI portrays the variation in rate of photosynthesis in plant cover. It is calculated according to Carlson & Ripley (1997) as:

$$NDVI = [IR - RED] / [IR + RED] \qquad [1]$$

where IR is the infrared band multispectral channel bandwidth (Sentinel's Band 8) and RED is the red band multispectral channel bandwidth (Sentinel's Band 4). The values range from -1.0 to 1.0. Higher positive values of the index mean better condition and production of biomass in a given area.

The statistical significance of differences between the dome remnants and peat extraction areas - in terms of vegetation height distribution, vegetation types and NDVI index - was examined using the χ^2 test.

RESULTS

Dimensions of the peatland

The total area of Ludźmierz Bog, as measured in 2018, is 68 ha of which 39 ha is occupied by three peat domes separated from each other by peat extraction areas (Figure 3). The belt of peat extraction surrounding the domes covers 29 ha and its average width is 52 m. The geological drillings showed that the peatland border zone contains only an acrotelm, with no catotelm (which is commonly classified as the abiotic layer of a peat bog). The bog stretches east–west. The domes are similarly oriented and will be referred to hereafter as the west, middle and east domes.

The middle dome is the largest and occupies an area of 34 ha (Figure 3). The mechanical peat extraction has given it a complicated shape and a border length of over 5 km (Figure 3B). The shape index of this dome is 2.57, which is the highest value amongst the three study objects. The east dome is second largest. It covers 3.8 ha. It is roughly triangular as a result of past peat extraction (Figures 3A, 3B). The shape index of the east dome is 1.84, which is decidedly lower than that of the middle dome. The west dome is the smallest, at only 0.2 ha, and its shape index is 1.67. This dome and its peat extraction area are already isolated from the rest of the bog by a drainage ditch with flanking agricultural plots, and this isolation will probably cause the west dome to disappear completely in the future.

The steep dome edges are visible in the 1-m-resolution terrain model, both in the shaded relief model and in the slope map (Figure 3A). The east dome has a clear and distinctive edge along its entire length. The middle dome has visibly steep slopes, primarily on its northern edge. Here, the area of mechanical peat extraction makes a series of deep incisions into the peat dome. The west dome is least clearly distinguishable on the model (in places of minor peat extraction).

The primary (uncut) bog surface is distinguished by a prominent hummock-hollow system presenting as small topographical disturbances in the model. Arable fields surrounding the bog are visible on the model as a series of parallel, narrow plots separated by agricultural terraces. The plots have been levelled, and their low topographical diversity makes them stand out from the bog area in the model.

The dome–extraction area edge

The border between the dome remnants and the peat extraction area is visible in the 1-m-resolution DTMs, e.g. for slope (Figure 3A) and shaded relief. Individual edge types are listed in Table 1.

Peat extraction has extended much more deeply into the peat body from the north than from the south. Mechanical peat extraction occurred mainly in the western part of the middle dome (Figure 4A), whereas small-scale peat extraction areas were located mainly on the east dome. In total, extraction has taken place along more than one-third (34 %) of the peatland's circumference (Figure 4B). Evidence of mechanical exploitation is clearly visible in the ALS terrain model (Figure 3C).

The middle dome is thus transected by narrow strips of peat extraction. In the narrowest place, the distance between the southern boundary and the extraction wall to the north is currently 142 m (Figure 3). It is possible that peat extraction in this vicinity will eventually divide the domed peat body into two separate features.

Scarps in different stages of transformation by mass movements constitute 52 % of the total perimeter of the peat dome remnants (Figure 4). The east dome has a steep boundary around its entire circumference, and is the only object in the research area that can be completely delimited using the high-resolution ALS terrain model unassisted by other methods (Figure 3A). Steep escarpments up to 4–5 m in height are present along a quarter of the dome edges, and are especially visible on the east dome and on the north-western and north-eastern sides of the middle dome. Evidence of displacement of peat (flows/slips and landslides) was observed along a similar length (27 %) of dome perimeter (Figure 4B).

Only 14 % of the total length of dome edge is in a near-natural state with a relatively gentle transition at the border between dome and extraction areas (Figure 3B). This state was observed on two long sections, along the southern edge of the middle dome and on part of the west dome (Figure 4A).

