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THE POTENTIAL OF USING HYPERSPECTRAL AIRBORNE DATA IN MONITORING POST-MINING NOVEL ECOSYSTEMS

Purpose. Improving the efficiency and accuracy of monitoring post-mining landscapes through the use of hyperspectral remote sensing and analysis of airborne data for vegetation management on post-mining heaps, in line with the principles of modern geoinformation technologies and remote sensing science.

Methodology. Based on remote sensing methods, particularly hyperspectral airborne data, monitoring and assessment of post-mining areas are carried out. Hyperspectral remote sensing provides an effective approach for assessing contamination levels, vegetation condition, and restoration processes, thereby supporting decision-making in land reclamation and sustainable management of post-mining landscapes.

Findings. An improved, validated model for monitoring post-mining ecosystems using hyperspectral airborne data has been developed, thereby increasing the accuracy of assessing the ecological condition of waste heaps and the dynamics of vegetation recovery. The spectral characteristics of areas with different levels of anthropogenic impact have been identified, enabling the detection of degradation zones and areas of natural regeneration. The effectiveness of integrating hyperspectral data and geoinformation technologies for reclamation control and post-mining landscape management has been proven.

Originality. The monitoring approach for post-mining ecosystems based on the use of hyperspectral airborne data and geoinformation technologies has been proposed and validated. Its main principles include:

- the determination of spectral characteristics of vegetation cover and waste heaps with different levels of anthropogenic impact;
- the identification of degradation, contamination, and natural regeneration zones;
- the integration of remote sensing data with geoinformation systems;
- the provision of reclamation process control as well as forecasting the development of new ecosystems in areas affected by mining activities.

Practical value. The proposed approach to monitoring post-mining ecosystems using hyperspectral airborne data and geoinformation technologies improves the accuracy and efficiency of assessing the ecological condition of waste heaps and adjacent areas. The obtained results can be used to identify zones of degradation and natural vegetation recovery, as well as to monitor reclamation processes in landscapes affected by mining activities. The practical implementation of this approach improves environmental monitoring systems in mining regions and enhances the effectiveness of management decisions for restoring disturbed territories.

Keywords: *remote sensing, minerals, mineral heaps, hyperspectral data, environmental resilience assessment tool*

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Introduction. Hyperspectral airborne data are commonly used in agriculture and forestry because they provide high-resolution, continuous spectral information that allows detailed assessment of vegetation condition and functioning. By capturing hundreds of narrow spectral bands, these data enable detection of subtle changes in plant physiology, including chlorophyll content, water status, nutrient availability, and stress responses. In agriculture, they support precision farming, crop monitoring, yield estimation, and early stress-detection. In forestry, hyperspectral data facilitate the identification of tree species, biodiversity assessment, forest health monitoring, and the evaluation of disturbance impacts [1, 2]. This detailed spectral insight improves sustainable management and decision-making in complex and changing environments [3]. Hyperspectral airborne data have been used to monitor ecosystem processes during the development of novel ecosystems on post-mining mineral sites, such as heaps [4, 3].

Post-mining heaps are piles of mineral material left behind after hard black coal extraction, located in many parts of the world. Post-mining heaps represent specific habitat conditions.

For a long time, post-mining sites have been considered as biological deserts. However, biological and envi-

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ronmental studies have shown that diverse organisms, particularly plants, spontaneously colonize post-mining mineral sites [3]. The colonizer plant species are assembling into non-analogous species communities, leading to the establishment of novel ecosystems sensu Hobbs, et al. [4]. Over time, herbaceous vegetation is replaced by a diverse species composition in heap forests [3, 5]. The mechanisms of these processes are known to a very limited extent. The natural processes of novel ecosystem development on mineral habitats of post-mining sites are common and effective, driven by spontaneous, nature-based solutions, e.g., the relationship between primary producers and decomposer organisms in terrestrial and wetland habitats [6–8]. Understanding the mechanisms of spontaneous, nature-based processes in novel ecosystems is essential for the effective management of mineral post-mining habitats by using geoinformative methods [9–11].

