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MOBILE GIS IN MAPPING VEGETATION ON MINE HEAPS: A MODERN APPROACH TO RECLAMATION OF POST-MINING AREAS

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Abstract

This paper presents the application of mobile geographic information systems (mobile GIS) in the study of successional vegetation in the Schöttelheide area, a degraded heap of the former Prosper-Haniel mine in the Ruhr region. This area, left to natural succession, became the focus of research using Survey123 and Flora Incognita for the automatic identification of plant species. The aim of the study was to make a spatial inventory of the plant communities taking into account the stage of succession, the presence of invasive species and the natural valorisation. The results showed that mobile GIS is an extremely effective and flexible tool for monitoring ecological succession in hard-to-reach and heterogeneous post-mining habitats.

Keywords: geomonitoring, mine waste dumps, biodiversity assessment, ecological succession

1. INTRODUCTION

Post-mining land reclamation poses a complex environmental and spatial planning challenge. While mineral extraction has played a central role in industrial and regional development, it leaves behind vast areas of heavily degraded land. Reclaiming these landscapes is not only an ecological necessity but also a social responsibility. As noted by [1] and [2] reclamation should be planned as an integral part of the mining lifecycle, not as an afterthought. When implemented effectively, it can restore and even enhance the ecological and functional value of affected areas, creating opportunities for biodiversity, recreation, and local development.

Among the most recognized reclamation strategies are forestation, agriculture, recreation, water body formation, and industrial reuse-each selected based on the site's ecological and socio-economic context [3,4]. Increasingly, however, attention is being paid to natural succession as an ecologically sound and cost-effective alternative. This nature-based approach allows ecosystems to regenerate spontaneously, often leading to structurally diverse, stable habitats with high conservation value [5].

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Heaps due to their steep topography, poor soil quality, low water retention, and high susceptibility to erosion, are among the most difficult post-mining features to reclaim [6].

Recent research supports the value of spontaneous vegetation succession not only for soil stabilization but also for enhancing soil biochemical processes and supporting rare species habitats [7-9]. The monitoring of such dynamic processes has greatly benefited from advancements in geospatial technologies. Remote sensing and GIS-based approaches have become essential in reclamation planning and adaptive management [10], enabling researchers to track successional changes across large and heterogeneous areas.

Within this technological context, mobile geographic information systems (mobile GIS) have emerged as transformative tools for conducting ecological fieldwork in difficult to access or logistically challenging terrains, such as post-mining heaps, where traditional survey methods may be limited or impractical. These systems enable real-time, georeferenced data collection, integrating photographs, species observations, and standardized survey formats into a unified digital platform. As highlighted by [11], mobile GIS tools significantly reduce the time and cost of data acquisition while improving spatial precision.

The integration of GIS with remote sensing has further expanded the analytical potential for monitoring vegetation dynamics and succession trajectories [12]. Moreover [13] demonstrated the practical value of linking mobile GIS platforms with cloud-based systems such as Google Fusion Tables for real-time data visualization and interactive ecological mapping. The technology's versatility is reflected in its successful use beyond the natural sciences, including urban planning and cultural heritage management [14].

In the case of the Schöttelheide heap a remnant of the Prosper-Haniel mine in Bottrop (North Rhine-Westphalia), mobile GIS tools were applied to assess vegetation development and ecological succession. When discussing the democratization of ecological monitoring through mobile GIS technologies, it is crucial to distinguish between open-access and commercial tools. Open-access mobile GIS applications, such as Flora Incognita and several others described in [15], including open-source GIS mobile tools like QField and Locus Map, serve as pioneers in democratizing environmental data collection by enabling free and open participation from non-specialists and citizen scientists. These platforms empower not only trained scientists but also local communities, students, NGOs, and citizen scientists to engage actively in ecological assessments. This bottom-up model fosters inclusivity, transparency, and rapid knowledge sharing, which are key elements in democratizing ecological monitoring.

In contrast, commercial applications such as Survey123, developed by ESRI, although well-suited for research and widely used in practice, present inherent limitations regarding democratization. While some limited free access is available for personal or educational use, full access to the application's features typically requires a paid subscription. This subscription model restricts unrestricted participation and poses barriers for broader community involvement. Thus, representing Survey123 as a democratizing tool can be misleading, as subscription costs and licensing restrictions limit access, especially for citizen scientists or smaller organizations with limited resources.

To fully realize the democratizing potential of mobile GIS technology, it is necessary to critically assess software accessibility, including licensing models, hardware requirements, and internet availability. Open-access platforms such as QField, Locus Map, and Flora Incognita exemplify tools that better support inclusive and participatory ecological monitoring. Meanwhile, commercial solutions like Survey123, despite their powerful capabilities, may inadvertently restrict democratization due to cost and licensing constraints.

But both sides – open source and commercial products – has both their benefits. While open source is available under free-of-charge open licences it needs much more technical understanding to create applications. Commercial software – on the other side – delivers an end user approach which makes it much easier to build the mapping application. Thus, the reason for the closed source fees.