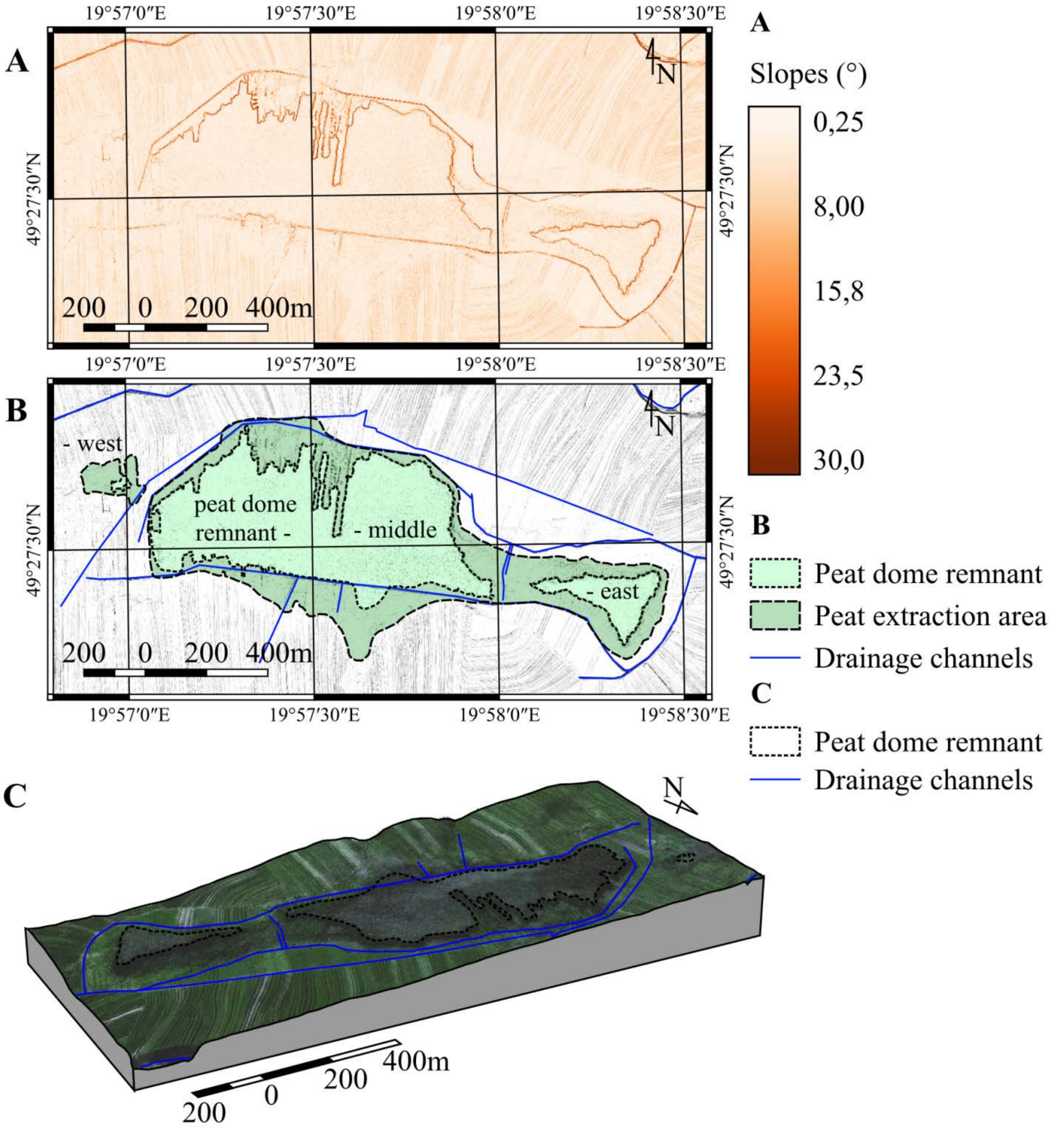


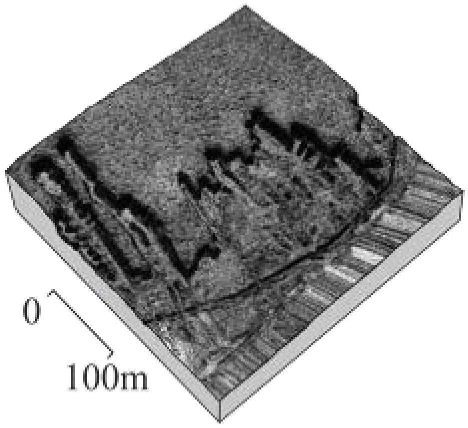
Figure 3. Ludźmierz Bog. A: slope map of study area; B: division of the bog into domes and cutover areas; C: 3D model of the study area showing natural colours.

Table 1. Edge typology of the Ludźmierz bog. The linear depressions visible in the terrain model are parts of a system of drainage ditches around the bog.

<table>
<tr><th>Edge type and subtypes</th><th>Description</th><th>Appearance (3D model)</th></tr>
<tr><td>Place of peat extraction:

1) mechanical peat excavation

2) domestic peat extraction</td><td>1) Excavation, visible traces of heavy equipment; broken water table; exposed vertical wall of peat across a large area.

2) Small disturbance or hole in the slope after extraction of a small amount of peat.</td><td>
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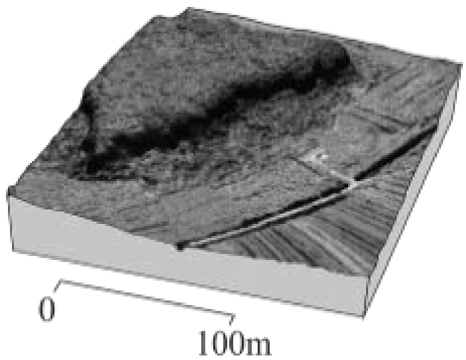
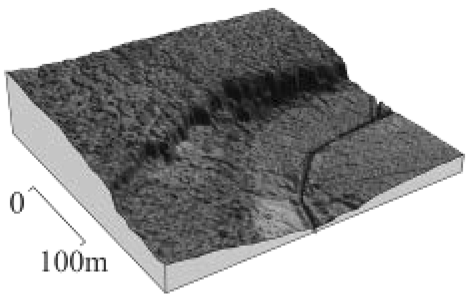
<tr><td>Scarp on bog edge</td><td>Visible steep slope up to 4 m high, thinly covered with vegetation; established on the boundary of an area of previous peat extraction.</td><td>
</td></tr>
<tr><td>Scarp transformed by mass movements:

1) flow of peat mass

2) landslide</td><td>1) Peat packages displaced down the slope, above some existing fissures.

