

Remote Sensing Techniques for Assessing Successional Changes on Former Military Areas

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Abstract

Remote sensing plays a crucial role in monitoring and evaluating transformations of vegetation cover. Of particular interest in this type of research are former military areas, which may bear traces of soil contamination and significant alterations from military activities for many years. The use of satellite and aerial data, including multispectral and hyperspectral imagery, as well as LiDAR data, allows for tracking the dynamics of vegetation development, from initial colonization stages to more advanced stages of forest succession. This approach was utilized in an analysis of a former military unit area spanning 63 hectares. The data sources included, among others, aerial photos from 1995, 2010, 2014, and 2016, along with a digital terrain model. 14 years after the military unit withdrew from the occupied area, advanced successional changes were observed, largely masking the traces of former military activity. However, noteworthy differences in the dynamics of plant growth allowed for the detection of traces of former military structures. Such observations may also potentially be useful in identifying areas modified by humans in the more distant past (a subject of interest in archaeology).

Keywords

Aerial Photos, Terrestrial Plant Succession, Digital Terrain Model

1. Introduction

The succession is one of the main concepts in ecology explaining ecosystem development over time (Poorter et al., 2024). This concept has become particularly important in recent decades, when vegetation is undergoing intensive changes caused by human activity and climate change.

There are many methods for studying vegetation transformations (Konatowska & Rutkowski, 2021). One of the commonly used ones is based on phytosociological research (Konatowska & Rutkowski, 2019). This is a terrestrial method, very precise, but arduous and difficult to apply, especially in hard-to-reach areas. Therefore, methods based on remote sensing (Zaitunah & Sahara, 2021; Thi Huyen et al., 2022; Salcedo et al., 2024) are becoming increasingly common, allowing for the monitoring of vegetation changes both spatially and temporally. Remotely sensed data also allows for combining research on vegetation with the interests of other scientific disciplines, such as archaeology. This aligns with the rapidly developing approach of using non-invasive methods to identify traces of the past (Sever, 2000; Rączkowski et al., 2025). The diversity of remote sensing includes, among others: Optical, Radar, and Thermal Remote Sensing, LiDAR, Multispectral, and Hyperspectral Imaging (Janga et al., 2023). Each of these methods has its advantages and limitations.

Despite the importance of research on vegetation succession for understanding ecological phenomena, a comprehensive successional theory is still lacking. This results from the heterogeneous nature of succession, where many factors are involved and many different successional pathways exist (Poorter et al., 2024). One of the significant limitations in interpreting the results of vegetation succession studies is their time scale (the longer, the better). Comparing the results of succession studies is also hampered by the diverse spatial scale, from local to global. The interpretation of results is also influenced by the complex nature of successional phenomena, including the overlapping of diversity in the studied habitats, the interaction of both natural factors (soil diversity, climate change, fires, influence of animals, etc.) and anthropogenic factors, or the difference in the methods used.

Abandoned military bases are among the poorly understood objects in terms of successional research. This is primarily due to the low availability of materials concerning military objects. Reif et al. (2023) studied the biodiversity of abandoned military training areas in the Czech Republic from 2009 to 2010 and from 2020 to 2023, but this was not a study of vegetation succession. The authors, however, showed a varied influence of the passage of time, both positive and negative, depending on the group of organisms they studied (vascular plants, grasshoppers, butterflies, birds) and the way the abandoned areas were used.

Fornal-Pieniak et al. (2025) in turn drew attention to the influence of the use of post-military landscapes in the Polish capital, Warsaw, on the species diversity of plants, indicating the dominance of deciduous species in tree communities, including those native to the Polish flora, as well as geographically alien ones. In turn, the non-managed greenery zones were dominated by grasses. Bajnok et al. (2024), in turn, explored the impact of military activity on sandy grasslands in Hungary and showed—despite the expectations that military activity always causes vegetation degradation—a positive effect on the conservation of grassland ecosystems. Ellwanger and Reiter (2019) also emphasize, based on German experiences,

the importance of decommissioned military training areas for nature conservation. Post-military areas thus arouse the interest of researchers from various countries.

The cited research results, however, indicate the use mainly of ground-based inventory techniques for individual components of nature. The aim of our research is to demonstrate the usefulness of remote sensing for assessing changes taking place in former military areas

2. Methods

2.1. Study Area

The research area is situated near Trzaskowo Village (Poland) and comprises about 63 ha (**Figure 1**).