Knowledge of nature-based solutions is crucial for modern post-mining heaps, enhancing the potential for abiotic mineral habitats [7, 12–14]. Growing social awareness of the need to protect, or rather develop, the environmental potential has increased research focused on adequately assessing the habitat potential of mineral mining sites and ensuring their sustainable management and monitoring [15, 16]. The management of those mineral habitats has become an important focus in the mining industry, as the industry increasingly emphasizes sustainable development and environmental protection [15, 16]. The success of spontaneous, nature-based processes is often measured by changes in the biodiversity of organisms, particularly vegetation, found on heaps left to spontaneous organisms' colonization, vegetation patches, and ecosystem establishment [8, 14]. One of the key challenges in managing post-mining heap habitats is obtaining precise, up-to-date data on their chemical, mineralogical, and biological composition over time. The conventional approach relies on on-site sampling, which is time-consuming and labor-intensive, such as biomass assessment, and can only provide information about a restricted geographical area, and needs a new approach [15, 16]. In contrast, remote sensing offers and delivers a more efficient and comprehensive approach to monitoring and post-mining environmental management of heaps and mineral habitats. Environmental data obtained from one aeroplane or drone overflight can provide information about the entire area of interest [17, 18].

A wide range of methods, including satellite imagery analysis, must be used to understand the mechanisms of Novel Ecosystem development [4]. As a result, the spontaneous, nature-based solutions that could be implemented in the management of heap habitats have become a significant priority in the mining areas, identifying and understanding novel ecosystem functions: a scientific approach to nature restoration law, including the geoinformatics methods, is promising [8–14].

The success of nature-based management processes is often measured by increases in biodiversity, particularly in vegetation species composition, that develop spontaneously on mineral material in post-mining habitats, as well as in biomass parameters [15–17]. The development of remote sensing technologies has opened new opportunities for monitoring and collecting data on the functioning parameters of post-mining heap habitats [17, 19], with satellite data available in increasing volume and data from unmanned aerial vehicles (UAVs) and aeroplanes also becoming more accessible [18]. Using hyperspectral data collected from airborne sensors, it is now possible to obtain detailed spectral signatures of the surface and model soil or soil substratum composition, vegetation cover, and some ecosystem functioning parameters in these mining heap habitats, enabling more effective monitoring and management practices [20].

Post-mining heaps in urban areas pose unique challenges for enhancing the natural potential of the mosaic of habitats to support optimal biodiversity [21, 22]. These processes are called by some authors as ecological restoration and land reclamation [23, 24]. These heaps are often situated near residential and commercial areas, making their management and restoration particularly important for the surrounding urban environment. Urban post-mining heaps can contribute to issues such as air and water pollution and soil degradation, highlighting the necessity of effective monitoring and management strategies, on the one hand, while providing precious, poor, and oligotrophic habitats that are prerequisites for unique biodiversity composition. The serious environmental problem is eutrophication of most habitats. The establishment of mineral and poor habitats by mining is an environmental chance to enhance biodiversity and establish processes, including relations between plants and microorganisms [22, 25].

The use of hyperspectral airborne data for monitoring urban post-mining heaps has great potential to address these challenges. By employing this type of data, together with the ground sampling campaigns, researchers can gain valuable insights into the composition of the heaps, the distribution of vegetation, and the effectiveness and progress of restoration efforts. The usefulness of airborne data is in large part due to its relatively high spatial resolution compared to satellite data and its ability to cover larger areas than UAVs. This information can be used to map vegetation cover and soil quality, and to mitigate environmental impacts in urban settings [8–14].

In the following chapters, this paper explores the advantages and limitations of using hyperspectral airborne data for monitoring and managing vegetation on post-mining heaps. It will discuss the basic flow of hyperspectral data processing, vegetation identification using spectral features, and the potential benefits of using hyperspectral data for monitoring post-mining heaps [12–16].

Problem statement. The restoration and monitoring of post-mining landscapes remain a significant challenge due to their complex physicochemical conditions, spatial heterogeneity, and dynamic ecological succession. Post-mining heaps often evolve into novel ecosystems, where vegetation develops under stress factors such as poor soil structure, limited nutrients, and contamination. Traditional ground-based monitoring methods are time-consuming, spatially limited, and often insufficient to capture the variability in vegetation patterns across large, inaccessible areas. Therefore, there is a clear need for advanced, scalable, and non-

invasive approaches that provide detailed, continuous information on vegetation status and ecosystem development in these environments.

