

Identification of forest ploughing traces in the soils of the Soil Reference Area in the Osie Forest District, northern Poland, based on LIDAR data analysis

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Abstract

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Network of GPW (Soil Reference Areas, in Polish: Glebowe Powierzchnie Wzorcowe) is a form of soil protection in Poland, initiated in 1975 by the Soil Science Society of Poland and the Polish State Forests. Currently, 135 such areas operate in Poland, but they have not been properly monitored for a long time, and their condition in most cases remains unknown. The lack of studies and the extensive form of protection are causing controversy among foresters, who are faced with management restrictions on forest areas covering several hundred hectares. The aim of this study is to assess the current soil condition of Soil Reference Area located in the Osie Forest District, northern Poland, and in particular, the soil surface distortions resulting from soil preparation for stand planting (forest ploughing), based on remote microrelief analysis (LIDAR data and GIS tools), photointerpretation of available orthophotomaps and fieldwork. The minimum curvature interpolation method and an attempt to identify correlations between the visibility of ploughing traces and stand age were applied. Three classes of soil surface condition were established with respect to the presence of traces of forest ploughing: no marks, faint marks, and clear marks. This method enabled precise identification of the most severely plough-affected sections of the GPW. Ploughing traces were identified on 43% of the entire GPW, most of which are located under stands planted during the GPW's existence. The least transformed areas are located under the oldest forest stands.

1. Introduction

In the Polish nature conservation system, very little attention has been paid to the protection of soil resources. Among the sites covered by various forms of legal protection listed in the Nature Conservation Act (Ustawa o ochronie przyrody, 2004) there are only two soil reserves (out of 1,694) and two documentation sites (out of 195) dedicated directly to soils (Internet source 1). In this context, the creation of a network of Soil Reference Areas (in Polish: Glebowe Powierzchnie Wzorcowe – GPW) in areas managed by the State Forests (National Forest Holding) should be considered particularly valuable. The GPW network comprises 137 areas distributed more or less evenly across the country, covering approximately 1% of Poland's forest area (Prusinkiewicz, 1986). Soil Reference Areas were established in 1975, pursuant to a decree of the Supreme Board of State Forests, in response to the growing intensification of forest management (Prusinkiewicz et al., 1977). The purpose of the Reference Areas was to “protect soils representing typical soil cover elements for a given region (district) as fully

as possible against artificially induced changes in morphology and physical, chemical, and biological properties” (Prusinkiewicz, 1975). According to the decree, the Soil Reference Areas should: cover areas of at least 300 hectares; be approximately square in shape; include stands of all age classes; and represent habitats typical of the region. Only shallow tillage may be used, and water melioration should not be used. The physical, chemical, and biological properties of soils should remain intact (Prusinkiewicz, 1975).

After selecting the protected areas, the next step in establishing the GPW network was to prepare dedicated soil and habitat maps, which would serve as a source of detail information on soil cover, excavated soil pits, and management characteristics for each site. The first and only such study was prepared for GPW located in the Osie Forest District (Komen-darczyk, 1988). Currently, all areas have soil and habitat documentation in accordance with the standard used in other forest areas (Forest Management Instruction, 2023). Since the establishment of the GPW network, scientific research has been conducted sporadically, on single sites (Chojnicki et al., 2021,

Chojnicki et al., 2025, Zielony, Chojnicki, 1996). The matter of GPW was forgotten at the turn of the 1980s and 1990s, receding into the background of forest management (Zielony, Chojnicki, 1996). Since then, these areas have been unmonitored and their condition is largely unknown. Due to the lack of studies and the extensive form of their protection, Soil Reference Areas have become controversial and problematic for foresters, who are restricted in their management practices over areas of several hundred hectares.

Due to the poor recognition of most Soil Reference Areas and the lack of control over their actual state, there is a need to analyze them in terms of the condition of the soils and verify whether they still meet the primarily established protection criteria. The aim of this study is to assess the current condition of soils of Soil Reference Area located in the Osie Forest District, and in particular, the soil surface distortions resulting from soil preparation for tree planting (forest ploughing), based on remote analysis of the terrain's microrelief and interpretation of available orthophotomaps. The intended outcome of this work is to identify parts of this reference soil area that have been transformed to varying degrees and those with preserved natural microrelief.

The need to "resurrect" the idea of GPW and modify the management practices conducted there was emphasized by Zielony and Chojnicki (1996). Despite the passage of time, they constitute a very important element of soil protection and the entire nature conservation system in Poland, as well as a form of soil protection unique worldwide (Kowalkowski and Prusinkiewicz, 1976).

2. Study area

The studied Soil Reference Area is located within the Osie Forest District, Regional Directorate of the State Forests in Toruń, in Świecie County in the northern Kuyavian-Pomeranian Voivodeship (Fig. 1). According to the physiogeographic regionalization (Solon et al., 2018), the study area is located within the Tuchola Forest mesoregion (314.71). The lithology of the GPW in Osie is dominated by outwash loose sands of the Upper Vistulian Glaciation. In the central part, there is an elongated moraine island composed of eluvial silty sands and outwash sands overlying loamy glacial till (Szczegółowa Mapa Geologiczna Polski 1:50,000, Osie sheet, 2009). The terrain is relatively morphologically diverse. The moraine island is elevated several meters above the surrounding outwash plain. The surface of both, moraine and outwash plain, is diversified by small, irregular dead ice melt depressions (Filbrandt-Czaja, 2009). The sandy sediments of the study area are dominated by rusty soils, while the moraine island is dominated by clay-illuviated (lessive) soils (Komendarczyk, 1988). According to the climatic regionalization of Poland by Okołowicz and Martyn (1979), the study area is located in the Vistula River region, with the average annual temperature approximately 7.7°C (Araźny and Strzyżewski, 2018), and the average annual precipitation 550 mm. The GPW in the Osie covers a total area of 336 ha. GPW lies entirely within Natura 2000 protected areas and the Wdecki Landscape Park. It is also surrounding the Brzęki Nature Reserve named after Zygmunt Czubiński. The study area is currently uninhabited. However, in the past, this area was