2) Displacement of packages, creating a landslide circus and landslide tongue.</td><td>
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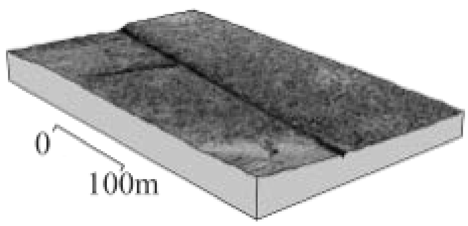
<tr><td>Semi-natural border</td><td>Bog border poorly outlined in the topography due to lack of extraction or disappearance of traces of extraction by natural processes; scarp lacking; near-natural state.</td><td>
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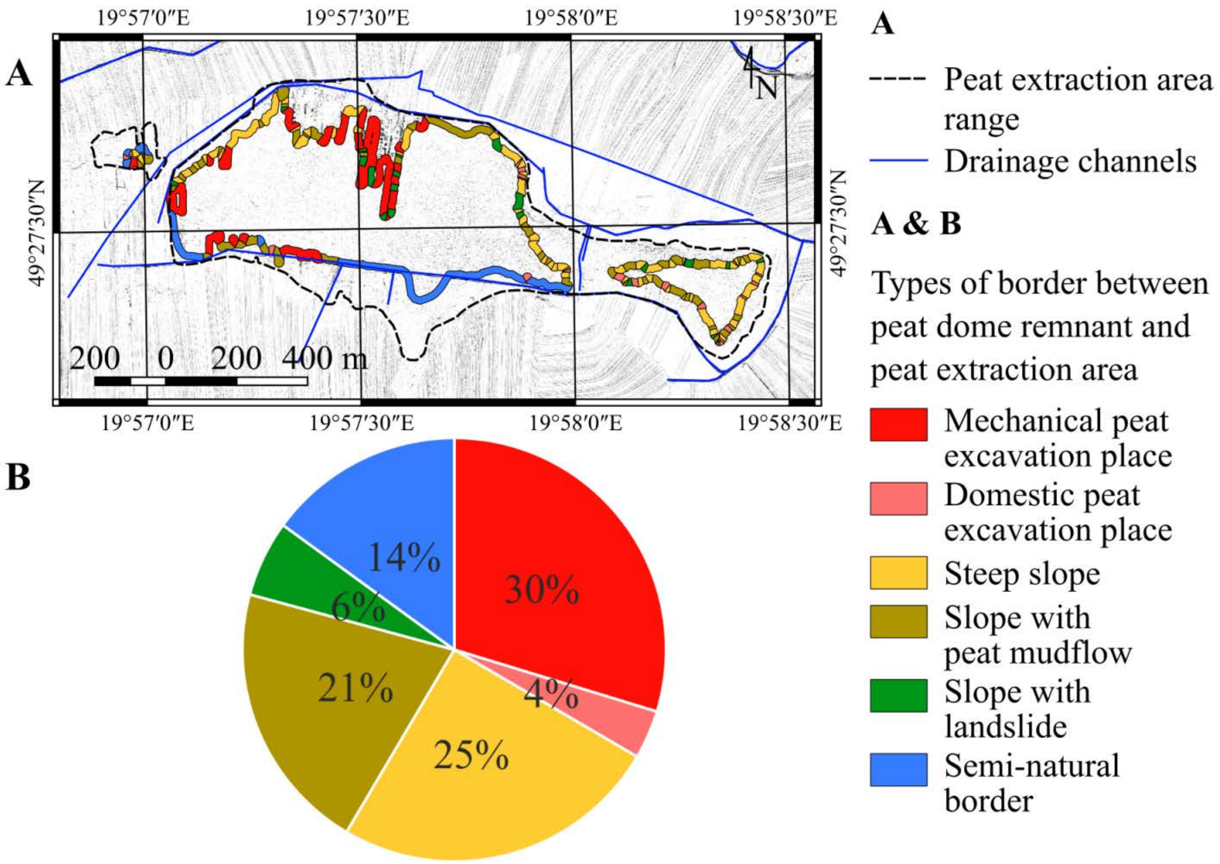

Figure 4. The borders between peat dome remnants and cutover areas. A: map showing the different types of border; B: diagram showing the proportions of different border types.

Vegetation characteristics

Hummock-hollow complex accounts for only 14 % of the vegetation cover of the peat dome remnants, occurring in the central part of the middle dome up to the boundary with the mechanically extracted area to the south (Figure 5). The largest part (more than 40 %) of the peat dome remnants is covered by dense wet coniferous forest consisting of bog pine and dwarf mountain pine trees up to 11 m in height (Figure 5A). Components of the coniferous forest cover are located in the western middle and eastern parts of the peat dome remnants. They also form a strip around the drainage channel that penetrates into the middle dome from the south. The south-west part of the middle dome is occupied by deciduous trees, which encroach onto the dome from the peat extraction area.

Compared to the dome remnants, a much smaller fraction of the peat extraction area is occupied by hummock-hollow complex, shrubs and coniferous trees (Figure 5). In the peat extraction area surrounding the dome remnants, there is a strip of birch grove up to 20–25 m tall, and deciduous trees correspondingly account for the highest percentage (> 40 %) of the vegetation cover. The differences in shares of individual vegetation types are statistically significant (χ^2 = 14.367; df = 4; p > 0.05). The 3D model shows a strip of tall vegetation surrounding the dome remnants (Figure 5A). The vegetation on the peat extraction area is on average 5 m taller than that on the dome remnants, especially due to the presence of tall deciduous trees. The differences in the distribution of vegetation height are statistically significant (χ^2 = 14.043; df = 4; p > 0.05).