Hyperspectral airborne data offer a promising solution by capturing high-resolution spectral information, enabling precise identification of vegetation species, health conditions, and biochemical properties. However, despite their potential, several challenges remain, including the complexity of data processing, the need for robust algorithms for spectral feature extraction, and uncertainties related to environmental variability and sensor limitations. This research addresses the challenge of evaluating the effectiveness and limitations of hyperspectral airborne data for monitoring vegetation on post-mining heaps, with a particular focus on their application for assessing and managing novel ecosystems.

Research methodology, methods, and materials of the research. This study is based on a review and analytical assessment of geoinformatics data, with a particular emphasis on the fundamentals of hyperspectral remote sensing and hyperspectral data processing. The methodological framework follows key stages: data acquisition, radiometric and atmospheric correction, geometric preprocessing, and the transformation of raw data into surface reflectance. These steps ensure data consistency and provide a reliable basis for further ecological interpretation of post-mining environments.

The research materials include hyperspectral airborne imagery acquired over post-mining areas, supported by auxiliary datasets such as high-resolution optical images, digital elevation models, and field observations. Data processing methods include noise reduction, spectral normalization, and dimensionality reduction techniques, such as principal component analysis. Vegetation assessment is performed using spectral signatures, vegetation indices (e.g., NDVI and red-edge indices), and spectral feature analysis. Classification techniques, both supervised and unsupervised, are applied to identify vegetation types, detect stress conditions, and characterize different stages of ecosystem development.

To assess the effectiveness of hyperspectral data in monitoring post-mining novel ecosystems, the study applies comparative and validation approaches. The obtained results are evaluated against available ground data and ecological information where possible. Additionally, the research considers temporal analysis to track vegetation changes and restoration progress. Attention is given to the limitations associated with hyperspectral data, including sensor constraints, environmental variability, and uncertainties in data interpretation. This integrated approach allows for a comprehensive evaluation of hyperspectral remote sensing as a tool for sustainable monitoring and management of post-mining landscapes.

Basics of hyperspectral remote sensing. Remote sensing is a technique for collecting detailed information about Earth's surface from a distance using sensors typically installed on satellites, aircraft, or unmanned aerial vehicles (UAVs). These sensors detect and measure electromagnetic radiation reflected or emitted by surface materials, enabling the observation of physical and chemical properties without direct contact. The acquired data span a wide range of the electromagnetic spectrum, including visible light, infrared, and microwave regions, allowing for comprehensive analysis of land cover, vegetation, soil conditions, and environmental processes (Figs. 1, 2). This non-invasive approach is particularly valuable for monitoring large, complex, or inaccessible areas, such as post-mining landscapes.

In contrast to conventional remote sensing systems, hyperspectral remote sensing offers extremely high spectral resolution, capturing data across hundreds or even thousands of very narrow, contiguous spectral bands. This fine spectral detail enables precise identification of materials and subtle variations in vegetation condition, mineral composition, and surface contamination. Furthermore, hyperspectral datasets are often complemented by laboratory spectroscopy and proximal remote sensing measurements conducted directly in the field, which improve calibration accuracy and support the interpretation of spectral signatures. As a result, hyperspectral remote sensing provides a powerful framework for advanced environmental monitoring and detailed surface characterization.

Every object on the earth's surface has its unique spectral signature, which is a characteristic pattern of the wavelengths of light it absorbs or reflects. Remote sensing sensors capture spectral information across various wavelengths, allowing researchers to identify and characterize different materials, vegetation types, and other features on the ground [26, 27]. The most used sensors in environmental studies detect reflected radiation in the visible and infrared parts of the spectrum.

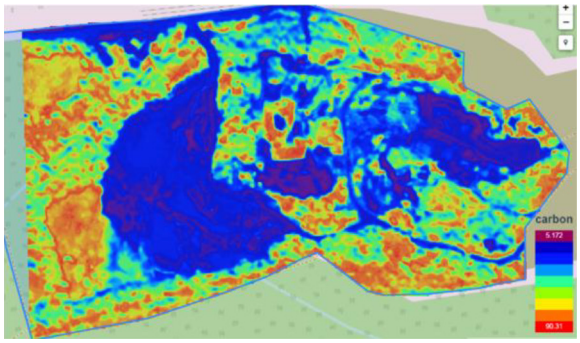

Fig. 1. The model of the total carbon content in the substrate of the "Wesoła" heap in Mysłowice – the area of the studied object is 37 ha, the modelling showed a total carbon accumulation of over 5 tons, with an average accumulation of 13.7 grams per m^2