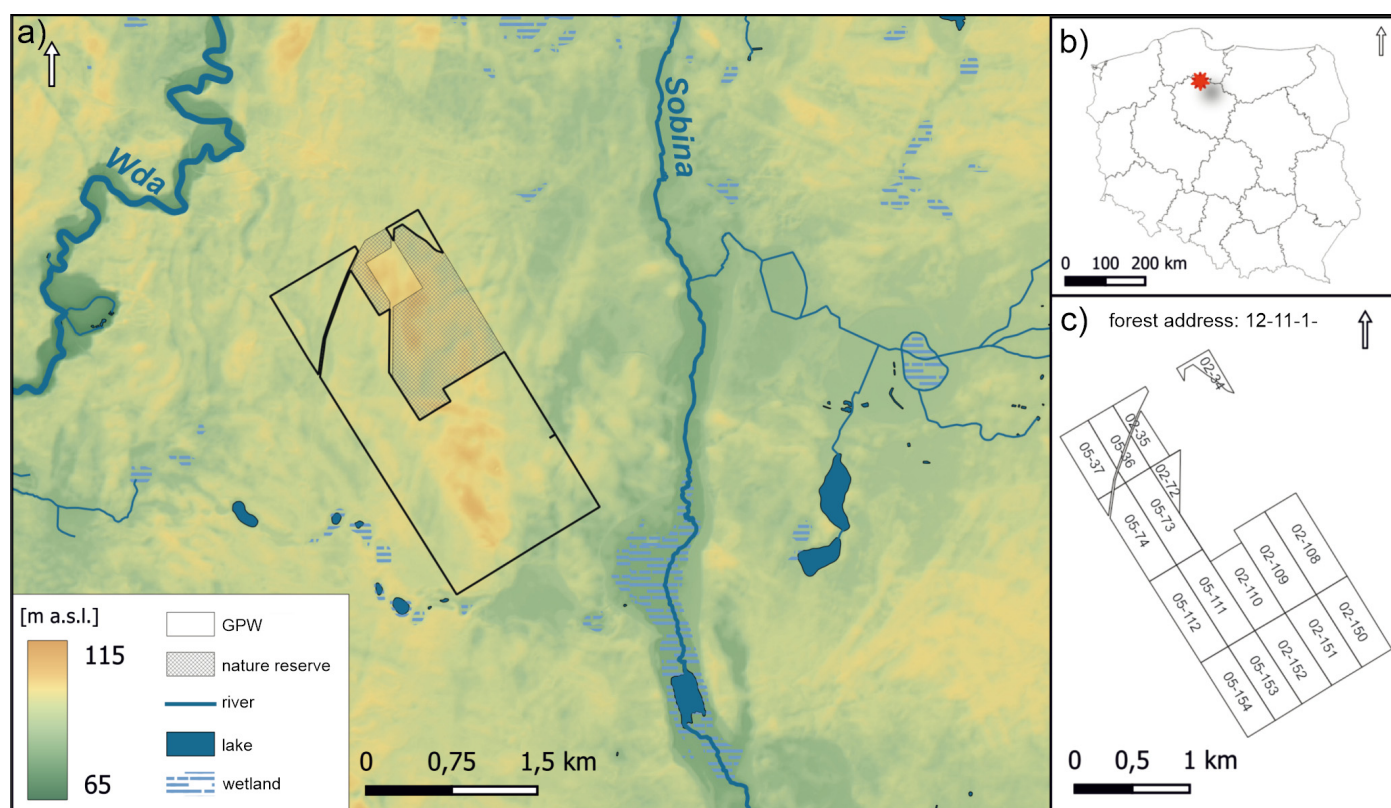


Fig. 1. Location of the GPW in the Osie Forest District: a) in local topography, b) in Poland, c) in spatial registry system of National Forests

used by humans, as evidenced by numerous archaeological features. Confirmed finds include, among others, the remains of a settlement of Goths who inhabited these areas during the Roman Period and the remains of the so-called Celtic fields system with well-preserved balks (Basista et al., 2023; Sosnowski et al., 2019, 2023).

3. Materials and methods

Basic data were provided by the Regional Directorate of State Forests in Toruń and the Bureau for Forest Management and Geodesy State Enterprise. They were obtained in vector format (shape files) containing information on the administrative division boundaries of the State Forests and Soil Reference Areas. ALS point files downloaded from the national Geoportal (Internet source 2) in LAZ format in sheets at a scale of 1:10,000 were the basis for the soil surface microrelief analysis. The obtained point clouds have a spatial characteristic of 4 points per square meter, a mean height error of 0.15, and a mean position error of 0.50. Their elevation system is PL-KRON86-NH and is current as of 2012. Initial processing and reclassification of the point clouds, aimed at extracting information about the terrain,

was performed in SAGA GIS (Fig. 2). The obtained data were reformatted into a grid format. To eliminate gaps (empty values in areas without measurement points), the “close gaps” tool was used, which uses the interpolation method between adjacent points. A raster was generated from the prepared data in two variants:

1. by creating a shaded terrain model with standard parameters (azimuth 315° and elevation 45°), which served as a base layer in subsequent analysis;
2. by applying the minimum curvature method, whose algorithm enables the detection of fine-grained terrain features, including traces of forest ploughing (Basista et al., 2023). The interpolated surface thus created resembles a thin, linearly elastic plate, passing through all data values with minimal bending (Yakar et al., 2010). This method generates the smoothest possible surface while simultaneously representing the data as accurately as possible (Bogusz et al., 2014).

The resulting rasters were exported from SAGA GIS and opened in ArcGIS Pro. A raster with the appropriate symbolization (red colour representing index values of minimum curvature above 0.1 and neutral pale representing values below -0.1 to enhance visual contrast) from the minimum curvature

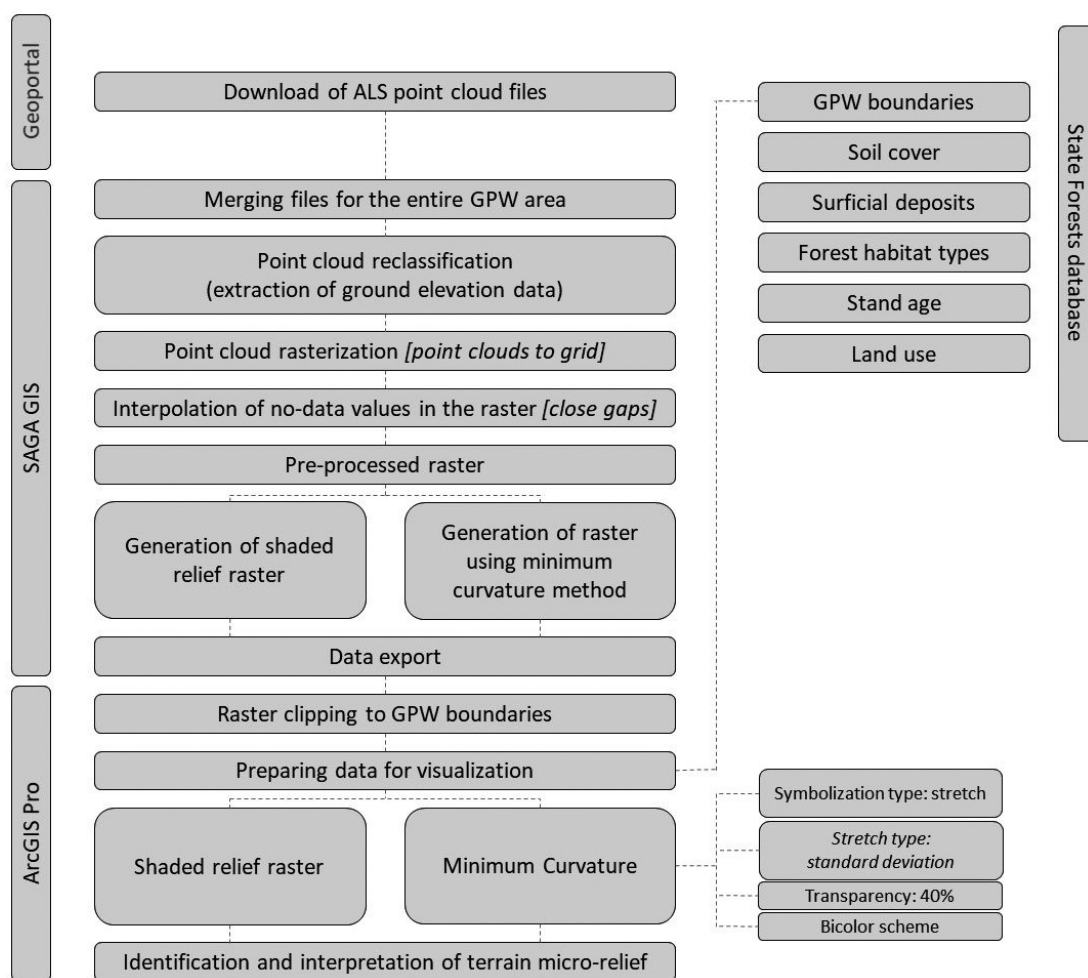


Fig. 2. Methodological procedure for preparing rasters for analysis

interpolation method and a 40% transparency was overlaid on the shaded terrain model layer. The resulting dataset clearly highlights the areas affected by ploughing, which appear as clusters of parallel red lines in the raster image. This method works best in areas without steep slopes (Erdede and Bektas, 2020). The values generated by the algorithm for individual pixels should be interpreted as follows: positive values indicate the presence of convex forms, values close to 0 indicate flat forms, while negative values are typical of concave forms (Conrad, 2013).