The difference in plant cover between the dome and the peat extraction areas is also visible in the multispectral satellite imagery (Figure 6). The different vegetation types described in this article have different spectra on channels 4 (RED) and 8 (IR), as shown in the dependence graph (Figure 6B). The lowest reflectance of red and infrared wavelengths on the bog is from areas covered by conifers. Areas of deciduous trees have reflectance values that are low in the red range, but distinctly higher in the infrared range. The spectra of areas occupied by wet grasslands and shrubs partially overlap, with grass having a slightly lower infrared reflectance. Areas occupied by hummock-hollow system have high reflectance values in both the red and the infrared ranges.

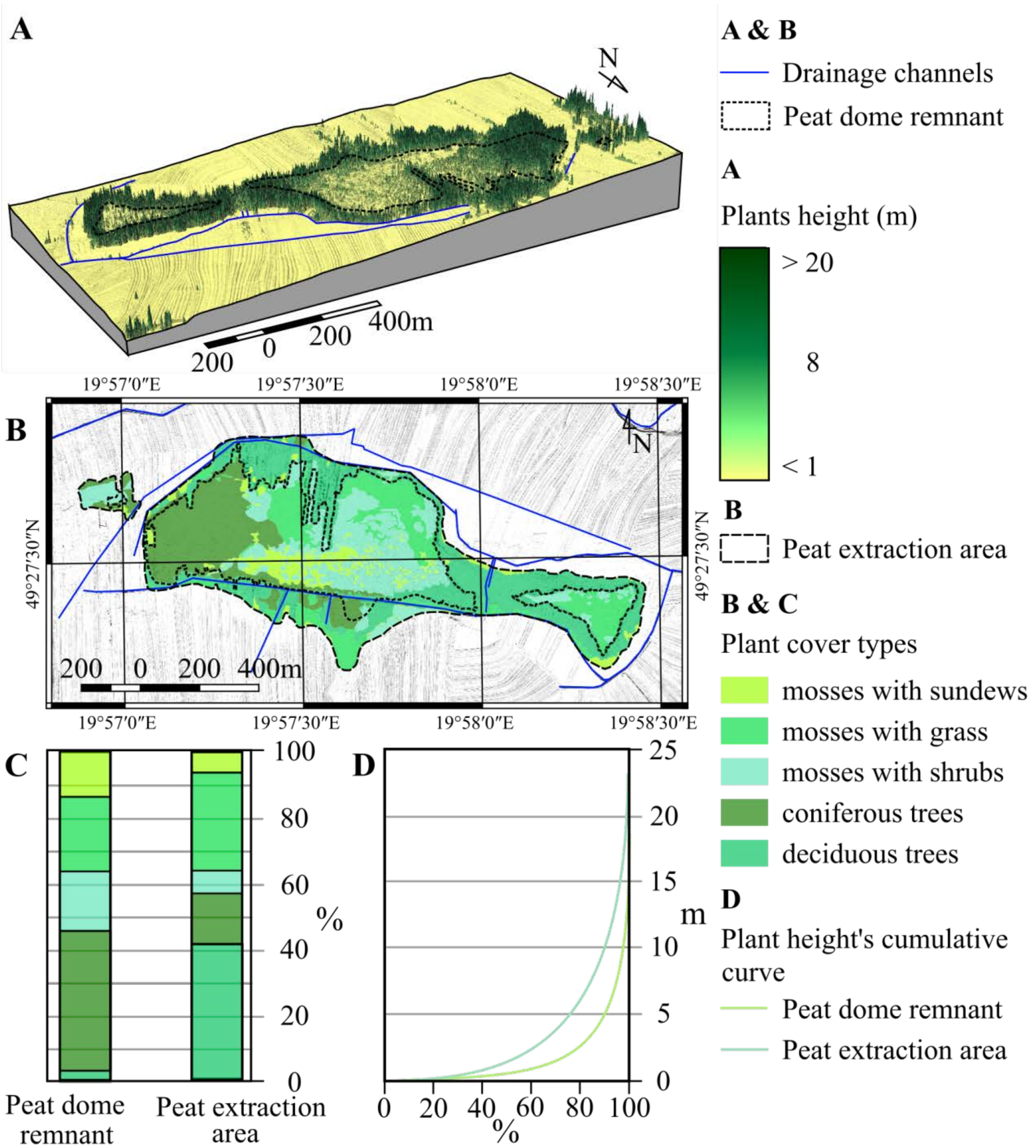

Figure 5. Characteristics of vegetation on the Ludźmierz bog from ALS data and the orthophotomap of Poland. A: differential model of vegetation height on the bog; B: vegetation types occurring on the bog; C: diagram showing the shares of different vegetation types on the dome and cutover areas; D: cumulative graphs of the relative (%) surface areas of domes and cutover occupied by vegetation of given stature (m).

The NDVI values calculated on the basis of RED and IR channels also differ between the domes and peat extraction areas (Figure 6D). The NDVI values are lower on the domes than on the peat extraction areas, by an average of 0.15 units. This difference is statistically significant (χ^2 = 17.023; df = 5; p > 0.05). The values of the index increase in the west and south-east parts of the middle dome remnant, due to the encroachment of trees into the dome area. The extent of the eastern dome is discernible because the NDVI values there are lower than in the peat extraction area.