Figure 1. Research area near Trzaskowo village marked with a blue outline (source: FDB, 2025).

In the past, the research area was occupied by a military unit. The Army was stationed in Trzaskowo from the 1960s to the end of 2011. Initially, it was the 30th Fire Division of the National Air Defense, a unit equipped with the SA-75 Dźwina medium-range anti-aircraft missile system. In addition to the 30th Division, in the Goślinia region, there was also the 83rd Anti-Aircraft Artillery Battery (AAB), equipped with 57 mm anti-aircraft guns, intended to provide direct anti-aircraft defense of the missile system's firing positions. Both units were part of the 79th Independent Artillery Regiment of the Air Defense Forces (until 1967, the regiment bore the number 14), intended to provide anti-aircraft protection for Poznań and its surroundings. In the 1980s, the process of reorganizing the 79th Regiment began. In 1986, the 83rd anti-aircraft battery was liquidated, and in 1990, after the Dźwina unit had exhausted its service life, the 30th Fire Division was dis-

banded. However, another division was moved to Trzaskowo in its place—the 77th Fire Division AAB, previously stationed in Złotkowo village (Suchy Las commune), equipped with the more modern S-125 Nawa anti-aircraft system. In 1991, the name of the division was changed—from then on, the 77th Air Defense Missile Division existed. Another reorganization of the Poznań center’s air defense took place in 1998, when the local 79th regiment was liquidated. However, three missile divisions were retained—the 31st and 76th from Poznań and the 77th from Trzaskowo and attached to the 1st Silesian Air Defense Missile Brigade from Bytom. At the beginning of the 21st century, the previous S-125 Nawa set was replaced with a newer, modernized in Poland, S-125 Nawa-SC set.

The 1st Air Defense Missile Brigade was liquidated on December 31, 2011. Along with it, the 77th Missile Squadron from Trzaskowo also ended its life (UMIGMG, 2013).

The unit had barracks, a fuel station, a vehicle repair pit, a shooting range, and anti-missile defense positions.

2.2. Sources of Data

The study was based on the aerial photos from the years: 1995 (analog photo), 2010, 2014, 2016, 2020 (digital photos, 0.25 m resolution) (CMMP, 2025), archival photographic images (Naszemiasto Portal, 2025) and own photographic images, as well as data from the Forest Data Bank (FDB, 2025) which included a tree stand maps (according to the 2023) as well as a digital terrain model, produced by laser scanning (Hédl et al., 2017).

3. Results

The first publicly available aerial photos covering the research area are from 1995, when military units were stationed within the research area. Therefore, the presented research results refer to the transformations of the vegetation cover in the years 1995-2025. A general comparison of the changes that occurred during this period is presented in **Figure 2**, while a detailed focus was placed on two features marked in **Figure 2** as the vehicle repair pit and the shooting range.

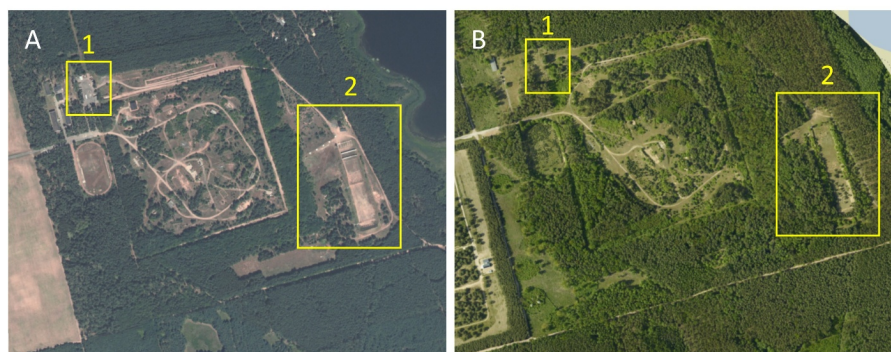


Figure 2. Comparison of aerial photos between the years 1995 (A) and 2023 (B); “1” marks the vehicle repair pit area, “2” marks the shooting range area.

Figure 3 illustrates the vehicle repair pit area in the years 2010 and 2014. **Figure 4** presents the changes that occurred within the vehicle repair pit area in the years 2014-2025.