In this study, we report the results of fieldwork conducted on the Schöttelheide heap using the aforementioned mobile GIS tools. The primary objective was to assess the usability and effectiveness of mobile applications in documenting plant diversity and to evaluate their potential in the context of sustainable post-mining landscape revitalization. The authors attempt to demonstrate that these technologies, despite their relative simplicity and wide availability, provide real support for practical conservation and landscape planning activities in post-industrial areas.

2. RESEARCH AREA

The mine heap Schöttelheide is one of the last large mine heap in the Ruhr, located in the Grafenwald district of Bottrop, in the immediate vicinity of the Haniel heap. It was created as a storage site for waste rock from the Prosper-Haniel coal mine, one of the last active coal mines in Germany. The process of heap formation began in 2001 and continued until the end of the mine's operation in 2018 (Fig. 1). During this period, approximately 32 million tonnes of rock material was deposited and covering an area of approximately 66.7 hectares [16,17].

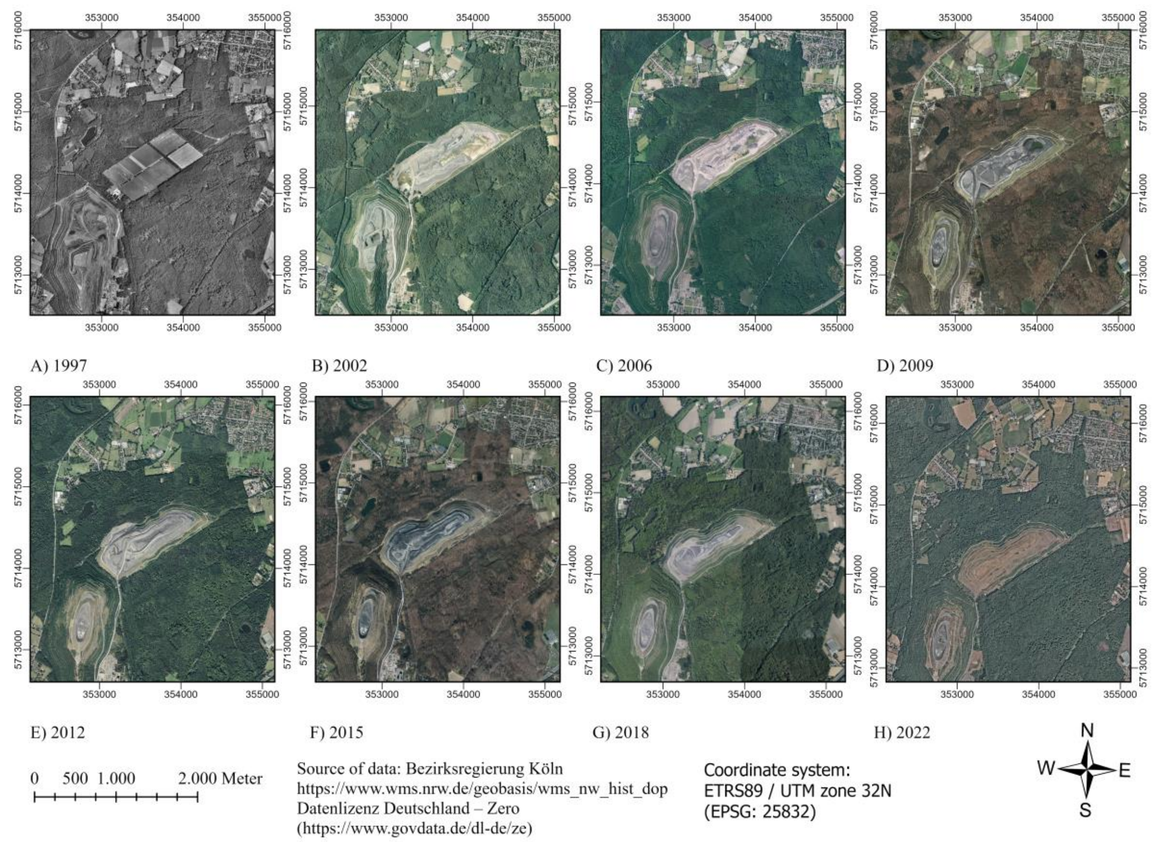

Fig. 1. Temporal analysis of mine heap – Schöttelheide. Source of data: [18]

The difference in elevation within the heap ranges from about 45 m above sea level at the foot to about 120 m above sea level at the top, giving a relative height difference of about 75 meters. The slope of the heap varies from section to section, averaging 12-20°, reaching maximum values of over 25° in places, particularly in the north-western and southern areas [19].