The developed rasters were first analyzed for differences in the character of microrelief depending on the age of the stand. The stands were divided into eleven age classes (taking into account the validity of the previously developed point cloud): 0–10, 11–20, 21–30, 31–40, 41–50, 51–60, 61–70, 71–80, 81–90, 91–100, 101+ and 5 test squares with sides of 50 meters were designated within each age class. A linear shape was drawn through the squares, running perpendicular to any ploughing traces, based on which linear graphs were created, which were also cross-sections of the given area. These cross-sections were used to characterize the density and amplitude of surface microrelief variations represented by furrows and ridges. Basic statistical parameters (mean, minimum, maximum, and standard deviation) were calculated for all 55 plots. Differences in standard deviation values between the analyzed groups were assessed using the non-parametric Kruskal-Wallis test. Significant differences were further examined using Dunn's post-hoc test with Bonferroni correction ($p < 0.05$). Comparative analysis of the obtained rasters, graphs and statistical parameters showed that the transitions between the 10-year age classes of the stands were relatively smooth. Therefore, soil surface distortions caused by ploughing were divided into three classes defined as: 1. clear ploughing marks, 2. faint ploughing marks, and 3. no ploughing marks. The threshold values for the three classes were determined based on statistical data analysis (Jenks natural breaks method) and are therefore presented in the Results section. The generated set of rasters was vectorized to cover the entire Soil Reference Area with three classes of ploughing marks visibility. Data continuity was supplemented by an analysis of orthophotomaps from 2013–2025, conducted to identify areas cleared and ploughed after 2012 for which ALS data were not obtained.

The final stage of the work was field verification of the obtained results. Fieldwork involved digging a total of 45 soil pits distributed on the entire GPW area, exposing the morphology of the upper soil layers to a depth of 40–50 cm. The pits were located in zones representing designated ploughing visibility classes. Indicators assessing the scale of soil morphology transformation included the visibility of ridges and furrows, the height differences between the ridge and the furrow, and the degree of mixing of the surface soil horizons. The pit locations were determined using a GPS device and integrated with the distribution of ploughing visibility classes to compare the actual ground surface condition with visualizations obtained using the remote sensing method (minimum curvature).

4. Results

4.1. Relationship between the degree of soil surface distortion and stand age

Analysis of the visibility of ploughing marks in 10-year age classes of stands in GPW revealed a correlation between microrelief and tree age (Fig. 3). The younger the stand, the more visible the signs of forest ploughing. Over time, these signs become blurred. The transitions between successive 10-year age classes are smooth and not distinct enough to be clearly distinguished. There are no significant differences between stands in the youngest age classes, ranging from 1 to 50 years old, and ploughing marks are equally distinct and easily identifiable in visual analysis. In stands aged 51–60 and 61–70 years, the ploughing marks are significantly discontinuous, but still identifiable. The subsequent stand age classes, 71–80, 81–90, and 91–100 years old, show either very faint or complete absence of ploughing traces, indicating the disappearance of this microform of topography or that no soil preparation procedures were applied. The area under the 100-year-old and older stands is devoid of any traces of forest ploughing and, for analysis purposes, can be treated as a single, large age group.

The disappearance of traces of forest ploughing with stand age is also clearly visible in cross-sections of the analyzed fields representative of each age class. The values of the minimum curvature parameter, located on the vertical axis, show large fluctuations (from 0.0 to –0.5 interpolated units) with a fairly regular frequency in the youngest age classes (up to 50 years). This indicates the occurrence of repetitive, concave landforms, very close together, representing furrows created by ploughing. In subsequent stand age classes, a decrease in the amplitudes (from 0.0 to –0.3) achieved by the cross-section line and a decrease in their regularity are visible. This, in the oldest stands, leads to the curves almost flattening out and oscillating close to 0. This indicates a gradual disappearance of terrain irregularities in the form of the levelling of ridges and furrows.

4.2. Classification of the visibility of forest ploughing marks

Changes in the surface microrelief made for eleven 10-year age classes of stands were confirmed by statistical analysis. Significant differences in standard deviation (SD) values were observed among the eleven stand age classes (Kruskal-Wallis test: $\chi^2 = 41.603$, $df = 10$, $p < 0.001$). Post-hoc Dunn's test identified significant differences between the 0–10 and 101+ age classes ($p = 0.017$), 11–20 and 101+ ($p = 0.011$), 21–30 and 101+ ($p = 0.002$), and 21–30 and 81–90 ($p = 0.048$) (Fig. 4). However, smooth differences among the eleven stand age classes allowed the identification of three more general classes of the visibility of forest ploughing marks: no marks; faint marks; clear marks. The thresholds were defined using the Jenks natural breaks method applied to mean minimum curvature standard deviation (SD) values in R software (Table 1). No marks were characterized by the absence of regular linear patterns on the soil