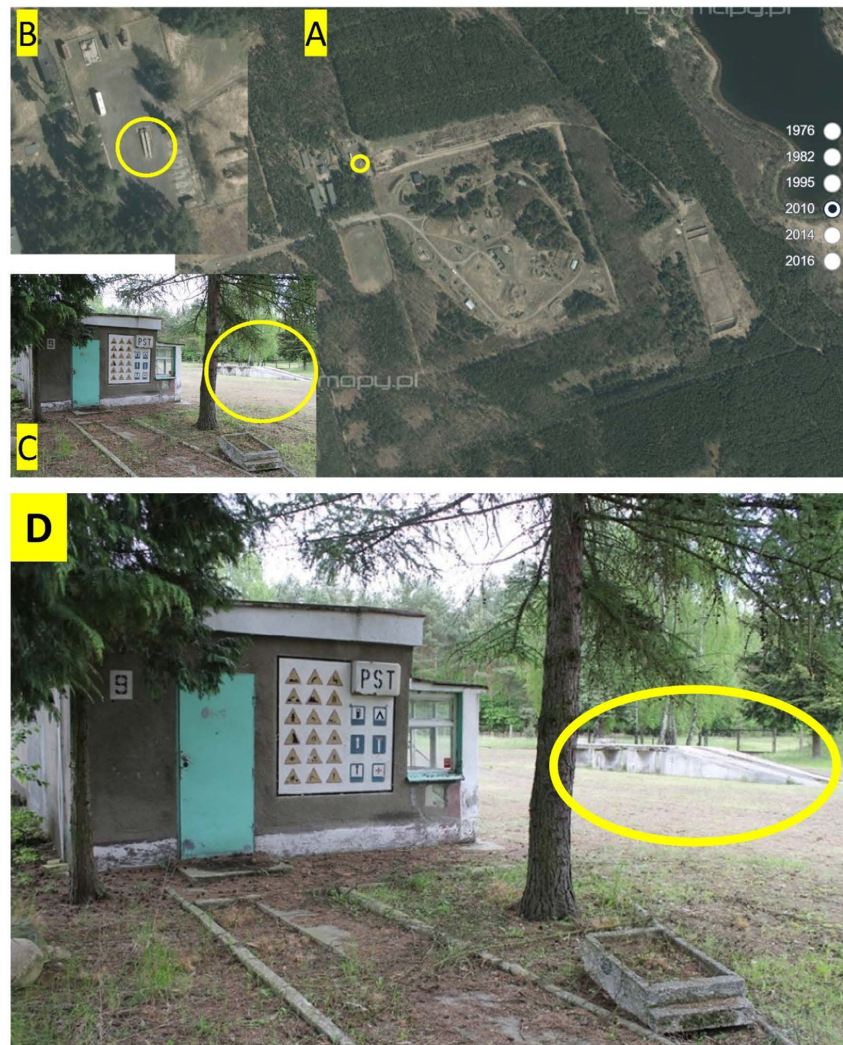


Figure 3. Technical and military, the vehicle repair pit: A—Aerial photo from 2010, the vehicle repair pit is marked with a yellow circle; B—enlarged part of **Figure 3(A)**; C—Photo of the repair point from around 2014 (Naszemiasto Portal, 2025); D—Enlarged part of **Figure 3(C)**.

As shown by the materials presented in **Figure 4**, between 2014 and 2016, the vehicle repair pit and all related structures were removed, simultaneously leveling the ground to create the current flat surface. The year 2016 can be considered the beginning of secondary vegetation succession, following which the area was already covered by a grassland community in 2020 (dominated by grass species—*Calamagrostis epigeios*), with clumps of natural Scots pine (*Pinus sylvestris*) regeneration and individual regeneration of invasive black cherry (*Prunus serotina*). The images from 2020 and 2025 also show the mosaic nature of the grassland vegetation, related to the varying growth dynamics of the *Calamagrostis epigeios*, espe-

cially visible in the 2025 photo as the intense green of more vigorously growing grasses. Considering the area's former use as a vehicle repair location, this could be associated with both differences in soil characteristics (e.g., varying density) and the potential impact of various substances entering the soil from repaired vehicles, such as petroleum products. This may form the basis for further research aimed at explaining the differing dynamics of plant growth.