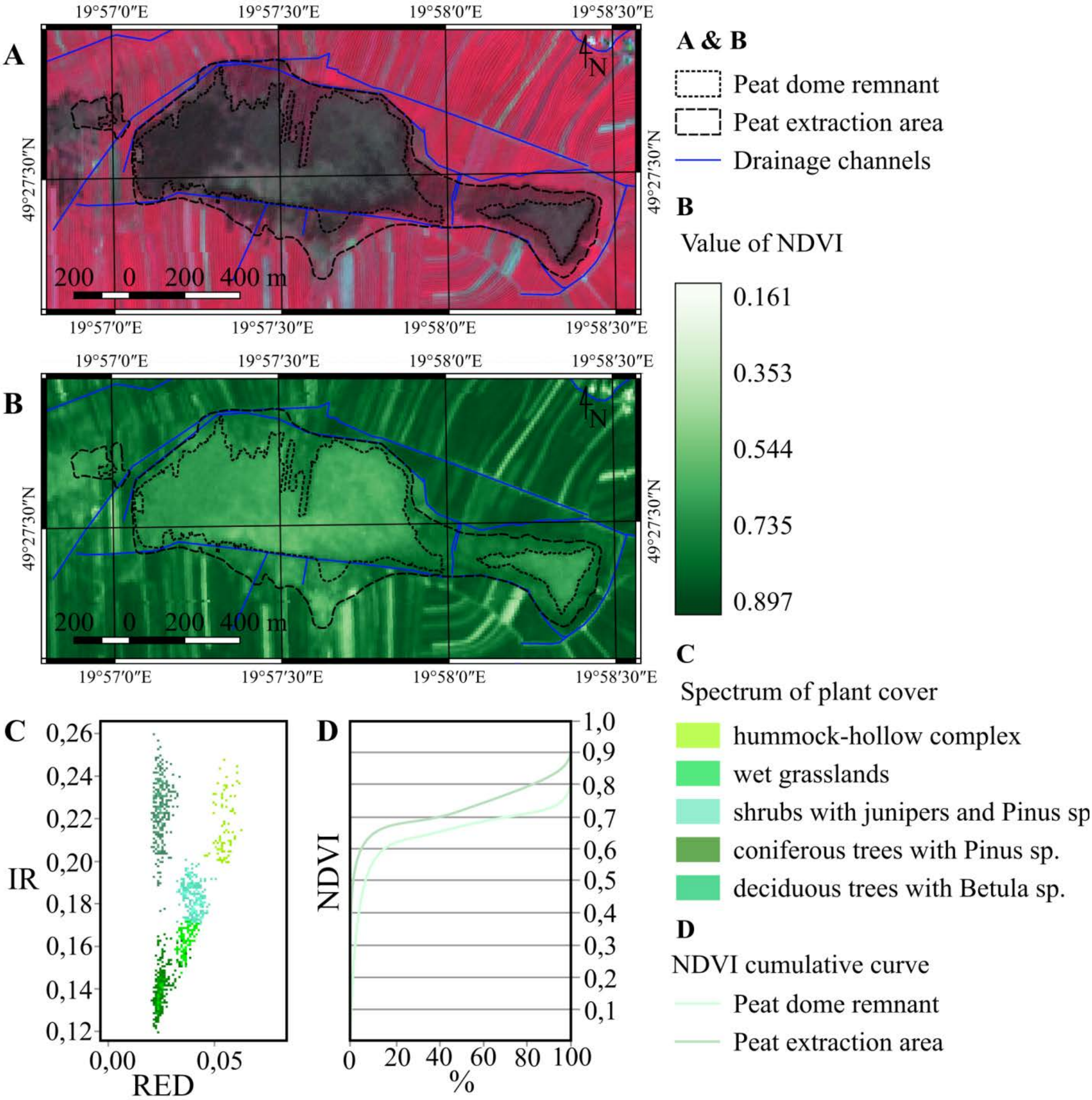

Figure 6. Vegetation characteristics on the dome from satellite data. A: Colour Infrared (CIR) satellite image of the study area; B: map of NDVI values; C: spectrum diagram of the vegetation types mapped in Figure 5B (bands RED and IR); D: cumulative curves of NDVI for the peat domes and peat extraction areas.

The development of vegetation and the shape of the slope at the boundary between dome remnant and peat extraction areas

Originally, the peat dome was unforested with a shallow water table (Figure 7A). Trees (mainly conifers) covered only the edges of the dome. Where exploitation preceded by tree felling is underway or has recently ended, a steep slope is formed (Figure 7B), at the foot of which there is outflow of water from the peat dome. The area of drained peat extraction areas around the drainage ditch is gradually being adopted as arable fields and meadows (Figures 7B–D).