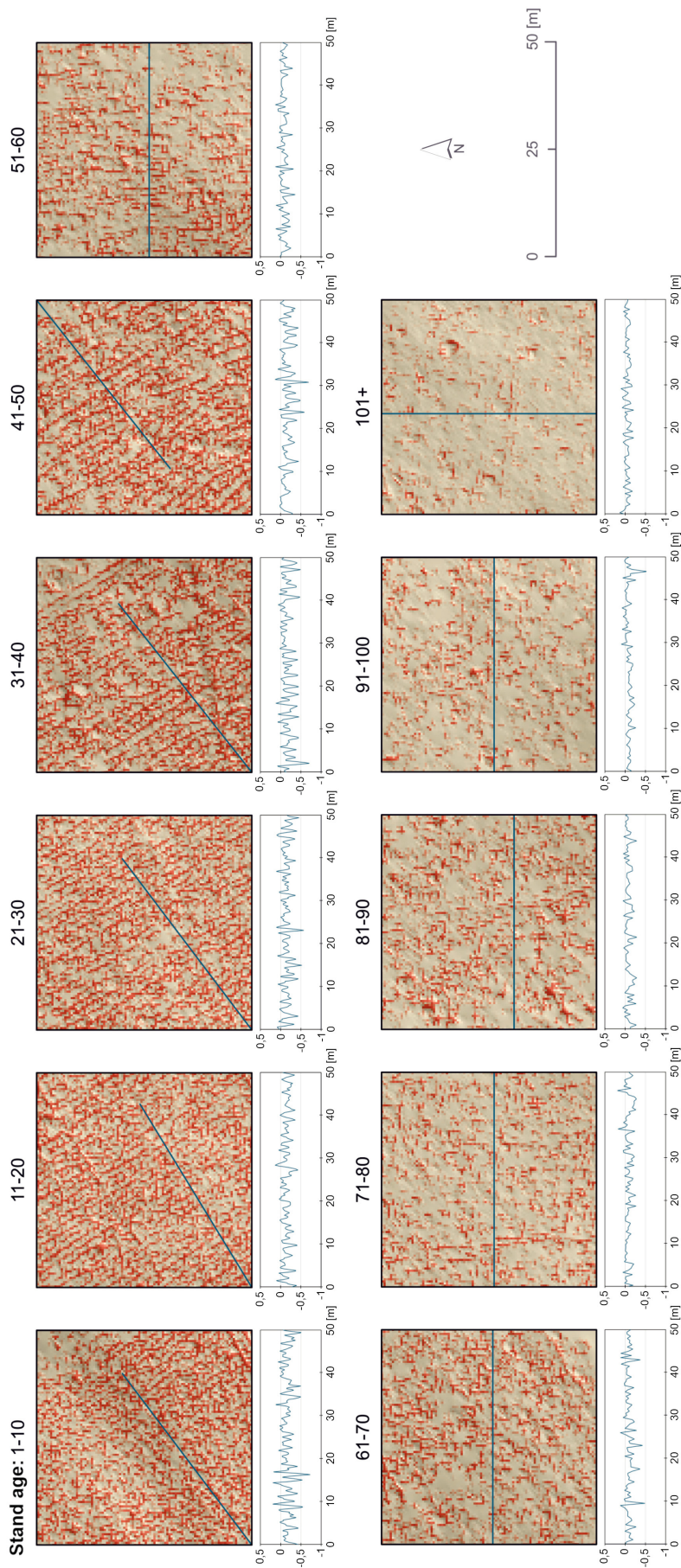


Fig. 3. Characteristics of the terrain microrelief with cross-sections visualized using the minimum curvature method in 10-year stand age classes in the GPW area of the Osie Forest District

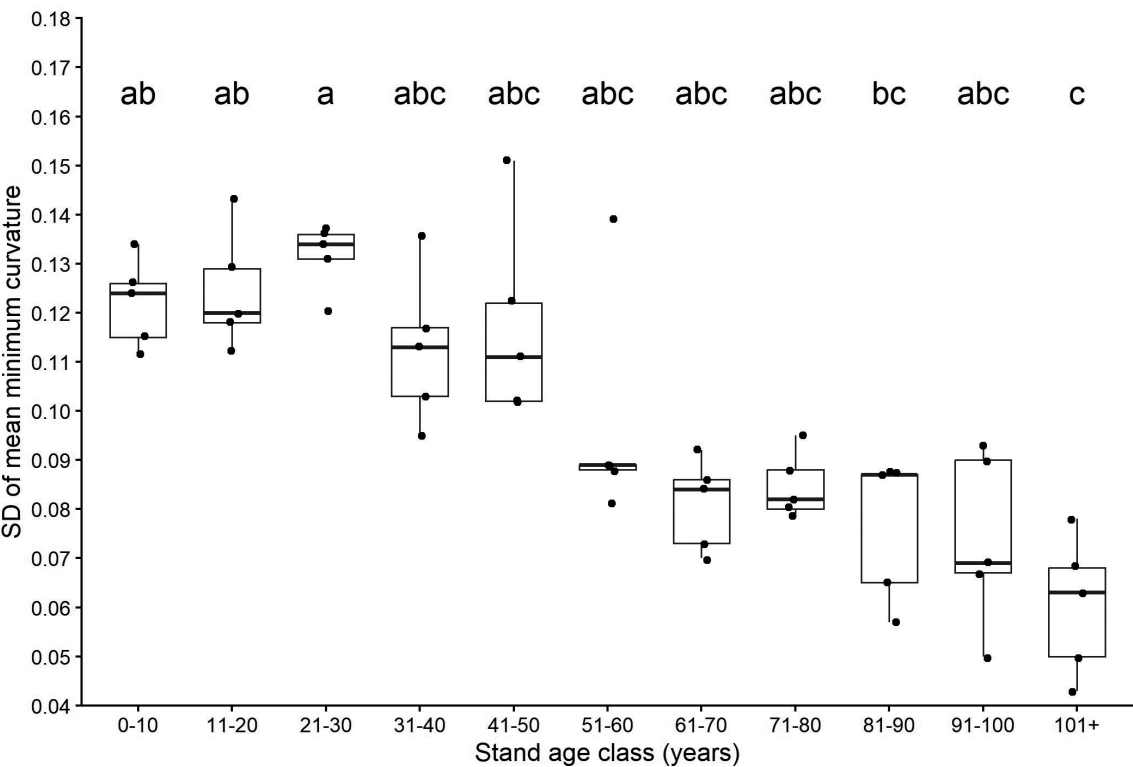


Fig. 4. Standard deviation of mean minimum curvature across stand age classes. Boxes represent the interquartile range, horizontal lines indicate medians, and individual points represent observations. Different letters indicate homogeneous groups based on Dunn's post-hoc test with Bonferroni correction ($p < 0.05$)

surface and $SD < 0.08$; faint marks by discontinuous parallel red linear marks and $SD = 0.08\text{--}0.1$; and clear marks by distinct parallel red lines and $SD > 0.1$. The three ploughing mark visibility classes differed significantly in SD values (Kruskal-Wallis test: $\chi^2 = 47.272$, $df = 2$, $p < 0.001$). Post-hoc Dunn's test confirmed significant differences between these three classes:

no marks vs. faint marks ($p = 0.010$), no marks vs. clear marks ($p < 0.001$), and faint marks vs. clear marks ($p < 0.001$) (Fig. 5). Based on a raster containing the results of the minimum curvature method applied to a shaded terrain model (Fig. 6a), the analyzed GPW area was vectorized to identify areas belonging to these three classes (Fig. 6b).

Table 1
Statistical characteristics of minimum curvature profiles for 11 stand age classes, with standard deviation values indicating microrelief variability (Kruskal-Wallis test, $p < 0.001$).

Stand age class (years)	Min	Max	Mean	Standard deviation
1–10	–0.704	0.247	–0.147	0.122
11–20	–0.617	0.185	–0.158	0.124
21–30	–0.718	0.324	–0.151	0.132
31–40	–0.731	0.234	–0.136	0.113
41–50	–0.619	0.199	–0.124	0.118
51–60	–0.700	0.207	–0.111	0.097
61–70	–0.479	0.167	–0.097	0.081
71–80	–0.524	0.302	–0.098	0.085
81–90	–0.712	0.227	–0.079	0.077
91–100	–0.503	0.242	–0.081	0.074
101+	–0.444	0.176	–0.074	0.060