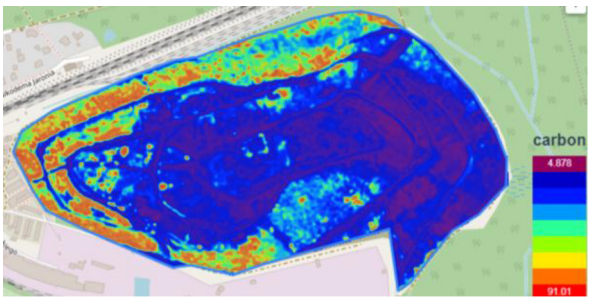

Fig. 2. The model of the total carbon content in the substrate of the "Makoszowy" heap in Zabrze – the area of the studied object is 277 ha, the modelling showed a total carbon accumulation of over 30.4 tons, with an average accumulation of 10.98 grams per m^2

The amount of spectral data collected by these sensors distinguishes hyperspectral remote sensing from more traditional multispectral remote sensing, which typically uses fewer, broader wavelength bands [27].

The key advantage of remote sensing is its ability to cover large areas and gather data in inaccessible or hazardous locations, thereby reducing the labor and costs of traditional sampling [28]. This data can be processed and analyzed to monitor environmental changes, map land use, assess natural resources, or study the Earth's surface in detail and at regular intervals.

Remote sensing data is collected from various airborne and spaceborne platforms, each with unique advantages and disadvantages. Spaceborne sensors can cover large geographic areas but have lower spatial resolution than airborne sensors [28]. Airborne sensors, such as those mounted on manned aircraft or UAVs, offer higher spatial resolutions and the ability to target specific areas of interest. Comprehensive monitoring campaigns often use data from various types of sensors, including multispectral, hyperspectral, and LiDAR technologies, mounted on diverse platforms.

Hyperspectral remote sensing, a specialized form of this technology, captures information across a wide range of contiguous spectral bands. This enables detailed identification and analysis of materials based on their unique spectral signatures. It is beneficial in applications such as mineral exploration, environmental monitoring, and agricultural assessment, where precise material characterization is required. In the context of post-mining heap restoration monitoring, hyperspectral remote sensing can provide invaluable insights into the composition, structure, and vegetation of these areas.

Advantages and limitations of hyperspectral remote sensing. Hyperspectral imaging has numerous advantages:

Detailed spectral information: Hyperspectral sensors capture data across hundreds of narrow, contiguous wavelength bands (usually between 400 and 2,500 nm), providing much higher spectral resolution than traditional multispectral sensors. Together with spectral information stored in various spectral databases, this enables more accurate identification and characterization of vegetation, minerals, and other surface features [29, 30].

Rapid data acquisition: Hyperspectral sensors mounted on airborne platforms can rapidly collect data over large geographical areas, enabling efficient monitoring of post-mining heaps. Also, the data for the whole scene can be collected roughly at the same time.

Versatile applications: The detailed spectral information from hyperspectral data can be used for a wide range of applications, including vegetation mapping, mineral identification, soil composition, and environmental monitoring.

Integration with other technologies: Georeferenced hyperspectral data can be effectively integrated with other remote sensing technologies, including LiDAR, higher-resolution multispectral data, and radar.

However, there are also some limitations and challenges connected with hyperspectral remote sensing:

1. High acquisition cost: the sensors used in airborne hyperspectral imaging are state-of-the-art, expensive instruments, and the cost of conducting overflight missions can be prohibitive, especially for smaller-scale projects. Additionally, there are still relatively few companies offering such services.

2. Data volume and processing complexity: hyperspectral datasets are large and complex, requiring specialized software and expertise to process, analyze, and interpret them effectively. The efficient processing also requires powerful local hardware or access to fast cloud services.

3. Atmospheric interference: accurately interpreting hyperspectral data (as with any optical data) can be challenging because of atmospheric conditions, such as haze, clouds, and aerosols, on measured spectral signatures. Sun angle and illumination conditions can also limit successful data acquisition to specific periods of the day and year.

4. Spatial resolution trade-off: hyperspectral sensors often sacrifice spatial resolution to achieve higher spectral resolution, which can hinder the detection of small-scale ground features. This is less pronounced in airborne data than in satellite remote sensing, as the spatial resolution depends on flight altitude but must be balanced with flight time and spatial coverage.