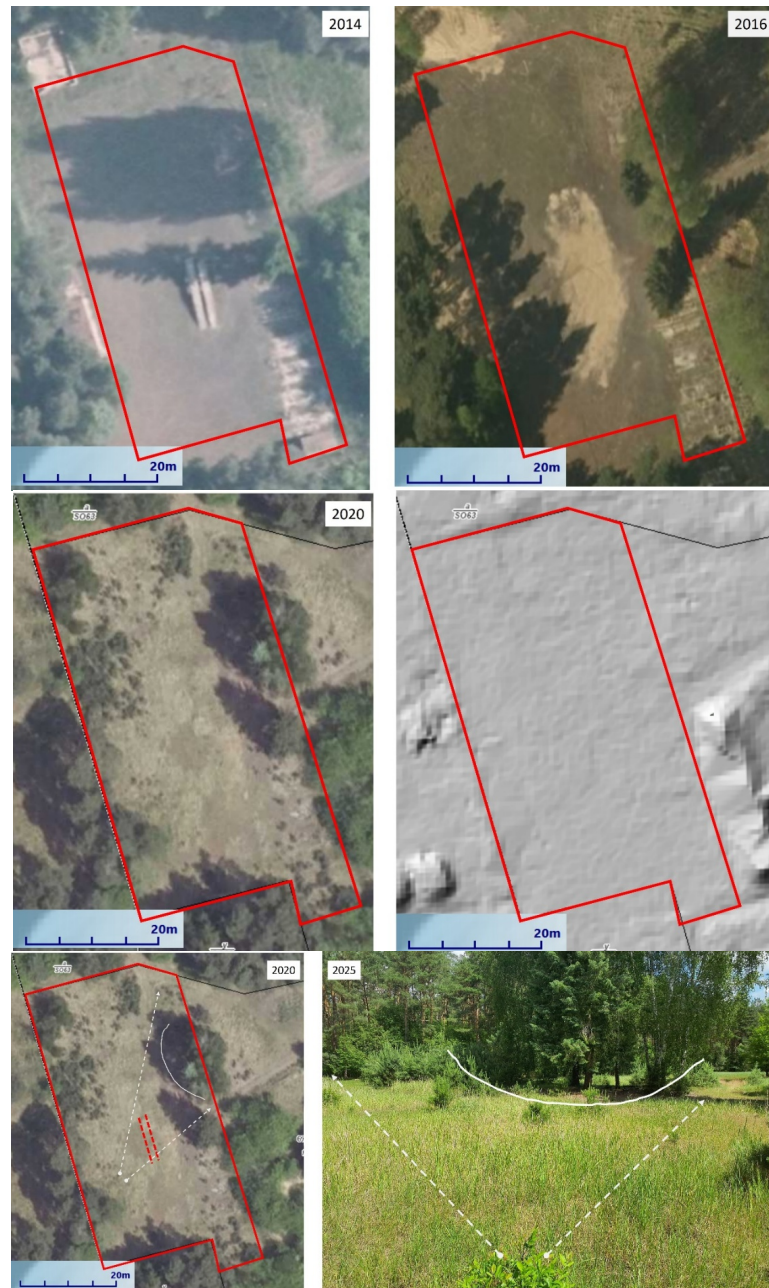


Figure 4. Comparison of vegetation changes within the vehicle repair pit area in the years 2014-2025; the figure also presents a fragment of the digital terrain model (gray image) illustrating the topography (flat); the photo of the research area from 2025 is also included, with reference points marked for the state from 2020 (arrows and a continuous line marking a characteristic clump of trees).

The second object subjected to detailed analysis is the area of the former shooting range, where the course of vegetation cover transformations is presented in **Figure 5**.



Figure 5. Transformations of the vegetation cover in the years 1995-2023; the area marked by the yellow square in the 2023 figure is shown enlarged in **Figure 6**.

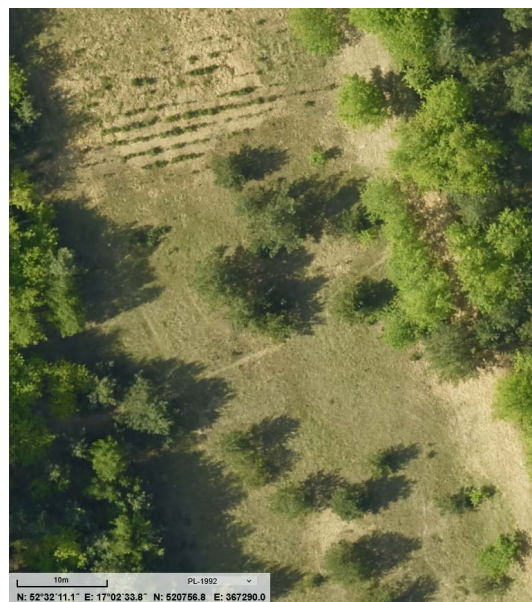


Figure 6. The fragment of the shooting range image from 2023 shows the difference between pine regeneration planted in rows (northern part of the photo) and its natural regeneration (in the central part).