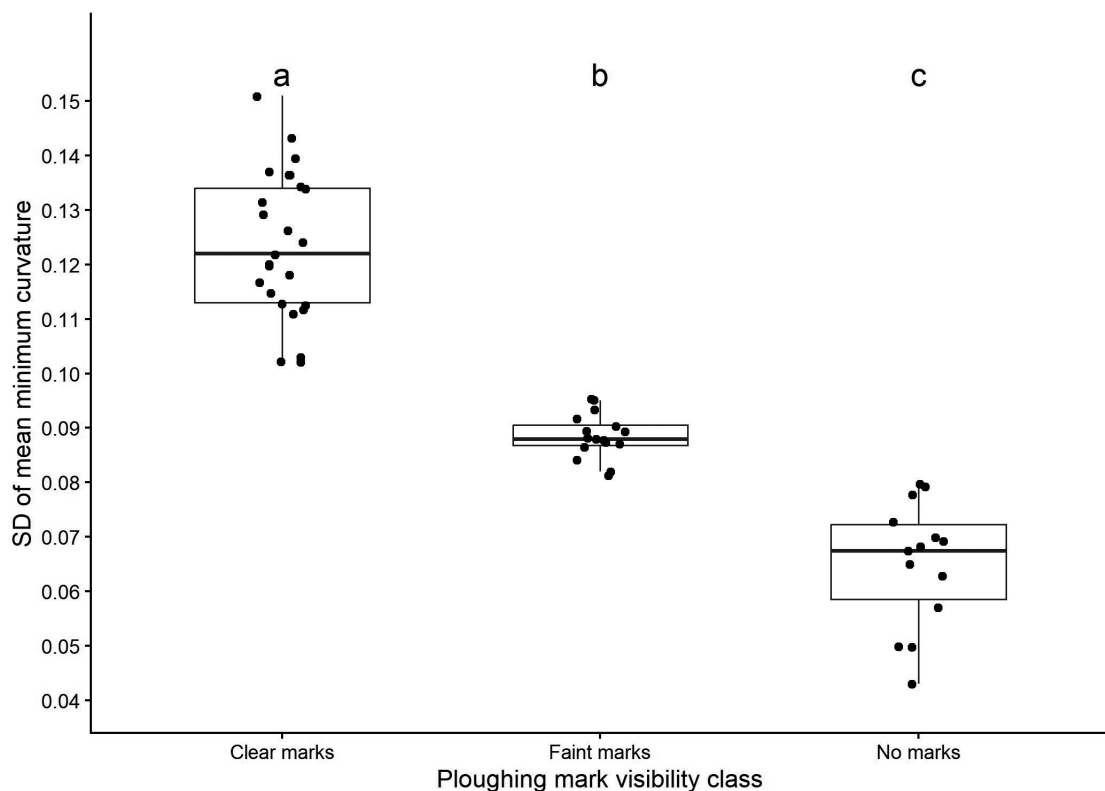


Fig. 5. Standard deviation of mean minimum curvature across the three ploughing mark visibility classes. Different letters indicate homogeneous groups based on Dunn's post-hoc test with Bonferroni correction ($p < 0.05$)

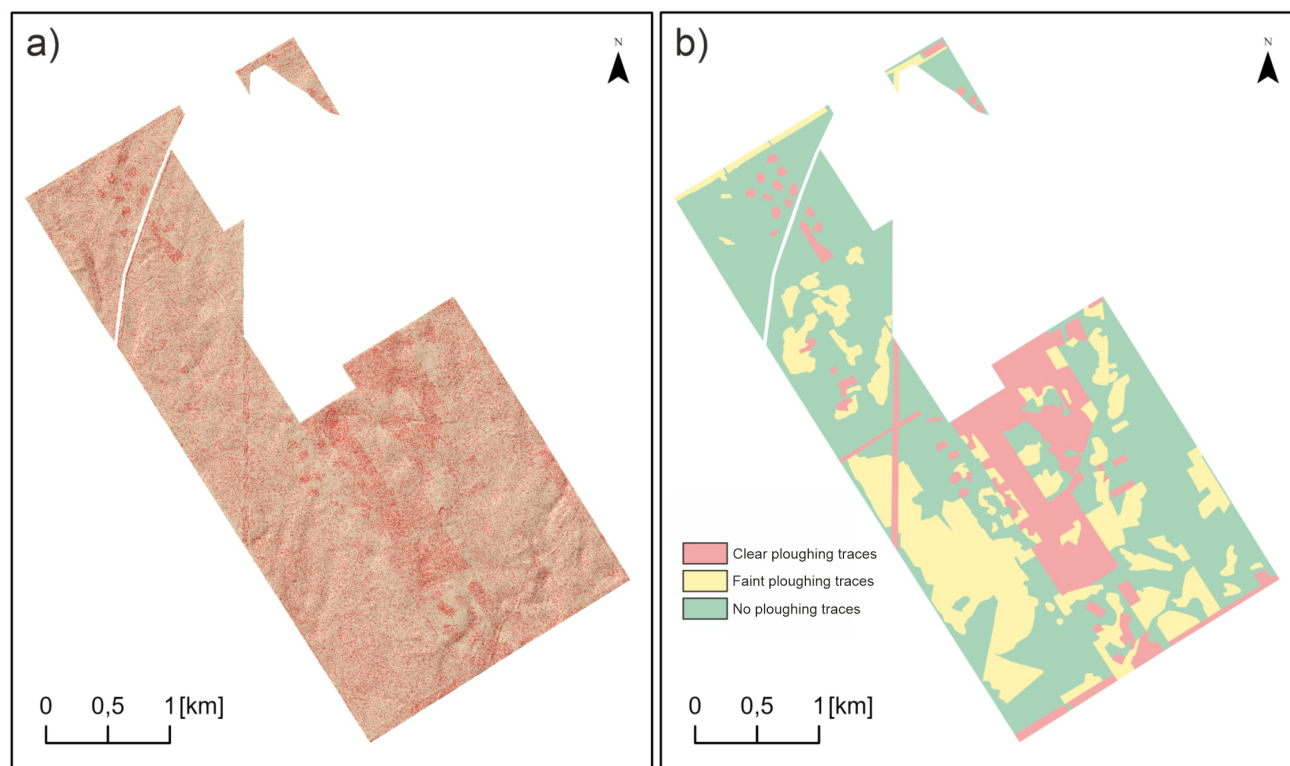


Fig. 6. a) The GPW area in the Osie Forest District visualized using the minimum curvature method, prepared for interpretation, b) GPW in the Osie Forest District classified for the visibility of ploughing marks

Clear ploughing marks are visible throughout the entire GPW area, occupying the surfaces of entire subdivisions. The most significantly transformed by ploughing are the subdivisions located in the central and southern parts, where areas of several dozen hectares are affected, visible in the visualization as dense clusters of parallel lines. Also clearly visible are fragments of the area subjected to nested felling, which constitute groups of small polygons with shapes similar to circles. The area in the form of a strip running meridionally through the analyzed GPW, a remnant of an old power line that has been ploughed and reforested, was also classified as the most transformed class. Areas classified as faint ploughing marks are also scattered throughout the GPW and occur primarily under middle-aged and older stands. Very often, they are adjacent to the clear marks class and complement the areas of individual forest subunits. In other cases, they form larger areas under older stands where ploughing was performed decades ago. The passage of time has blurred the continuity of these marks in the terrain's microrelief, making them difficult to identify in the field based on visual inspection, without excavation.

Areas classified as no ploughing marks primarily occur in the oldest stands. The largest and most compact areas of this class are located in the northern parts of the GPW. These areas, despite intensive forest management practices in the surrounding area, still retain their natural character.

Clear marks of ploughing cover 17% of the total area of GPW, faint marks cover 26%, and no transformation was identified in 57% of the analyzed area (Table 2). Among stands aged 0-50 years, planted after the GPW was established, clear marks of ploughing cover two-thirds of the area, with no marks occurring in only 18%. Among stands that were 20 years or younger at the time of GPW establishment (range 51–70 years), clear and faint marks of ploughing account for a total of 60% of the area. No distortion was detected in 40% of this age group. This means that when the Soil Reference Area in Osie was established, more than half of the youngest stands had visible marks of preparation for planting. In the case of the oldest stands (which were over 20 years old at the time of GPW establishment), the situation is opposite. Clear marks of ploughing are present here marginally, constituting only 3% of the total area. Faint marks, blurred over time, cover 30%, and no marks of ploughing cover 67% of the area of this age group.