5. Spectral mixing: the spectral signatures recorded by hyperspectral sensors can be influenced by the mixing of signals from different materials and objects within a single pixel, making it challenging to isolate the contribution of individual components.

6. Limited ground reference: Acquiring sufficient ground truth data to validate and calibrate the hyperspectral data can be labor-intensive and logistically challenging, especially in remote or inaccessible areas.

Hyperspectral remote sensing data processing. Extracting meaningful information from hyperspectral remote sensing data is like extracting information from other types of remote sensing data [3, 30].

The typical workflow includes:

1. *Preprocessing*. This includes correcting for atmospheric effects, geometric distortions, and sensor-specific artifacts to ensure the data is suitable for further analysis.

2. *Dimensionality reduction*. The high dimensionality of hyperspectral data can be challenging for some analysis techniques; therefore, dimension-reduction methods such as principal component analysis or independent component analysis are often applied to extract the most relevant features [28, 29]. This is especially important for machine learning-based approaches.

3. *Feature extraction*. Specific spectral features, such as absorption bands or reflectance peaks, can be extracted from hyperspectral data for material identification, vegetation analysis, and other applications.

4. *Classification and mapping*. Supervised or unsupervised classification algorithms can be used to segment the hyperspectral data into meaningful classes, such as different mineral types, vegetation communities, or land cover categories.

5. *Regression modelling*. Numerical data, such as concentrations of various minerals in the soil, can be modelled based on spectral responses in specific spectral regions.

6. *Integration with other data sources*. Hyperspectral data is often combined with other remote sensing data, such as LiDAR or multispectral imagery, to provide a more comprehensive understanding of the study area.

The process of using hyperspectral airborne data to monitor vegetation on post-mining heaps typically involves several steps. The first step is preprocessing the raw hyperspectral data, which may include atmospheric correction, geometric correction, and data normalization [30]. Once the data is prepared, various techniques can be used to identify and classify vegetation on post-mining heaps. One common approach is spectral feature analysis, which uses the unique spectral signatures of different vegetation types to distinguish among them [8, 10, 28, 29]. This allows mapping of vegetation distribution and health, providing valuable information for assessing the ecological restoration process [26–29]. Additionally, machine learning algorithms can be applied to hyperspectral data to automate vegetation type classification and detect temporal changes. This can be particularly useful for monitoring the long-term success of revegetation efforts. While conventional classifiers (Random Forest, SVM) remain useful, recent advances increasingly employ deep learning architectures, notably Convolutional Neural Networks and hybrid models, which improve accuracy and allow automated monitoring at finer temporal and spatial resolutions [28, 30].

Research results and discussion on the application of hyperspectral airborne data for monitoring post-mining ecosystems. The high spectral resolution of hyperspectral imagery enables detailed characterization of surface conditions, vegetation cover, and material composition in highly heterogeneous post-mining environments. When combined with advanced data processing techniques, hyperspectral data enable improved discrimination among vegetation types, bare substrates, and mining waste, thereby providing a more accurate representation of spatial and temporal ecological dynamics. These capabilities are particularly important in areas where traditional field-based methods are constrained by accessibility, scale, environmental complexity, safety, and circular-economy principles.

The integration of hyperspectral data with other geospatial datasets significantly enhances the interpretability of results. By combining hyperspectral imagery with LiDAR-derived terrain models, geological information, and multispectral satellite data, a more comprehensive understanding of ecosystem structure and functioning can be achieved. Such data fusion approaches support multi-scale analysis, enabling both detailed local assessments and broader regional monitoring of post-mining landscapes. Consequently, hyperspectral remote sensing emerges as a key component in developing integrated frameworks for the observation, assessment, and management of novel ecosystems formed in post-mining environments, as well as for improving evidence-based decision-making in mining-related environmental management.

Integration of hyperspectral data with other spatial data. The integration of hyperspectral airborne data with other spatial data can further enhance the monitoring of post-mining heaps. For example, combining hyperspectral data with geological information, such as soil composition and terrain data, can provide a more comprehensive understanding of the post-mining heap environment [3, 27–30]. This integrated approach can help identify the spatial distribution of vegetation, assess the suitability of different plant species for revegetation, and monitor the progress of ecological restoration over time.