Similarly, as with the vehicle repair pit and its surroundings, the shooting range area also saw the complete removal of its associated infrastructure between 2014 and 2016, although the use of the facility ceased in 2011, as evidenced by individ-

ual natural Scots pine regeneration visible in the 2014 image. The enlarged fragment of the 2023 image shows, however, that this process was supplemented by artificial pine regeneration, which is evidenced by the distinct rows in which the trees were planted (**Figure 6**).

Historical data show that at the end of the 19th century, the research area was primarily non-forested (agricultural) land (**Figure 7(A)**). Currently, most of the area is covered by forestland (**Figure 7(B)**), mainly Scots pine (*Pinus sylvestris*), with a small proportion of black locust (*Robinia pseudoacacia*) and birch (*Betula pendula*) stands (**Figure 7(C)**). Only the topography reveals its military past, as presented in **Figure 7(D)** in the form of a hypsometric map.

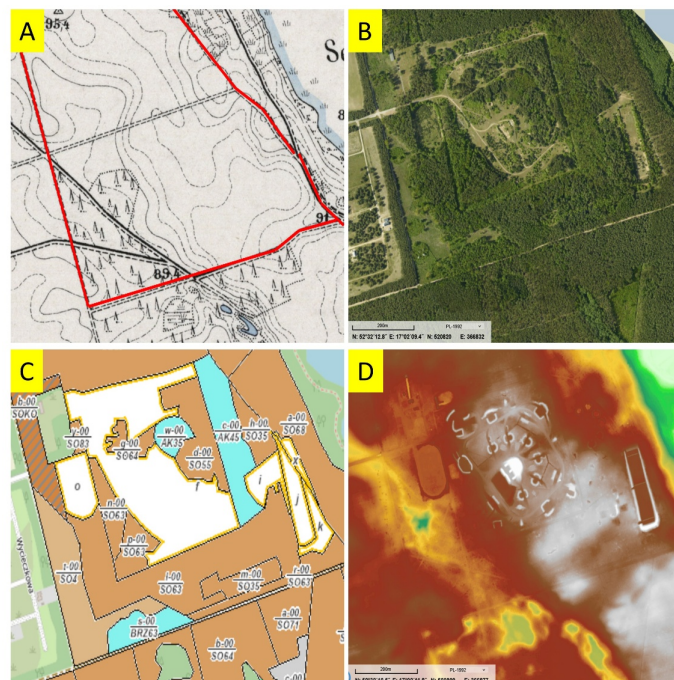


Figure 7. Changes in the vegetation cover in the years 1890-2023: A—A fragment of the map from 1890; B—Aerial photo from 2023; C—A fragment of the stand map: brown color (symbol So) indicates pine forests, blue color (symbol Ak) indicates forests composed of black locust (*Robinia pseudoacacia*), blue color, symbol Brz—birch forest (*Betula pendula*), white color—areas currently undergoing succession; the numbers provided after the tree species symbols denote the stand age; D—Hypsometric map of the research area.

4. Discussion

In the period described as the Anthropocene, vegetation is undergoing rapid transformations linked to human activity, which are compounded by phenomena related to climate change. Separating the influence of human activity from natural phenomena requires broad ecological research, conducted on permanent observation plots. Despite the clear advantages of permanent experimental plots, their main disadvantage is their limited temporal and spatial extent (Hédél et al., 2017). Most field observations and experiments are short-term, which provides rather limited knowledge about the dynamics of ecosystems functioning under the influ-