Although the heap is currently officially closed to visitors due to ongoing reclamation work, there are plans to transform it into a recreational area with access for pedestrians and cyclists. A path leading to the top of the heap, offering panoramic views of the surrounding area, is to be built in the future. While the site is being prepared for future public use, parts of the heap are already undergoing natural succession, with pioneer plant species gradually colonizing the slopes. This coexistence of planned reclamation measures and natural vegetation processes is typical for post-mining landscapes in the Ruhr region and has been documented for several similar sites [16,17].

The Schöttelheide mine heap, as one of the last major reclamation projects in the region, exemplifies the combined approach to post-mining land use, integrating ecological restoration with landscape architecture and public access. Its development reflects broader trends in the Ruhr area, where former industrial sites are being transformed into multifunctional green spaces that promote biodiversity, climate resilience, and recreational use for residents.

3. METHODOLOGY

The study was carried out during the 2025 growing season on the Schöttelheide heap. This area, devoid of technical reclamation, has been subject to plant succession for more than two decades. The aim of the study was to document the current state of the plant communities using simple, available mobile technologies - without the use of remote sensing or elevation data. It was assumed that a methodology based on mobile tools (Survey123 and Flora Incognita) would enable the creation of a functional database of habitats and species under field conditions typical of post-mining areas: morphologically diverse, difficult to access and not covered by monitoring infrastructure.

The choice of survey tools was dictated by both functional and operational considerations. An Android smartphone equipped with a GNSS receiver with a locational accuracy of 1 to 5 metres was used for data collection. The Survey123 for ArcGIS application was installed on the device, enabling the design of field forms and automatic recording of survey locations [20]. The form contained standardised fields for location description, plant species and photographic documentation (Fig. 2).

In parallel, the Flora Incognita app was used, which, thanks to deep learning algorithms, allows plant species recognition from photographs taken under field conditions [21,22]. This mobile application employs deep learning algorithms for automatic plant species identification. Specifically, the image recognition is based on convolutional neural networks (CNNs) trained on a large dataset of plant images. The architecture and training strategies are detailed in the work by [21], where the authors describe the use of ensembles of CNNs to improve accuracy across diverse species and image conditions. For each measurement point, a photograph was taken: a snapshot of the plant habit, which was then analysed in the app (Fig. 2). In the case of automatic identification, the indicated result was verified against a list of species typical of the Rhineland region and available field atlases. In doubtful situations and where there was no good internet connection (e.g. species with similar morphology: grasses, carnations), the identification was postponed for later verification on the basis of the collected photographic documentation.

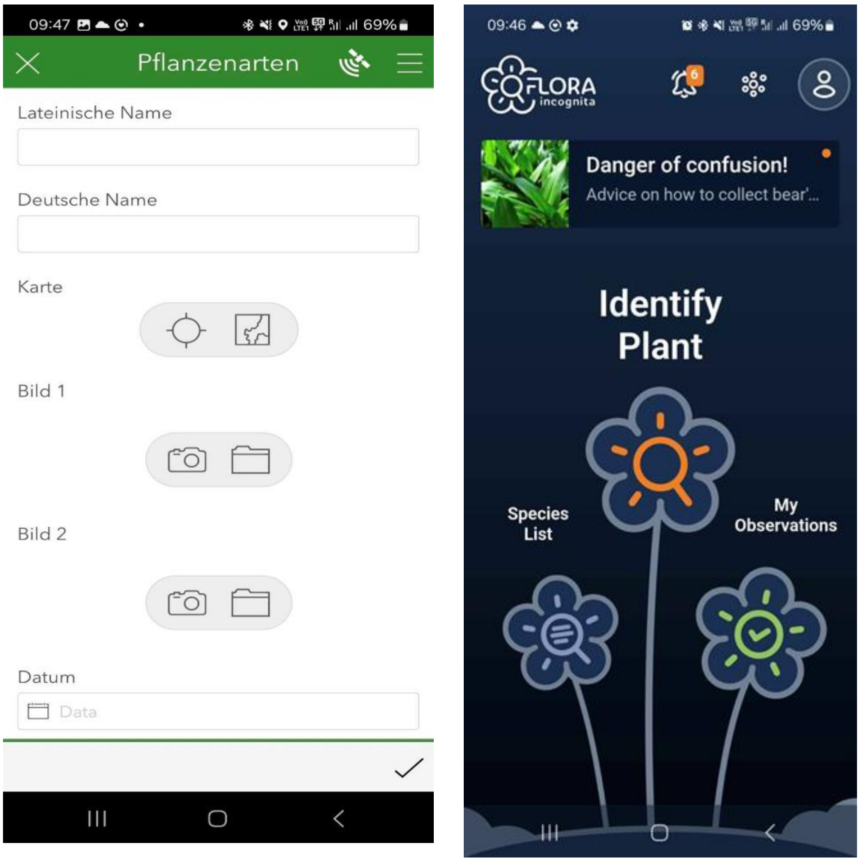

Fig. 2. Application: Survey123 (left) and Flora Incognita (right)

Observation points were selected using a purposive sampling method with elements of a mosaic strategy, meaning that points were located in areas representing the morphological and habitat diversity of the heap. Particular attention was given to: (1) south-facing slopes, characterized by intensive colonization by grassland and ruderal communities; (2) terrain depressions, where moisture-loving plant communities developed; (3) areas along technical roads and drainage ditches; and (4) enclaves exhibiting an advanced degree of woody succession, where young shrublands were present. In total, data were collected from 220 points (Fig.3).