Table 2

Percentage of ploughing mark visibility classes by selected age ranges in the area of GPW in the Osie Forest District

Stand age	Ploughing mark visibility		
	No	Faint [%]	Clear
Overall	57	26	17
0-50	18	16	66
51-70	40	34	26
71+	67	30	3

4.3. Field verification of remote sensing results

The results of the remote sensing analyses were confirmed during field reconnaissance (Fig. 7). The series of pits revealed a diminishing height difference between the ridge and the furrow with increasing stand age. This trend is related to the ploughing trace visibility classes identified in the remote analysis. In the most transformed class, the height difference between the ridge and the furrow was approximately 18 cm, while in the middle class it was approximately 13 cm. In the area without ploughing traces, in a nearly 100-year-old stand, the surface and the upper soil horizons were undisturbed. Another significant effect is the degree of mixing of the surface soil horizons. In areas with no or faint ploughing marks, the effects of the podzolization process, occurring directly beneath the organic horizon, are visible. In areas without surface disturbances, the soil profile showed a consistent genetic horizon. In areas with visible marks of ploughing, the top horizons were significantly disturbed and mixed. However, in areas with faint marks of ploughing, secondary effects of the podzolization process are already visible, in the form of a thin but continuous AE horizon.

The presence of ploughing marks in the youngest stands and clear-cut areas can be identified in the field without the need for excavation. The regular arrangement of ridges and furrows resulting from the process of preparing the soil for new plantings is clearly visible on the ground surface (Fig. 8a).

4.4. Areas of clear-cutting carried out after 2012, according to orthophotomaps

Based on photointerpretation of historical orthophotomaps, an additional 25 hectares of the GPW area were identified where clear-cutting occurred between 2012 and 2025. The transformed forest subdivisions are located in the northwestern and southeastern parts of the GPW (Fig. 9). In all cases, these areas showed no or only faint marks of ploughing, according to ALS data. Actually they should be included in the class of clear marks of ploughing. The presence of clear-cutting and soil surface condition were confirmed during field verification (Fig. 9).

5. Discussion

Transformations of surface soil horizons caused by the LPZ plough in Polish forests are widespread (Sewerniak et al., 2011). Considering the general use of soil preparation for planting trees over the past 200 years, it can be assumed that in the vast majority of forests, the soil cover has been subjected to at least one ploughing process that interfered with its surface mineral horizons. Transformed surface horizons are problematic for soil protection within the Soil Reference Areas, which aimed at the presence of surfaces unaltered by human activity. Progressive forest ploughing extent among the youngest stands in the GPW area is causing their degradation. With such highly intrusive cultivation methods, even a 150-year period

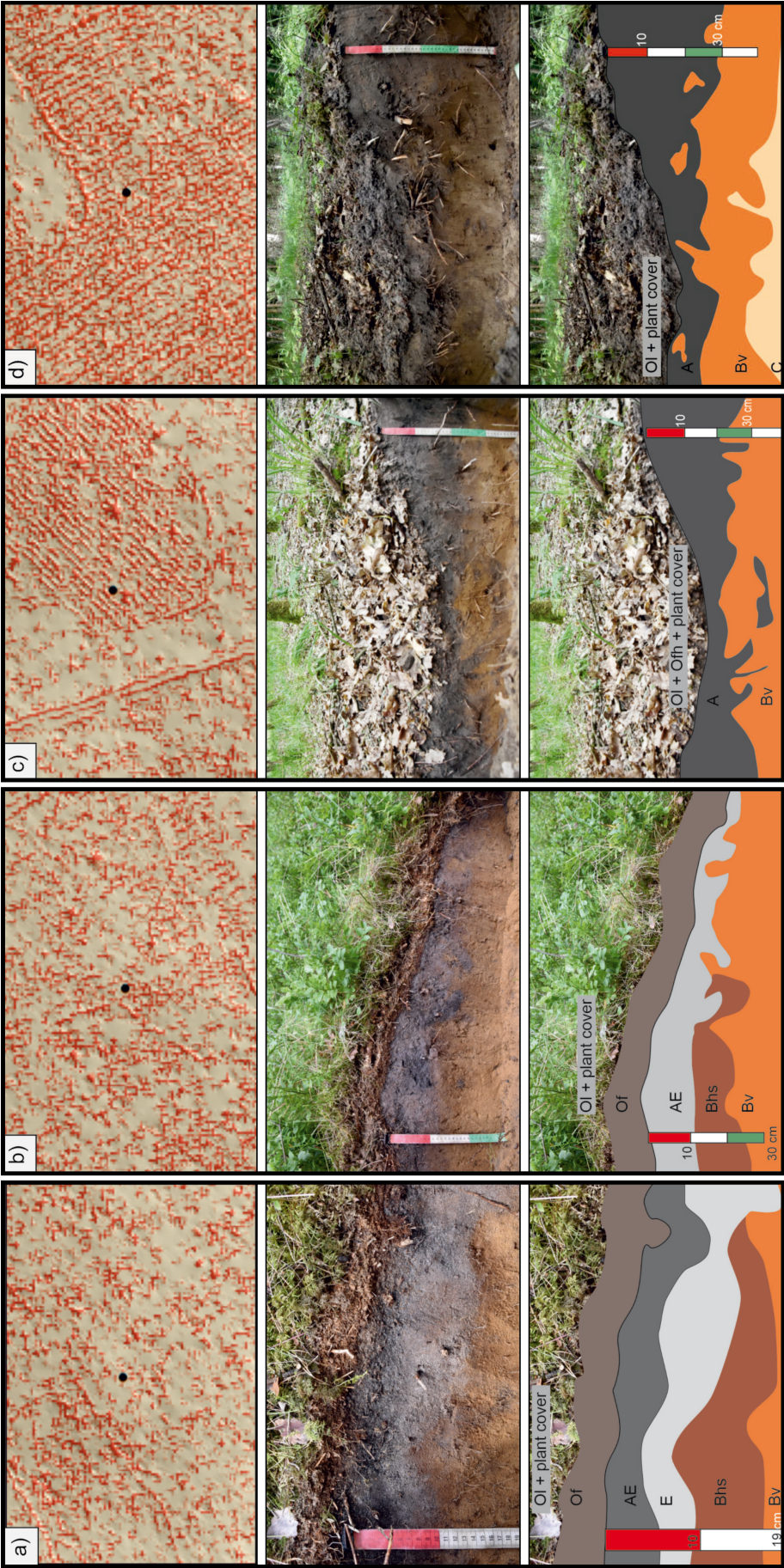


Fig. 7. Morphology of the upper soil horizons in the GPW area of the Osie Forest District against the background of the minimum curvature method visualization: a) in an area with no ploughing marks, b) in an area with faint ploughing marks, c) in an area with clear ploughing marks, d) in a nested felling.