Integration with LIDAR data helps understand the terrain features and surface characteristics of the post-mining heaps in greater detail [30]. Digital Elevation Models can enhance modelling by providing elevation or slope data, locating local high and low points, and providing aspect data, which determines the amount of sunlight received.

Furthermore, the fusion of hyperspectral data with multispectral satellite imagery, such as Sentinel-2 or Landsat, can enable the monitoring of vegetation at larger scales and over longer periods, with frequent revisits [24, 26, 29]. In that application, the high spatial and spectral resolution of hyperspectral data can serve as a detailed reference, while multispectral satellite data can fill gaps, as it is usually collected more frequently.

Use of hyperspectral data in monitoring post-mining heaps. Hyperspectral airborne data provides a powerful tool for monitoring the vegetation on post-mining heaps. Unlike more uniform landscapes, these areas consist of a complex mosaic of bare ground, mining waste, and sparse, emerging vegetation, which creates significant spectral mixing within pixels. Hundreds of narrow, contiguous spectral bands captured by hyperspectral sensors are essential for addressing this challenge, enabling techniques such as spectral unmixing to differentiate the signatures of various vegetation forms and developmental stages. Different objects and cover types exhibit distinct spectral responses, which can be used to classify vegetation into various species and functional groups [24, 26]. Hyperspectral data obtained from aircraft were used to monitor vegetation on post-mining heaps, as they capture spectral details not available in more general satellite imagery [27].

One study [28] demonstrated the effectiveness of hyperspectral imaging for tracking revegetation progress on mine tailings over time, using multitemporal analysis of imagery collected over several years. Due to the highly heterogeneous nature of the study area, with a complex mosaic of bare ground, mining waste, and emerging vegetation, hyperspectral data were highly mixed, so spectral unmixing was performed, with spectra of the 30 target endmembers derived from iterative error analysis.

The ability of the hyperspectral imagery to distinguish between plant species was used by Jiménez and Díaz-Delgado [29] to create spectral libraries that facilitate the identification of different vegetation types. The authors have also proposed a standard protocol for creating spectral libraries of plant species that accounts for their spatiotemporal variation. They then tested the procedure in a shrubland in Doñana National Park, Spain, where it was used to classify various shrub species.

However, in the context of post-mining heaps, hyperspectral data have primarily been used to map mining waste, tailings, and heavy-metal pollution. In the work by Ogen, et al. [30], the geochemical composition of the tailings was classified using laboratory and airborne spectral data. The authors sought to minimize the impact of measurement variability, i.e., differences in moisture states, sampling variability, and differences among sensors (Table). Davies and Calvin [10] have tested the mapping potential of hyperspec-

tral imaging as a function of spatial resolution. According to their findings, based on the site at the Leviathan mine in the Eastern Sierra Nevada, resolutions of 15 m or finer were required to map mineral concentrations. This, however, relates to the size of those features, and small patches of vegetation would require much finer resolution, achievable only with airborne or UAV data. More recently, integrated drone systems covering the full VNIR-SWIR spectrum (400–2,500 nm) have been successfully deployed for the comprehensive environmental assessment of legacy mine sites [18]. This approach was successful but is constrained in the study area by UAV flight limitations and, consequently, limited area coverage.

Post-mining mineral sites, once considered biological deserts, now play an increasingly recognized role in enhancing biodiversity and novel ecosystem functioning. These human-established habitats sequester carbon (Figs. 2, 3), provide oligotrophic poor, and support rare species refugia. The spontaneous processes on the mining site, such as the rapid colonization by fast-growing organisms, vegetation patches composed of non-analogous plant species assemblages, and varied microbial activity in the plant root system, are the basis for the development of a novel ecosystem [8]. The plant species composition of vegetation in natural and semi-natural habitats differs significantly from that in the mineral habitats of post-mining sites. As a result, novel ecosystems sensu Hobbs, et al. [6] are becoming established on the mineral post-mining habitats. The functioning parameters of novel ecosystems differ in the amount of synthesized biomass [15, 22], microbial community parameters [9, 10], and soil respiration.