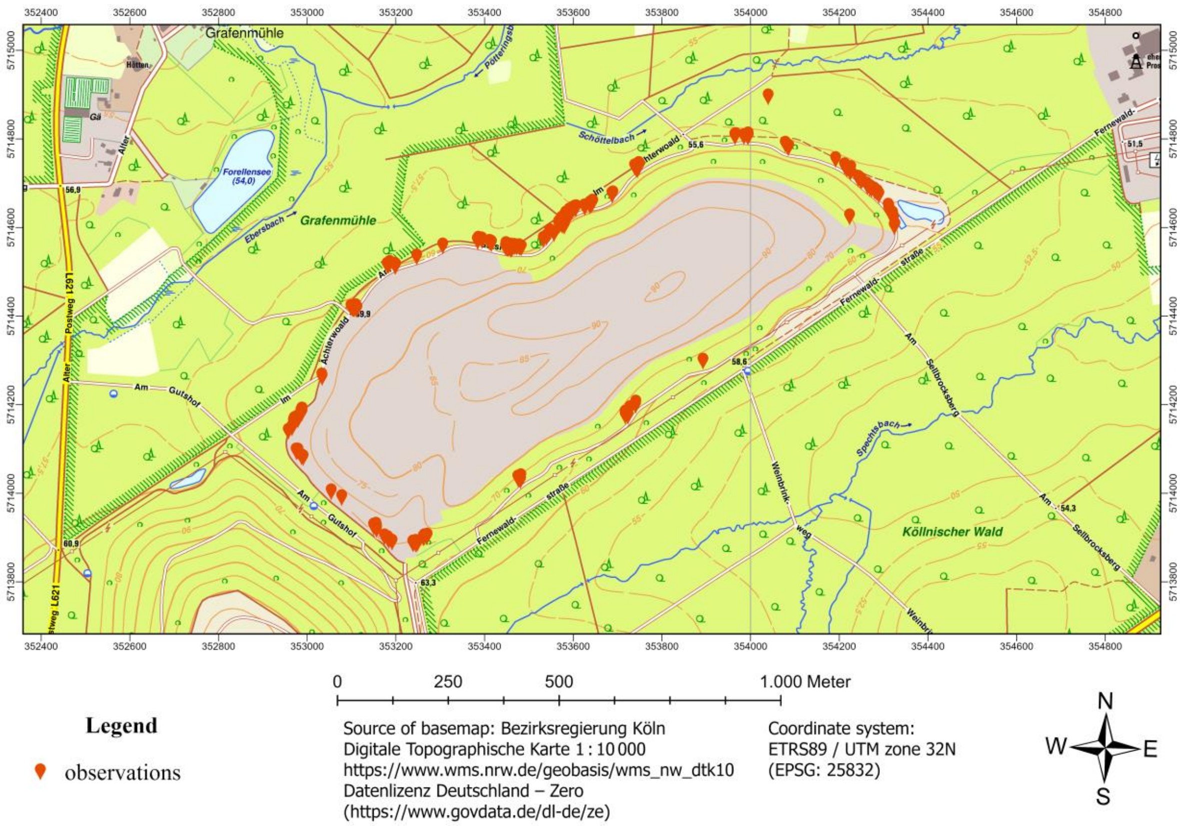

Fig. 3. The research area with the observation points. Source of basemaps: [23]

Each survey point contained: (1) automatic GNSS data, (2) close-up and general photographs, (3) plant species name in Latin and (4) plant species name in German, Once the fieldwork was completed, the data from Survey123 were synchronised with the ArcGIS Online platform. At this stage, a preliminary spatial analysis was carried out, including visualisation of the distribution of community types. The collected data formed the basis for creating a cartographic database of the vegetation of the Schöttelheide heap. This methodology - despite the lack of specialised equipment and remote data - allowed a detailed mapping of the diversity of communities and an assessment of their state of succession. Importantly, all of the data could be collected by a two-person research team within one field day, confirming the efficiency and scalability of the technology used. This example can successfully serve as a starting point for the development of a method for monitoring ecological succession on other brownfield sites, also in the context of revitalisation, restoration and participatory environmental management projects.

4. RESULTS

An analysis of the vegetation colonizing post-mining dumps reveals a diverse group of plant species, reflecting various stages of ecological succession and the influence of habitat conditions typical of heavily transformed environments. The flora includes pioneer, expansive, and more stabilized species, indicating the dynamic nature of vegetation development on these sites. Among the most prominent pioneer species effectively colonizing nutrient-poor, dry soils are Pinus sylvestris and Betula pendula

(Fig.4). Both species are characterized by a high tolerance to environmental stress and an ability to thrive in habitats with limited nutrient availability. Populus tremula is also frequently encountered, showing similar adaptability to harsh conditions.