The steepness of the dome-edge slope and the fact that is built of poorly bound material that readily absorbs water (i.e. peat) make the scarp unstable (Figure 7C). Mass movements begin relatively quickly, including peat creep or small flows onto the extraction area, and even landslides (with a landslide circus and tongue) on the slope. After a longer time,

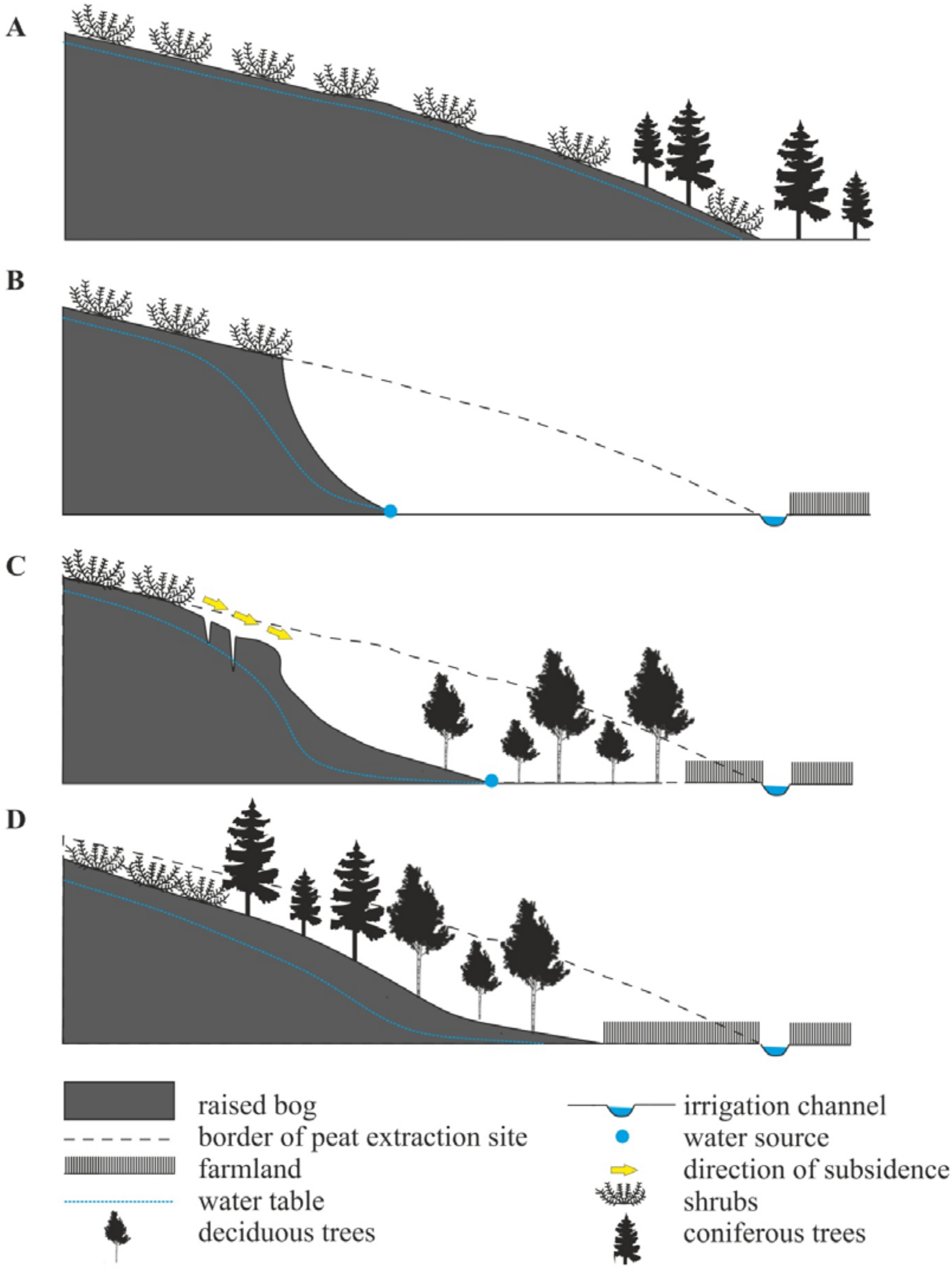

Figure 7. Schematic cross-sections of the transition between raised bog and cutover areas, before and after peat excavation (after Łajczak 2006, modified).

the edge at the new border of the peat layer becomes more stable, although it is steeper than in the natural state (Figure 7D). The lowered water table and reduced layer of peat cause shrubs and coniferous trees (dwarf mountain pine, bog pine) and birch to encroach onto the peat extraction area. As a result of the processes described above, aeration increases in the surface layer of the deposit and partial decomposition of organic matter takes place.

DISCUSSION

Peat extraction on the bog in Ludźmierz is ongoing. The area covered by peat has decreased by 7 ha since 2006 (Łajczak 2006) and by more than 100 ha since the earliest documented measurement in the literature, at the end of the nineteenth century (Lubicz-Niezabitowski 1922). There is a possibility of the middle dome being split further into two parts.

According to the review of the Polish cadastral map (Polish National Geoportal 2019), the western part of the bog had been parcelled into long, narrow plots. Peat extraction progresses along the boundaries of these plots, and this may cause another division of the middle dome remnant in the future. Elsewhere in the Orawa - Nowy Targ Basin, cases of complete removal of the bog dome and disappearance of the wetland area have been reported (Obidowicz 1988; Łajczak 2002, 2006; Koczur 2008).

High-resolution models derived from airborne laser scanning data provide unique information about relief microforms (Ackermann 1999, Franczak *et al.* 2016, Jucha & Marszałek 2016). The 1-m-resolution model used in this article allowed us to trace the network of drainage channels around the peat bog, as well as most of the boundaries of peat dome remnants. Drainage ditches are visible as shallow, linear, almost rectilinear depressions. Their courses are related to the topography of the area, and especially to slope and aspect. They are also connected to the natural watercourses in the vicinity of the bog. Their appearance differs from that of other linear features; for example, unmetalled roads are shallower and wider than drainage channels, and military trenches are not so straight and run independently of the slopes (Jucha *et al.* 2020).