The methodical challenges of the novel ecosystem studies. Studying novel ecosystems poses distinct methodological challenges when compared with traditional approaches used to investigate ecosystem functioning in relatively natural or semi-natural systems [4]. Classical ecosystem studies are usually grounded in well-defined reference conditions, predictable successional pathways, and long-established species interactions. In contrast, novel ecosystems lack clear historical baselines, which complicates the selection of appropriate controls and reference sites. Without a pre-disturbance state for comparison, it becomes difficult to evaluate ecosystem integrity, degradation, or recovery using conventional ecological indicators.

Another major challenge is the high environmental heterogeneity typical of novel ecosystems. Post-industrial, urban, or post-mining landscapes often exhibit sharp gradients in soil chemistry, microclimate, hydrology, and disturbance regimes over very small spatial scales. Traditional plot-based or point-sampling methods may fail to capture this fine-scale variability, leading to oversimplified interpretations of ecosystem processes. As a result, scaling findings from local measurements to the landscape level is more uncertain than in more homogeneous, traditional ecosystems.

Species composition in novel ecosystems also complicates methodological approaches. These systems often host unconventional assemblages of native, non-native, and stress-tolerant species, with functional roles that may not align with classical ecological classifications. Traditional functional groupings and trait-based frameworks may therefore require adaptation or redefinition to reflect new ecological interactions and feedback.

Table

Remotely sensed predictors that can be used in the study on the environmental potential of mineral post mining sites after [3]

Predictor	Abbreviation	Description
Coastal band reflectance	*c*	Reflectance of 400–450 nm
Blue band reflectance	*b*	Reflectance of 450–510 nm
Green band reflectance	*g*	Reflectance of 510–581 nm
Yellow band reflectance	*y*	Reflectance of 585–625 nm
Red band reflectance	*r*	Reflectance of 630–690 nm
Red edge band reflectance	*Re*	Reflectance of 605–745 nm
Near infrared band reflectance	*nir*1	Reflectance of 770–895 nm
Near infrared band reflectance	*nir*2	Reflectance of 860–1,040 nm
Normalized difference vegetation index	NDVI	$(nir - 1)/(nir1 + r)$ (Rouse, Hass, Deering, Schell, & Harlan, 1973)
Plant senescence reflectance index	PSRI	$(r - b)/re$ (Merzlyak, Gitelson, Chivkunova, & Rakitin, 1999)
Anthocyanin reflectance index	ACR	$(1/g)/(1/re)$; Gitelson, Merzlyak, Chivkunova, 2001
Carotenoid reflectance index	CRI	$(1/g)/(1/g)$; Gitelson, et all. (2002)
Photochemical reflectance index	PRI	$(b - g)/(b + g)$; Gamon, Serrano, and Surfus (1997)
Topographic wetness index	TWI	Function of slope and the upstream contributing area; Beven and Kirkby (1979)
Slope	Slope	Inclination of the slopes
Aspect	Aspect	Azimuth of slope
Digital surface model	DSM	Maximum elevation of points reflecting ALS beam
Digital elevation model	DEM	Minimum elevation of points reflecting ALS beam
Analytical hillshading	Annhill	the angle between the surface and the incoming light beams; Tarini, Cignoni, and Montani (2006)
Vegetation height	Vh	Calculated as DSM-DEM

Furthermore, ecosystem functioning in novel systems is frequently driven by multiple, interacting stressors such as contamination, altered nutrient cycles, and human management. Disentangling the effects of these overlapping drivers using traditional single-factor experimental designs is challenging. This necessitates integrative, multi-method approaches that combine field ecology, remote sensing, geochemical analyses, and modelling.

Overall, while traditional methods remain essential, studying novel ecosystems demands greater method-

ological flexibility, cross-scale integration, and interdisciplinary tools to adequately capture their dynamic and non-linear functioning.

The need to use hyperspectral airborne data to monitor and understand the complex processes of novel ecosystem functioning. Novel ecosystems, such as those developing on post-mining sites, often lack stable ecological baselines and exhibit non-linear successional trajectories, making them difficult to assess using conventional ecological approaches. In this context, hyperspectral airborne data provide a unique opportunity to capture fine-scale spectral information that reflects subtle variations in vegetation composition, stress responses, and surface properties.

By coupling hyperspectral data with ecological models and ground-based measurements, researchers can significantly improve the quantification of ecosystem services, biodiversity patterns, and functional processes. This integrated approach enables the identification of key ecological indicators that are otherwise difficult to detect using traditional field surveys alone. Furthermore, hyperspectral datasets enable spatially explicit analysis of ecosystem dynamics, supporting assessments of vegetation heterogeneity, species distribution, and ecological interactions across different stages of ecosystem development.