Fig. 4. *Pinus sylvestris* (left) and *Betula pendula* (right)

A significant feature of the analyzed sites is the notable presence of invasive and expansive species. Solidago gigantea is prime examples of plants capable of rapidly occupying open areas and displacing native vegetation (Fig.5).

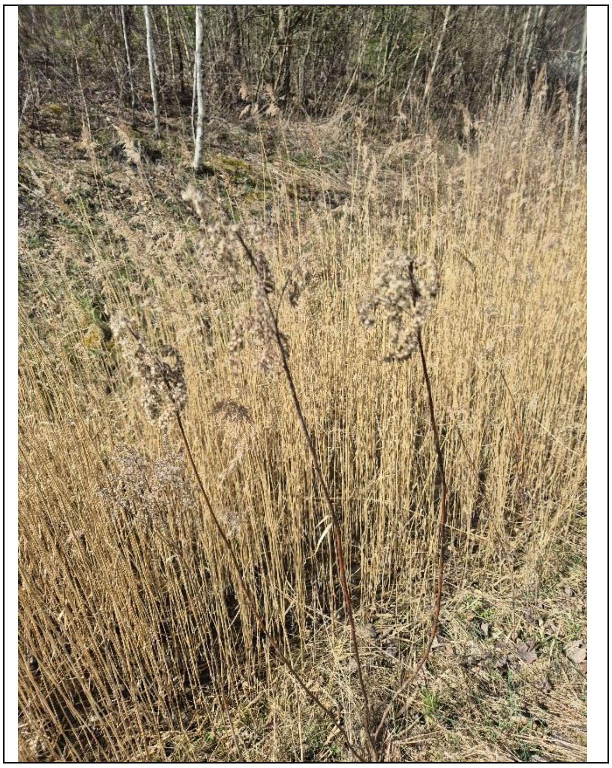

Fig. 5. *Solidago gigantea*

The occurrence of grassland species typical of dry, semi-natural meadows, such as Plantago lanceolata, Achillea millefolium agg., Dactylis glomerata agg., and Calamagrostis epigejos, indicates successional trajectories towards the formation of grass-dominated communities where site conditions are suitable. In certain sections of the dumps, species associated with moist or periodically flooded habitats have also been observed, such as Phragmites australis and Salix viminalis. Their presence suggests the existence of local hydrological niches resulting from the heterogeneous structure of the dumps and fluctuating groundwater levels. Vegetation succession on the studied sites also includes the development of young woodlands and shrub formations. The occurrence of species like Corylus avellana (Fig. 6 right), Prunus spinosa agg. (Fig. 6 left), Crataegus monogyna, Quercus robur, Ulmus glabra, Ulmus minor agg., and Fagus sylvatica indicates the gradual establishment of more complex and permanent forest communities. This natural progression points to the dumps' potential for spontaneous biological reclamation.

Fig. 6. *Prunus spinosa agg. (left)* and *Corylus avellana (right)*

The floristic composition further includes rare or habitat-specialist species such as Lysichiton americanus (an introduced species in Europe) and Pulsatilla albana, emphasizing the mosaic character of the surveyed areas. The presence of shrubs such as Rubus Rubus sect. (Fig.7), Rubus phoenicolasius, Rosa multiflora, Rosa canina, and Rosa rugosa highlights the intense progression towards shrub-dominated communities, which in the future may form dense thickets, limiting the development of herbaceous vegetation.

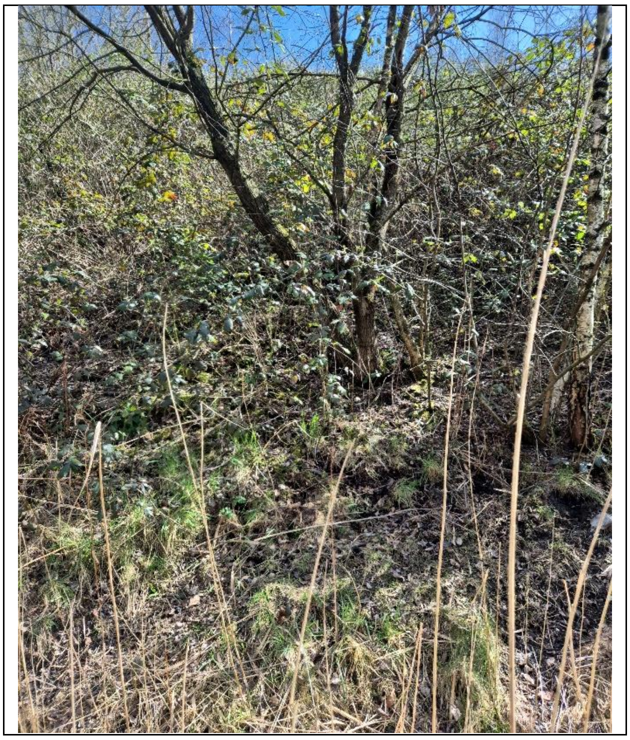

Fig. 7. *Rubus Rubus sect.*

During the feld survey at the Schöttelheide mine heap, a total of 61 plant species were identified using the Flora Incognita mobile application. The table 1 below summarizes the number and percentage of identified species.