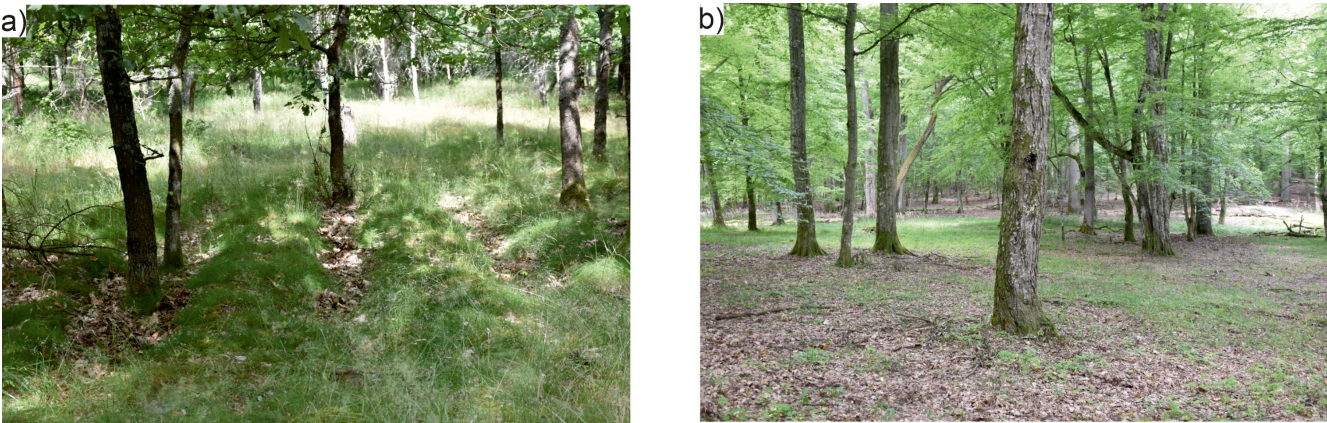


Fig. 8. a) a section of the area classified as having clear ploughing marks, b) a section of the area classified as having no ploughing marks

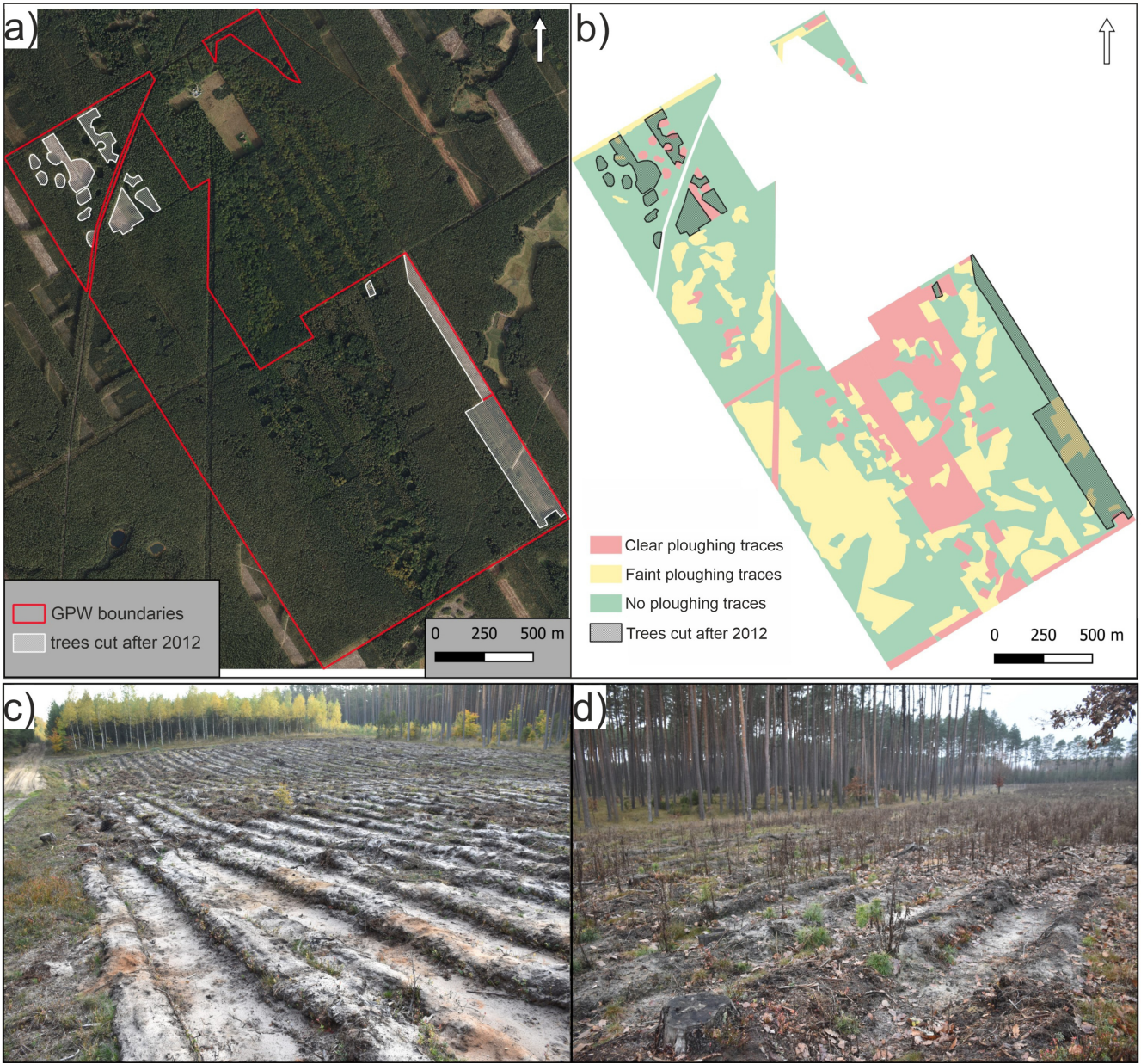


Fig. 9. Forest subdivisions in the area of GPW in the Osie Forest District, cut down after 2012: a) on the background of the orthophotomap from 2024, b) on the background of ploughing mark visibility classes, c) subdivision 108a, d) subdivision 37e

is too short for the full regeneration of soil genetic horizons (Jankowski and Rutkowska, 2024). Suitable soil conditions similar to those of the primary forest cannot be ensured even within the Soil Reference Areas, if standard forest management practices and regeneration of clearcuts, including ploughing the surface soil horizons are still in place. Already in the first years of the GPW existence, Sokołowski (1981) drew attention to the management methods used there.

Preparing the soil for planting with a forest plough (LPZ) clearly disrupts the surface genetic horizons in the soil, and on the ground surface, it creates microrelief in the form of alternating elevations (ridges) between rows and depressions (furrows) within rows (Sewerniak et al., 2011). Over time, the height difference between furrows and ridges decreases, which is primarily influenced by windblowing, washing away, and the activity of soil fauna, as observed in the Brodnicki Landscape Park (Sewerniak et al., 2014). Chojnicki et al. (2021), in their analyses of the Soil Reference Area located in the Biała Forest, also noted the presence of areas of soil with distorted surface layers after planting, which occurred mainly under 40-year-old stands. These traces are visible even several decades after ploughing. Research conducted by Kabala et al. (2013) in pine forests in Rudna (Lubin Forest District) showed that the characteristic microrelief with furrows is most visible for the first 30 years after preparatory treatments. In the case of 40-year-old stands, unevenness was also visible, but their height differences were smaller, approximately 8 cm. Sewerniak et al. (2011) found that the microrelief after ploughing with an LPZ plough disappears after approximately 60 years. Confirmation of the theses indicating a period of microrelief fading can be found in the analyses by Jankowski and Rutkowska (2024), conducted in the Toruń Basin, where the authors found that traces were most visible in the youngest classes of stands, and in the case of 52-year-old trees, they were already partially obliterated. In 70-year-old stands, only slightly undulating microrelief indicated remnants of ploughing, while no visible traces of soil disturbance were noted under trees over 100 years old. In the case of 100-year-old stands, disturbances may be visible at most in former inter-rows, where the presence of mineral material discarded during ploughing from the row may be noticeable, while underneath there should be a strongly decomposed, thin organic horizon from the previous generation of forest (Sewerniak et al., 2014). However, identifying this stage of soil transformation is almost impossible based on visual assessment and requires digging pits directly in the field. The periods of disappearance of ploughing traces described in the literature align very well with the results obtained in this analysis, where a change in microrelief was also visible in stands between 40 and 50 years old, and an almost complete disappearance of microrelief in stands older than 80 years. The thesis that identifying ploughing traces in the area of older stands requires fieldworks is confirmed as well.