Consequently, hyperspectral airborne data represent a powerful, non-invasive tool for advancing scientific understanding of novel ecosystem functioning. Their ability to provide continuous spectral information across large and inaccessible areas makes them particularly valuable for long-term environmental monitoring. In addition, they offer strong potential for supporting evidence-based decision-making and adaptive management strategies aimed at the restoration and sustainable development of post-mining landscapes in a rapidly changing environmental context.

Conclusions. In conclusion, the use of hyperspectral airborne data holds immense potential for monitoring vegetation on post-mining heaps, particularly in urban landscape settings. The detailed spectral information provided by these data can enable the identification and classification of different vegetation types, allowing for the assessment of the ecological restoration progress and the implementation of targeted management strategies. Additionally, the fine spatial resolution achievable with data from sensors installed on UAVs or airplanes is essential for mapping highly heterogeneous surfaces, such as post-mining landscapes. In contrast, hyperspectral imagery from spaceborne sensors enables frequent data collection, but the spatial resolution is too coarse to map finer details. The integration of hyperspectral data with other geospatial data sources further enhances the monitoring and understanding of post-mining heaps, ultimately contributing to the effective restoration and management of these critical urban environments.

Hyperspectral data have been used by many scientists to monitor various aspects of post-mining heaps. The majority of use cases are related to monitoring mineral distribution, controlling waste management, or ensuring water quality. Uses related to monitoring vegetation on heaps are less common, despite numerous examples of vegetation studies in other environments, such as agriculture or forests.

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Потенціал використання гіперспектральних даних аеророзвідки для моніторингу нових екосистем після видобутку корисних копалин

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Мета. Підвищення ефективності й точності моніторингу ландшафтів після видобутку корисних копалин на основі використання гіперспектрального дистанційного зондування й аналізу даних аеророзвідки для управління рослинністю на відвалах після видобутку корисних копалин відповідно до принципів сучасних геоінформаційних технологій і дистанційного прогнозування.

Методика. На основі методів дистанційного зондування, зокрема гіперспектральних аерозйомних даних, здійснюється моніторинг та оцінювання територій після видобутку корисних копалин. Гіперспектральне зондування забезпечує ефективну оцінку забруднення, стану рослинності та процесів відновлення, підтримуючи прийняття рішень у рекультивації.

Результати. Удосконалена й апробована модель моніторингу постгірничих екосистем із використанням гіперспектральних даних аерозйомки, що підвищує точність оцінювання екологічного стану породних відвалів і динаміки відновлення рослинності. Визначені спектральні характеристики територій із різним рівнем антропогенного впливу, що дозволяє виявляти зони деградації та природного відновлення. Доведена ефективність інтеграції гіперспектральних даних і геоінформаційних технологій для контролю рекультивації й управління ландшафтами після видобутку корисних копалин.

Наукова новизна. Запропоновано й апробовано підхід до моніторингу постгірничих екосистем на основі використання гіперспектральних даних аерозйомки й геоінформаційних технологій, основні положення якого полягають у:

- визначенні спектральних характеристик рослинного покриву й породних відвалів із різним рівнем техногенного навантаження;
- виявленні зон деградації, забруднення та природного відновлення;
- інтеграції даних дистанційного зондування із геоінформаційними системами;
- забезпеченні контролю процесів рекультивації та прогнозуванні розвитку нових екосистем на територіях, порушених гірничою діяльністю.

Практична значимість. Запропонований підхід до моніторингу постгірничих екосистем із використанням гіперспектральних даних аерозйомки й геоінформаційних технологій підвищує точність й ефективність оцінки екологічного стану породних відвалів і прилеглих територій. Отримані результати можуть бути використані для виявлення зон деградації та відновлення природної рослинності, а також для моніторингу процесів рекультивації в ландшафтах, що постраждали від гірничодобувної діяльності. Практичне впровадження цього підходу дозволяє вдосконалити системи моніторингу навколишнього середовища в гірничодобувних регіонах і підвищує ефективність управлінських рішень щодо відновлення порушених територій.

Ключові слова: *дистанційне зондування, корисні копалини, породні відвали, гіперспектральні дані, екологічна стійкість*