Table 1. The characteristic of identified species

Vegetation type	Number of records	Percentage (%)
Acer pseudoplatanus	2	0,91
Achillea millefolium agg.	1	0,45
Alnus glutinosa	3	1,36
Barbarea vulgaris agg.	2	0,91
Betula pendula	20	9,09
Buddleja davidii	1	0,45
Calamagrostis epigejos	1	0,45
Cichorium intybus	1	0,45
Corylus avellana	12	5,45
Cotoneaster horizontalis	1	0,45
Vegetation type	**Number of records**	**Percentage (%)**
Crataegus monogyna	4	1,82
Cytisus scoparius	6	2,73
Dactylis glomerata agg.	2	0,91
Fagus sylvatica	1	0,45
Geum urbanum	1	0,45
Heraclum sphondylium	1	0,45

Hippophae rhamnoides	6	2,73
Ilex aquiffolium	1	0,45
Jacobaea vulgaris	1	0,45
Leymus arenarius	1	0,45
Lysichiton americanus	2	0,91
Molinia caerulea agg.	2	0,91
Oenothera	2	0,91
Phragmites australis	16	7,27
Pinus nigra	3	1,36
Pinus ponderosa	1	0,45
Pinus spinosa agg.	1	0,45
Pinus sylvestris	10	4,55
Plantago lanceolata	4	1,82
Populus balsamifera agg.	2	0,91
Populus suaveolens	1	0,45
Populus tremula	1	0,45
Prunus avium	1	0,45
Prunus cerasifera	2	0,91
Prunus spinosa agg.	15	6,82
Pulsatilla albana	1	0,45
Pyrus calleryana	1	0,45
Quercus robur	1	0,45
Ranunculus acris agg.	1	0,45
Reynoutria japonica	1	0,45
Robinia pseudoacacia	1	0,45
Rosa canina	2	0,91
Rosa multiflora	2	0,91
Rosa rugosa	1	0,45
Rubus phoenicolasius	1	0,45
Rubus rubus sect.	7	3,18
Salix caprea	1	0,45
Salix viminalis	1	0,45
Vegetation type	**Number of records**	**Percentage (%)**
Sanguisorba minor	4	1,82
Solidago gigantea	5	2,27
Sorbus latifolia agg.	1	0,45
Spartium junceum	1	0,45
Taraxacum	4	1,82
Tussilago farfara	5	2,27
Ulmus glabra	1	0,45
Ulmus minor agg.	1	0,45
Urtica dioica	1	0,45
Viscum alum	1	0,45
Other/ unidentified	44	20,00
Total	220	100,00

A total of 220 plant records were collected, of which 31.36% represented pioneer species typical of ruderal habitats (e.g., Betula pendula), while 11.36% corresponded to species characteristic of meadow and grassland communities. The most frequently recorded species were:

- Betula pendula (20 records, 9.09%),
- Phragmites australis (16 records, 7.27%),
- Prunus spinosa agg. (15 records, 6.82%),
- Corylus avellana (12 records, 5.45%),
- Pinus sylvestris (10 records, 4.55%).

Pioneer species were particularly dominant in the central and steeper parts of the dump, where site conditions (shallow soil layers, high sun exposure, and erosion) favored vegetation with high ecological tolerance. In contrast, greater species richness was observed along the edges of the dump and in areas with gentler slopes, where more substantial soil accumulation had occurred. This spatial pattern reflects both the topographic variation of the site and the natural plant colonization processes typical of post-mining habitats.

Note*: No data on plant age or health condition were collected during this study, as the focus was on species identification and spatial vegetation patterns rather than plant physiology.*

A total of 44 records (20%) were classified as other / unidentified. These entries include observations that could not be reliably assigned to a specific species due to various limitations encountered during fieldwork. The most common issues included:

- Overexposed or poorly lit photographs, often caused by strong sunlight, which reduced image clarity and interfered with key morphological features needed for identification.
- Multiple species present in a single photo, which confused the identification algorithm and led to ambiguous results.
- Technical issues with mobile connectivity, which occasionally prevented the app from accessing the full database or uploading high-resolution images for server-side analysis.
- Such limitations are common in dynamic field conditions and highlight the importance of optimal photo quality, clear focus on a single plant, and stable app functionality for achieving high identification accuracy. Where possible, these records were flagged for later review or marked as "unidentified" to maintain data integrity.