It is also possible to map elements of a riverbed from ALS data, but interpretation is difficult or impossible to do when it is a slow-flowing watercourse or a water reservoir (Franczak *et al*. 2016). In our study area, small waterbodies can be formed in places where there is substantial water outflow from the dome, mostly associated with mechanical peat extraction (see Appendix). These objects are visible in the model as places with no ALS data, because the laser beam is strongly absorbed by the water column (Franczak *et al*. 2016, Jucha & Marszałek 2016, Jucha *et al*. 2020).

The boundary of the area of peat dome remnants, converted by peat extraction to a steep scarp, is shown as a line with high slope values. The part of this boundary examined during the field study is also mostly rectilinear and associated with a drainage ditch, suggesting that peat extraction was carried out here in the past, probably before the period of mechanical exploitation (Mirska 1956).

The extent of remnant peat dome mapped using field survey and ALS data, as well as its boundary with the peat extraction area, is also visible in the orthophotomap and satellite scene due to differences in vegetation cover. The birch grove surrounding the peat dome remnants is the result of natural vegetation succession across a drained area after peat removal, rather than artificial planting (Barabach & Milecka 2013). The ground in the peat extraction area can be stable enough to allow trees to grow to more than 20 m in height.

According to Malec (2012) and Sikora & Cieśliński (2017), an increase in diversity of ground plant cover in wetland ecosystems indicates variable humidity conditions on a given site. Hummock-hollow complex (the most typical vegetation type for raised bog in good condition) occurs only in a small part of the middle dome, which is also characterised by very low biomass growth according to NDVI values (Carlson & Ripley 1997, Adam *et al*. 2010). However, the study reported here uses only one satellite scene captured during the transition from spring to summer. Rastogi *et al.* (2018) recommend caution in drawing conclusions about the health of wetland vegetation from remote sensing differential indices (such as NDVI) and time series studies. Nevertheless, it is possible to see and map the boundary between dome remnant and peat extraction areas on the basis of NDVI. This suggests differences in vegetation condition reflecting disadvantage to the plants growing on the dome remnants.

In order to maintain or reinvigorate the peat-forming process and improve hydrological conditions for the development of peat-forming vegetation on the bog, it is necessary to stop peat extraction and land drainage (Obidowicz 1977, Denisiuk & Pioterek 1990). For example, the degree of degradation at the nearby Baligówka peatland has necessitated the reintroduction of peat-forming species in areas that have become extremely over-desiccated and dominated by alien vegetation or entirely denuded (Malec *et al.* 2016).

The thickness of the moorsh layer does not exceed 10 cm regardless of slope mass processes; while in the case of landslides and mechanical peat extraction areas, there is a transitional level of prismatic structure in which the peat breaks down into lumps and aggregates. This is a disadvantageous phenomenon, especially in the context of climate change, as it intensifies evapotranspiration and the occurrence of extreme phenomena, among other processes which are very important in the development of wetlands (Brinson 1993, Rastogi *et al.* 2019).

Signs of renewal of the peat-forming process, in the form of hummock-hollow microtopography, are visible in the peat extraction areas, as observed during the field study (Appendix 2). This phenomenon is partly caused by the large inflow of water from the undercut peat dome (Chlost & Cieśliński 2018, Lipka & Zając 2018).

Although attempts to establish environmental protection for some or all of the bogs in the Orawa

Nowy Targ Basin have been ongoing since the 1920s (Lubicz-Niezabitowski 1922), the only peat bog nature reserve in Kotlina – "Bór na Czerwonem" was established in 1925 (Staszkiewicz & Szeląg 2003, Tobolski 2012). Despite the negative changes described in this article, the peat bog in Ludźmierz remains a floristically rich ecosystem that could also be protected (Denisiuk & Pioterek 1990, Koczur 1996, Cichocki 2004).

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AUTHOR CONTRIBUTIONS

WJ made the GIS spatial analyses and the Figures containing maps. He also wrote the Methods, Results and Discussion in collaboration with PM, who made the non-GIS Figures. DO wrote the Introduction and the description of the development and previous studies of peatlands in the Orawa - Nowy Targ Basin.

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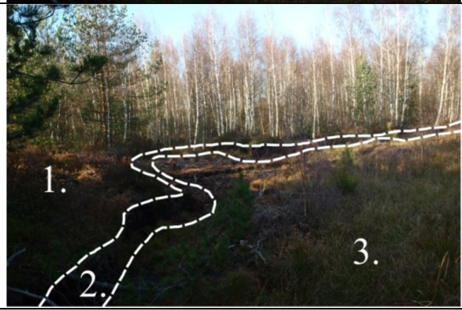
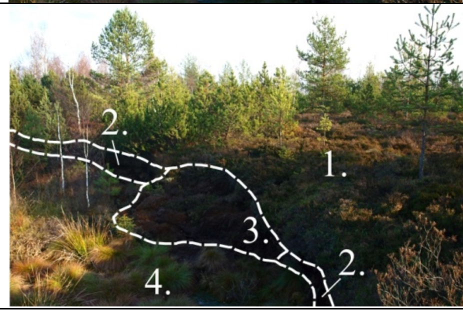
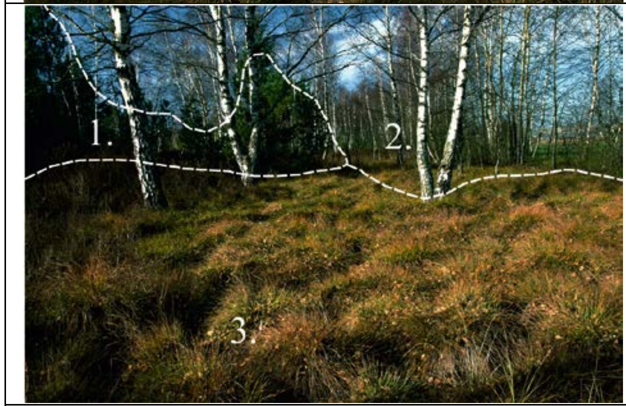
Appendix

Figure A1. Photographic documentation of types of border between dome and peat extraction area.