Previous studies analyzing anthropogenic transformation of forest soils caused by ploughing also attempted to classify the degree of soil transformation. Sewerniak et al. (2014) distinguished three main transformation classes, based primarily on the method of soil preparation for planting, the absence or presence of an organic horizon, and the degree of microrelief

loss following the treatment in the Brodnicki Landscape Park. Microrelief caused by soil preparation for forest planting was found on 45% of the total area of the Brodnicki Landscape Park (Sewerniak et al., 2014). In another similar analysis conducted in the Zielona Forest District, it was 42% of the total area (Sewerniak et al., 2011). In the case of the Soil Reference Area in the Osie Forest District, traces of ploughing were identified on 43% of its surface. These values are therefore very close.

The use of the minimum curvature method to identify traces of microrelief caused by forest ploughing offers a new perspective on the possibility of rapid, remote assessment for large-scale areas. In the case of plans to verify the condition of Soil Reference Areas, this method would enable the efficient identification of areas heavily transformed by forest management, which no longer serve their original protective function, as well as undistorted areas that are suitable for increased protection.

The versatility of LIDAR data is confirmed by numerous publications examining disparate natural environments. The primary advantage of LIDAR data is the ability to detect small microrelief features in hard-to-reach forests, which would be impossible to identify in traditional fieldwork (Howey et al., 2016). Shukla et al. (2024) used terrestrial and airborne LIDAR to map the microrelief of wetland forest areas. Gawrysiak and Kociuba (2023) combined high-resolution digital terrain models with a geomorphon algorithm in analysis of loess bank relief. The same method was used in the study by Kaźmierowski et al. (2015), where the combination of DEM and geomorphons allowed for the analysis of agricultural field surfaces in the context of distinguishing smooth and rough areas. The widespread use of LIDAR data is popular also in archaeology, where it is used to interpret the microrelief of archaeological structures and to plan excavations (Zapłata and Stereńczak, 2016; Berganzo-Besga et al., 2022). Comparative analyses of terrain model interpolation methods conducted by Yilmaz (2007) demonstrated the very high effectiveness of the minimum curvature method, placing it second only to the polynomial approximation method. However, the literature lacks publications focusing directly on the analysis of the visibility of ploughing traces in forests using the minimum curvature interpolation method. The closest approach to identifying microrelief caused by forest ploughing seems to be the publication by Basista et al. (2023), where the authors used DTM with indicators such as Openness Positive, Openness Negative, and Sky-View Factor, as well as morphological filters, to detect traces of contemporary forest ploughing in order to distinguish them from traces of linear archaeological structures. The authors confirmed the effectiveness of remote identification of ploughing traces.

Zielony and Chojnicki (1996) pointed to the declining importance of Soil Reference Areas and the neglect of this form of soil protection as early as the turn of the 1980s and 1990s. The coming years represent the best and, at the same time, one of the last opportunities to revive Soil Reference Areas, while surfaces unaffected by forest ploughing can still be found. Intensive forest management is progressively reducing the area of unaffected soils year by year, including GPW. If any action is taken, soil condition analyses should be performed nationwide, for all areas. Collecting a large amount of data from the interpolation method

would allow for a shift from manual to automatic classification of the analyzed areas, further accelerating the verification process. The method itself can be applied not only within Soil Reference Areas but also in any other forms of nature conservation, or in managed forests.

6. Conclusions

Remote analysis of the terrain microrelief and an attempt to identify traces of forest ploughing in the soils of the Soil Reference Area in the Osie Forest District based on LIDAR data analysis allowed the following conclusions to be drawn:

1. The application of the minimum curvature analysis method allows for the remote identification of forest areas transformed by ploughing.
2. A decline in the visibility of forest ploughing marks (soil preparation for tree planting) was observed with increasing stand age. There was a noticeable reduction in the visibility of microrelief in stands between 40 and 50 years old, and an almost complete disappearance of microrelief in stands older than 80 years.
3. Three classes of the visibility of forest ploughing marks were distinguished on the basis of the standard deviation of minimum curvature values: no ploughing marks (<0.08); faint ploughing marks ($0.08\text{--}0.10$); clear ploughing marks (>0.10).
4. A large part of the studied GPW is managed using soil preparation methods for stand planting typical of standard forest management practices, which leads to the disappearance of soils with natural characteristics. Ploughing marks have been identified on 43% of the total GPW area.
5. Preservation of areas unaffected by forest ploughing helps protect the natural characteristics of soils and, in some cases, historical and cultural heritage.

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Conflict of interest

The authors declare no conflict of interest and that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not involve human or animal subjects.

Author Contributions:

Bartłomiej Zawadzki – Conceptualization, Data curation, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Michał Jankowski** – Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. All authors read and approved the final manuscript.

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Identyfikacja śladów orki leśnej w glebach Glebowej Powierzchni Wzorcowej w Nadleśnictwie Osie (Polska północna), na podstawie analizy danych LIDAR

Słowa kluczowe

Glebowe Powierzchnie Wzorcowe (GPW)
Orka leśna
Mikrorzeźba terenu
LIDAR
Analiza zdalna

Streszczenie

Sieć Glebowych Powierzchni Wzorcowych (GPW) to forma ochrony gleb w Polsce, zainicjowana w 1975 roku przez Polskie Towarzystwo Gleboznawcze i Lasy Państwowe. Obecnie w Polsce funkcjonuje 135 takich powierzchni, ale od dawna nie są one odpowiednio monitorowane, a ich stan w większości przypadków pozostaje nieznany. Brak badań i ekstensywna forma ochrony budzą kontrowersje wśród leśników, którzy borykają się z ograniczeniami w zarządzaniu obszarami leśnymi o powierzchni kilkuset hektarów. Celem niniejszej pracy jest ocena aktualnego stanu gleb Glebowej Powierzchni Wzorcowej położonej w Nadleśnictwie Osie, w północnej Polsce, a w szczególności zniekształceń pokrywy glebowej powstałych w wyniku przygotowania gleby do nasadzeń (orki leśnej), w oparciu o zdalną analizę mikrorzeźby (dane LIDAR i narzędzia GIS), fotointerpretację dostępnych ortofotomap i badania terenowe. Zastosowano metodę interpolacji minimalnej krzywizny oraz próbę identyfikacji korelacji między widocznością śladów orki a wiekiem drzewostanu. W odniesieniu do obecności śladów orki leśnej wyznaczono trzy klasy stanu powierzchni gleby: brak śladów, ślady słabe i ślady wyraźne. Metoda ta umożliwiła precyzyjną identyfikację fragmentów GPW najbardziej dotkniętych orką. Ślady orki zidentyfikowano na 43% powierzchni całego GPW, z czego większość znajduje się pod drzewostanami nasadzonymi w okresie istnienia GPW. Najmniej przekształcone obszary znajdują się pod najstarszymi drzewostanami.