In summary, the flora of post-mining dumps reflects dynamic ecological succession processes, encompassing both pioneer colonization and the expansion of invasive species, as well as the formation of semi-natural meadow and young forest communities. The ongoing processes underline the need for continued monitoring and, where necessary, management interventions aimed at limiting the spread of invasive alien species and promoting the development of native vegetation.

5. DISCUSSION

The combined use of the Survey123 application and Flora Incognita provided an accessible, scalable solution for documenting plant diversity. Although Flora Incognita facilitated rapid species identification, its performance was limited in low-light conditions and for morphologically ambiguous specimens. Additionally, large parts of the study area lacked stable internet connectivity, which restricted real-time species verification and app functionality.

Therefore, basic knowledge in botany and a classic plant identification book can be of high value in delivering better results. Botanists often use a magnifying glass, especially when it comes to identifying minimal differences, such as the number of hair rows on the stem or microscopic features. Such magnification is almost impossible to achieve with a mobile phone camera under field conditions. However, most limitations of Flora Incognita were effectively mitigated by Survey123, which allowed all photos and metadata to be archived locally during fieldwork. This ensured that later post-processing, verification, and classification of species could be completed once internet access was restored. As confirmed by [15], this hybrid approach provided a robust and flexible workflow suitable for fieldwork in technically constrained environments.

The vegetation patterns observed on the Schöttelheide heap reflect a complex interplay between natural successional dynamics and anthropogenic disturbances that continue to influence these landscapes. The predominance of pioneer species such as *Pinus sylvestris, Betula pendula,* and *Populus tremula* indicates that many parts of the surveyed dump are in the early to intermediate stages of primary succession. These species, highly adapted to nutrient-poor and unstable substrates, successfully colonize degraded habitats without the need for intensive human intervention.

The results of this study confirm earlier hypotheses regarding ecological succession on post-mining sites. The observed diversity of vegetation types and the varying stages of succession demonstrate that natural regeneration processes can proceed effectively even under severely degraded conditions. The recorded mosaic of habitat types across Schöttelheide highlights the strong dependency between local factors such as slope aspect, microclimate, and water availability and both the direction and pace of succession. This finding supports the concept of succession as a spatially heterogeneous and non-linear process, where different forms of plant communities can coexist in close proximity. Thus, natural succession builds its own biodiversity.

Notably, the development of advanced successional communities, such as dense shrublands and young birch-willow forests, indicates the progressive formation of vertical vegetation structure and stabilization of habitat conditions. The emergence of shrub layers and herbaceous understories accompanying young tree stands points to the activation of soil protection mechanisms and an increase in local biodiversity. These observations align with existing literature suggesting that tree-dominated habitats tend to exhibit greater resistance to colonization by invasive plant species.

Nevertheless, the widespread occurrence of invasive alien species such as *Solidago gigantea* poses a serious challenge to the long-term ecological stability of the area. Invasive plants, characterized by their rapid growth and adaptability, threaten to outcompete native species, alter soil properties, and homogenize the vegetation structure. Their presence underlines the urgent need for continued monitoring and, where necessary, active management interventions.

From a methodological perspective, the applied survey approach combining the use of Survey123 and Flora Incognita applications proved to be effective, flexible, and well-suited to field conditions. The integrated methodology confirmed the propositions made by [21], who emphasized the growing importance of mobile technologies in rapidly acquiring ecological data. The Umweltkumpel [24] project is presented in this study as a representative case that illustrates how mobile technologies and citizen science can be effectively applied to environmental monitoring in post-industrial regions. It serves as a practical example of the methodology explored in this research, which focuses on participatory approaches to tracking ecological changes and promoting regional resilience after mining activities. By collecting data on environmental impacts in regions formerly affected by mining activities, the project utilizes mobile technologies to engage citizens in critical environmental monitoring. Participants employ applications like Survey123 to document changes in their local environments and upload their observations and photos onto an interactive map. This approach enables citizens to assist researchers at the Research Center of Post-Mining in their investigations of ecological changes. By providing data on where detailed measurements or drone images might be beneficial, and distinguishing changes attributable to mining from those caused by other influences such as climate change, Umweltkumpel embodies the integration of citizen science with advanced technological tools [25,26]. In addition to facilitating large-scale environmental monitoring, the project fosters community involvement and offers a platform for dialogue and exchange about issues such as the resilience and sustainable development of post-mining regions. Participants' contributions help identify key ecological factors and promote a deeper understanding of how these regions can adapt and thrive post-mining. Thus, Umweltkumpel not only supports scientific research but also enhances public engagement and awareness, illustrating the transformative potential of combining mobile technologies with citizen science.

Automated geolocation, photo integration, preliminary plant classification, and immediate data synchronization significantly reduce the time required for data processing and enhance spatial analysis capabilities [15]. Importantly, this method is applicable even in areas with limited internet access, making it valuable not only for academic research but also for environmental monitoring conducted by public authorities and non-governmental organizations.