ence of long-term factors (Hédli et al., 2017). The duration of this type of research usually does not exceed a few decades, with a few exceptions (e.g., Silvertown et al., 2006). Therefore, Hédli et al. (2017) suggest retrospective studies as an alternative to long-term observations on permanent research plots. The idea of conducting this type of research is not new. References to this method can be found as early as 1929 (Conard & Galligar, 1929), and contemporarily, among others, in the publication by Stockli et al. (Stockli et al., 2011). In turn, the disadvantages of reconstructing vegetation descriptions in a given area are mainly associated with possible shifts in the location of the compared plots and with observer subjectivity (Kapfer et al., 2017). These two sources of undesirable variability between the original and resurvey cannot be completely eliminated, although their impact can be estimated (Archaux et al., 2006; Ross et al., 2010). Essentially, the magnitude of the displacement of the compared plots depends on the heterogeneity of the vegetation patch, so each case is distinct. This error can be avoided by permanently marking the research plots. In the absence of such marking, the reconstruction of old experimental plots was considered risky (Chytry et al., 2014). However, the aforementioned limitations do not diminish the interest in this topic, exemplified by works dedicated to wetland areas (Alfonsi et al., 2017; Britton et al., 2017; Navratilova et al., 2017; Schweiger & Beierkuhnlein, 2017), forest ecosystems (Becker et al., 2017; Heinrichs & Schmidt, 2017; Reczyńska & Świerkosz, 2017; Vild et al., 2017), grasslands (Bernards & Morris, 2017; Giarrizzo et al., 2017; Koch et al., 2017), the Arctic (Kapfer & Grytnes, 2017), or coastal vegetation (Pakeman, Hewison, & Lewis, 2017). The cited publications point to yet another problem, which is the difficulty in synthesizing data from different types of plant communities associated with specific habitats, from various regions of the globe. It is also important to consider the significant fact that it is difficult to establish permanent research plots in inaccessible areas. Remote sensing techniques offer some opportunity for this type of research.

The intuitive perception of military objects suggests associations with areas devastated by fires, the impact of heavy equipment, or chemical contamination, but as Ellwanger and Reiter (2019) write, “military areas are of uttermost importance for the protection and preservation of biodiversity.” Undoubtedly, the negative consequences of using land for military purposes could also be pointed out.

In the case described in our research, the very rapid pace of succession should be emphasized, the final stage of which appears to be a forest community, which is the expected outcome in the temperate zone where the research was conducted, in an area free from natural factors limiting vegetation development. However, it should be noted that the succession documented by our research leads not so much to the creation of a natural plant community, but rather to a substitute community, in which the tree species black cherry (*Prunus serotina*), which is invasive in Poland, may play a significant role. Although the naturally regenerating dominant tree in the research area is scots pine (*Pinus sylvestris*), black cherry is a deciduous species that is ahead of native deciduous species that

could appear under the given conditions. Allowing nature to follow its natural processes can therefore be considered a significant natural value, but in some cases, spontaneous vegetation development leads to effects different from expectations. In the described case, natural successional processes could be interfered with by removing the invasive black cherry and introducing species such as oak, hornbeam, linden, or sycamore maple in its place. These species, which form potential natural plant communities in Poland, limit the growth of black cherry by shading the soil.

A significant research result is the demonstration of differences in plant dynamics using one of the grass species (*Calamagrostis epigejos*) as an example. Although these differences were shown using ground-based photography, aerial photos can help delineate the boundaries of vegetation with different growth dynamics. This could be a useful factor not only in ecological research but also worth testing in archaeological research for the possibility of indicating places associated with various types of human activity in the more distant past (see the concept of crop marks, e.g., Wilson, 2000).

5. Conclusion

The development of vegetation in the research area was mainly influenced by three factors noted since the 19th century: agricultural use, the establishment of a military unit on former agricultural land, and the liquidation of the military unit in 2011. Part of the area belonging to the former military unit is currently covered by trees, planted mainly after World War II (pine and black locust stands aged 35 to 64 years), and part of the area is undergoing secondary succession. The dominant direction of succession is towards a forest formation, with a predominance of *Pinus sylvestris*. However, the expansion of the black cherry tree species (*Prunus serotina*), which is invasive in Poland, has also been observed. Remote sensing techniques can help in its monitoring, but action should be taken to limit this species. This would, however, require interference with the process of natural succession by introducing native Polish deciduous tree species that shade the soil, such as oak, hornbeam, linden, or sycamore maple.

Drawing attention to whether to allow nature to follow its natural successional processes, or to interfere with these processes, and if so, when and how, is considered a significant research finding.

The grassland community, mainly formed by *Calamagrostis epigejos*, is considered an interesting observation object in the research area. The study showed different growth dynamics of this grass depending on the substrate, which can be used in further research, both ecological and archaeological.

At the current stage of technological development, remote sensing techniques should still be supported by ground observations, but it can already be stated that they provide sufficiently accurate data to track successional processes retrospectively, as well as the necessary data for making decisions that affect the future course of vegetation community succession.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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