Place of peat extraction	**Steep slope at bog edge**	**Scarp transformed by mass movements**	**Semi-natural border**
			
			
1. Peat dome. 2. Close up to vertical peat mining wall. 3. Peat extraction area with footprints of excavator and water outflow from the dome.	1. Peat dome. 2. Steep scarp. 3. Peat extracton area.	1. Peat dome. 2. Steep scarp. 3. Landslide at bog edge. 4. Peat extraction area.	1. Peat dome. 2. Peat extraction area (D. Okupny and W. Jucha standing at the border). 3. Out of peat bog area.

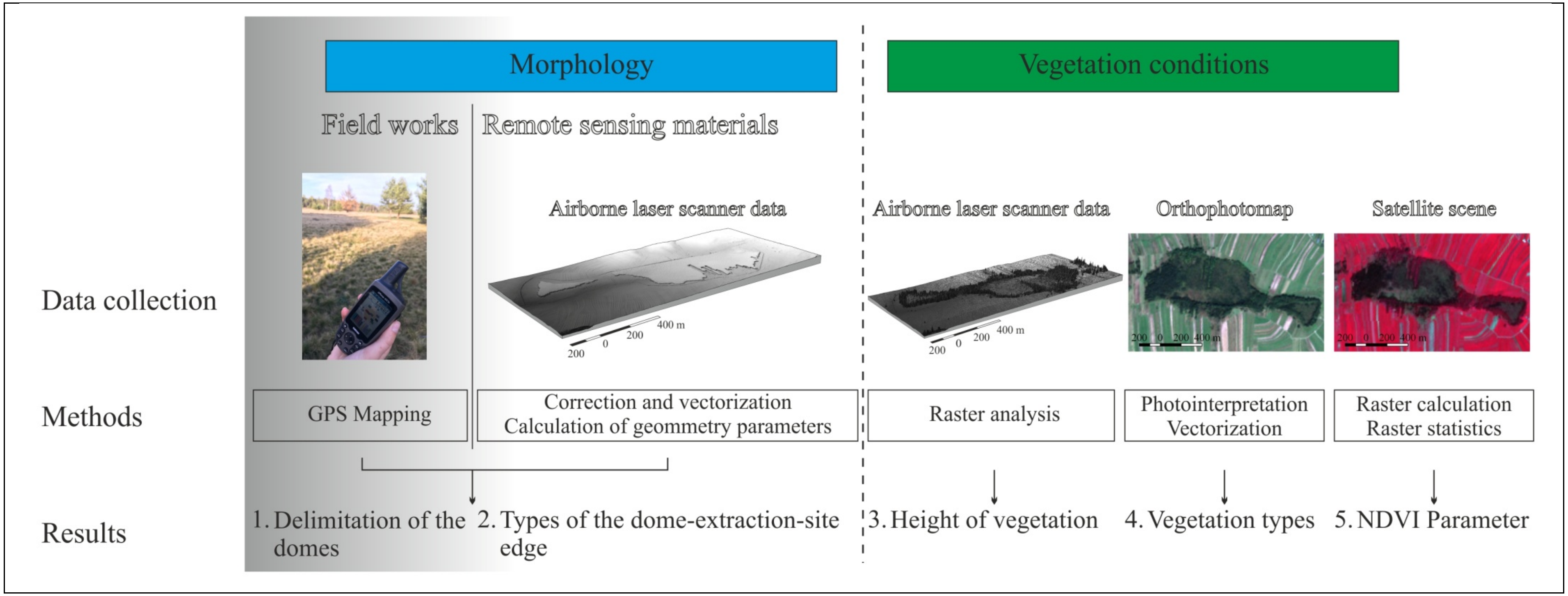
Photos by J. Karaś and W. Jucha, 2018.

Figure A2. Photographic documentation of vegetation types on domes, peat extraction areas and the border between dome and peat extraction area (examples).

<table>
<tr><th>Border between dome and peat extraction area</th><th>Deep incision into the middle dome</th><th>Renewing vegetation on the dome</th></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>1. Mountain pine trees on the peat dome.
2. Birch grove on the peat extraction site.
3. Renewing vegetation on the peat extraction site (hummocks and hollows of the modern peatland).</td><td>1. Mountain pine trees and junipers on peat dome.
2. Renewing vegetation on the peat extraction site.
3. A: reed; b: water table in small reservoir (water outflow from the dome).
4. Birch grove on the peat dome.</td><td>1. Renewing vegetation (hummocks and hollows of the modern peatland).
2. Non-bog vegetation entering the dome.</td></tr>
</table>

Photos by J. Karaś and W. Jucha, 2018.

Figure A3. Scheme of fieldwork and desk studies contributing to the article.



Own elaboration.