An important aspect of the fieldwork was the high efficiency of data acquisition using the Flora Incognita mobile app. Identification of a single plant specimen including photographing, submitting, and receiving results took about 30 to 60 seconds, depending on species complexity and conditions. This is a substantial improvement over traditional manual methods, which can take several minutes, especially for non-flowering plants. The app reduces the need for expert botanical knowledge, enabling broader participation in biodiversity monitoring and preliminary vegetation mapping. However, identification accuracy depends on image quality and species distinctiveness; challenges arise with morphologically similar species or poor-quality photos [27]. Another mapping method is data collection by UAV (unmanned aerial vehicle). Here, however, there are further limitations in terms of species identification, as can be realised with the Flora Incognita app, for example. However, the use of UAVs is important and conceivable if detailed mapping of plant communities in the area is required. Here, a classification and segmentation of certain biotope types could be realised. UAV-based remote sensing offers large-scale vegetation monitoring using multispectral sensors and machine learning algorithms [28]. UAVs provide broad spatial coverage and repeatability, ideal for remote or difficult terrains. However, UAV methods face limitations in species-level identification, especially for understory plants, and are constrained by regulatory and cost issues. Combining UAV data with ground-level AI-assisted surveys enhances vegetation classification accuracy and ecological understanding, as shown in research by [29]. This integrated approach leverages UAV spatial overview and mobile app taxonomic detail, crucial for monitoring complex, dynamic habitats like post-mining sites.

In summary, the Schöttelheide spoil heap represents a dynamic and ecologically valuable post-industrial landscape undergoing rapid succession. While natural processes are driving the recovery of these environments, the influence of invasive species and spatial heterogeneity presents both opportunities and challenges. Strategic, adaptive management that supports native biodiversity while controlling invasive species will be crucial for ensuring the long-term resilience and ecological integrity of post-mining ecosystems.

In summary, mobile AI-assisted applications like Flora Incognita offer a fast, cost-effective, and relatively accurate method for species-level plant identification directly in the field, significantly reducing the need for specialized taxonomic expertise. Meanwhile, UAV-based remote sensing expands the spatial and temporal scale of vegetation assessments but requires ground truthing for precise species identification. The integration of both approaches presents a forward-looking, comprehensive framework for vegetation monitoring that balances taxonomic detail with spatial coverage and efficiency-particularly relevant for dynamic and heterogeneous ecosystems such as post-mining sites and other anthropogenically transformed landscapes.

The Schöttelheide heap exemplifies such a dynamic and ecologically valuable post-industrial landscape undergoing rapid succession. Natural processes are driving the recovery of this environment, yet the influence of invasive species and spatial heterogeneity introduces both opportunities and challenges. Strategic, adaptive management that supports native biodiversity while controlling invasive species will be crucial to ensuring the long-term resilience and ecological integrity of post-mining ecosystems.

6. CONCLUSIONS

The field research conducted on the Schöttelheide heap clearly demonstrates that ecological succession processes under post-industrial conditions can successfully lead to the development of dynamic and diverse natural habitats. Despite the absence of active reclamation interventions, the site exhibits a distinct mosaic of vegetation communities-ranging from grassy pioneer stages, through wetland habitats, to successional shrublands and young woodlands. A particularly significant finding is the observation that woody communities, as well as those exhibiting more complex vertical structures, are associated with greater ecological stability and a reduced susceptibility to colonization by invasive alien species. In contrast, a high concentration of non-native species was observed along roadsides and technical infrastructure zones, underscoring the need for continuous ecological monitoring and the implementation of biological control strategies.

Regarding the methodology employed, it is important to highlight the high effectiveness of simple mobile tools such as the Survey123 and Flora Incognita applications. These tools enabled the rapid and precise acquisition of both spatial and botanical data, facilitating comprehensive field inventories without the need for costly equipment or remote sensing technologies. However, fieldwork revealed certain challenges. Difficulties in correctly identifying some plant species using the Flora Incognita application were encountered, particularly in the case of poorly developed individuals, complex vegetation layers, and under suboptimal lighting conditions. Moreover, the lack of internet connectivity across significant areas of the study site limited the real-time functionality of species validation and information access.

Nevertheless, the concurrent use of Survey123 provided a robust solution: the automatic saving of photographs and metadata in the app allowed for the archiving of critical information during fieldwork. This enabled later verification and correction of species identifications once an internet connection was re-established, thus ensuring the accuracy and completeness of the botanical inventory. When combined with open-source GIS platforms, the datasets created enable extensive opportunities for spatial analysis, habitat conservation planning, monitoring program development, and early threat identification, including invasive species pressures.

Ultimately, it can be concluded that the Schöttelheide heap serves as a valuable model for the natural regeneration of post-mining areas and confirms the validity of reclamation strategies based on natural succession. The findings provide a solid reference for the design and implementation of green infrastructure projects in post-industrial regions, particularly within the broader context of energy transition and ecological restoration initiatives.

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