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Utilizing UAV technology and GIS analysis for ecological restoration: A case study on *Robinia pseudoacacia* L. in a mine waste dump landscape rehabilitation

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Abstract

The rehabilitation of mine waste dumps is a critical environmental challenge, particularly in areas like Uricani, Romania, where such sites are often characterized by hazardous conditions and poor ecological recovery. This study addresses the need for efficient, low-cost solutions for land reclamation by employing UAV photogrammetry and GIS spatial analysis to assess the potential for afforestation with *Robinia pseudoacacia* L., a species known for its soil stabilization and ecological benefits. Using UAV technology, high-resolution digital terrain models and orthophotos were generated, with an RMSE of 0.086 m, demonstrating the accuracy and efficiency of this method for large-scale landscape initiatives. GIS spatial analysis was performed to create six key terrain maps and four pedoclimatic factor maps, essential for evaluating the site's suitability for ecological restoration. The pilot afforestation project, which involved planting *R. pseudoacacia*, achieved a 75% survival rate after four years, suggesting that the species can thrive under the site's conditions. The landscape design proposal incorporates recreational spaces aimed at benefiting the local community and attracting tourism, thereby contributing to the area's economic and cultural revitalization. The interdisciplinary integration of UAV surveying, GIS, and landscape design highlights the cost-effectiveness and interdisciplinary nature of this approach, offering a sustainable model for mine waste dump reclamation and future ecological restoration projects.

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Keywords: afforestation; black locust; GIS analysis; landscape ecology; mine waste dump; photogrammetry; UAV

Introduction

The application of UAV technology for surveying mining waste dumps has become a notable achievement in environmental management, providing a flexible and economical alternative for mapping and monitoring these complex sites (Saratsis *et al.*, 2023). UAVs deliver high-resolution imagery and subsequent three-dimensional models essential for evaluating the geometry and stability of mine waste dumps (Nguyen, 2023). The capacity to generate intricate digital terrain models (DTMs) and orthophotos facilitates accurate examination of terrain characteristics, including slope stability, erosion patterns, and vegetation regeneration. UAVs provide distinct advantages in hazardous areas, where access is challenging or unsafe for conventional survey techniques (Carrera-Hernández *et al.*, 2020). They are able to monitor surface movement, identify possible hazards such as mine drainage, and evaluate the efficacy of rehabilitation initiatives. Furthermore, UAVs equipped with specialized sensors can facilitate the mapping of heavy metal concentrations and various soil attributes through hyperspectral data, enhancing thorough environmental monitoring (Ren *et al.*, 2024). Their capacity to collect data fast and securely considerably diminishes the necessity for manual surveys (Martínez-Carricondo *et al.*, 2018), offering a more efficient and accurate method for waste dump management and mine tailings dams monitoring.

Nevertheless, mining waste dumps pose several substantial environmental and physical hazards that hamper both immediate safety and long-term ecological restoration (Venkateswarlu *et al.*, 2016). A significant concern is acid mine drainage, which arises when sulphide minerals in waste interact with water and oxygen, generating sulfuric acid and contaminating adjacent water supplies (Valente *et al.*, 2012). This pollution, along with the emission of fine particulate matter from the landfills, severely affects adjacent ecosystems and water quality. The physical instability of mine waste dumps is a significant concern. Numerous landfills have steep inclines susceptible to erosion, resulting in soil loss and aggravating environmental degradation. Subpar soil quality, worsened by heavy metal contamination, restricts vegetation establishment, thereby increasing erosion risk (Lei *et al.*, 2016). Moreover, coal waste dumps are prone to spontaneous combustion, which not only emits harmful gasses into the atmosphere but also poses considerable fire risks that may rekindle even post-rehabilitation. The environmental and physical concerns present significant hurdles for effective remediation, necessitating meticulous planning and monitoring to guarantee safe and successful restoration (Wang *et al.*, 2017).

Vegetation, especially afforestation, is crucial for the rehabilitation of mining waste dumps. Vegetation stabilizes soil, mitigates erosion, and enhances the land's physical qualities, fostering conditions that promote additional plant development. Pioneer species are often utilized in the early stages of restoration due to their resilience and ability to improve soil structure and fertility (Galván-Moreno *et al.*, 2024). These plants enhance soil organic matter and porosity, hence enhancing water infiltration and further stabilizing the landscape. The strategic introduction of vegetation can reduce combustion risk by decreasing surface temperatures and establishing a natural barrier against erosive forces such as wind and water. Unmanned Aerial Vehicles (UAVs) are important instruments for monitoring vegetation restoration, enabling accurate evaluation of vegetation cover and biomass, which are key indications of ecosystem recovery (Danilov *et al.*, 2015). The integration of UAV data with environmental restoration efforts enables a more effective and adaptable rehabilitation approach, as improving vegetation cover and soil quality promotes the long-term stability and ecological recovery of mining waste sites, transforming degraded regions into functional ecosystems (Xiao *et al.*, 2022). The 3D model and orthophoto derived from UAV photogrammetry can be incorporated into specialized landscape design software, facilitating comprehensive terrain analysis and the development of data-driven rehabilitation strategies (Sun *et al.*, 2021). Such instruments assist in visualizing topographical characteristics, determining slope stability, and optimizing vegetation layout for efficient erosion control and ecological restoration.

Robinia pseudoacacia L., generally referred to as black locust, is a rapidly growing, nitrogen-fixing tree indigenous to the eastern regions of North America (Grünewald *et al.*, 2009). Introduced to Europe in the 17th century, it has emerged as one of the most widely cultivated species, especially in areas with degraded or disturbed soils. Black locust is highly valued for its versatility, thriving in diverse settings from wet to arid conditions, and it endures cold winters and moderate frost. Its tolerance to environmental challenges, including drought, severe temperatures, and suboptimal soil quality, has rendered it a pivotal species in land reclamation initiatives, particularly in areas where other plant species find it challenging to establish (Nicolescu *et al.*, 2018). Black locust serves numerous purposes, including as timber production, biomass for energy, honey production, and erosion control, rendering it an economically significant plant throughout Europe (Puchałka *et al.*, 2021), especially in Romania, where it is essential to agroforestry systems.

R. pseudoacacia has demonstrated significant potential in Romania, particularly in regions affected by soil erosion and desertification (Nicolescu *et al.*, 2020). This species is widely used in reforestation and land reclamation initiatives, aiding in the stabilization of degraded soils, enhancement of soil fertility, and mitigation of erosion risk (Ciuvăț *et al.*, 2022). Black locust is especially beneficial in areas such as Oltenia and the Bărăganului Plain, where it significantly contributes to soil erosion prevention and the stabilization of sandy soil. The species' capacity to fix nitrogen not only improves soil quality but also fosters the growth of other plant species, thus enhancing biodiversity in otherwise desolate landscapes. Additionally, black locust exhibits potential as a biomass crop in Romania, yielding substantial quantities of dry matter per hectare yearly, therefore serving as a significant resource for renewable energy production (Roman *et al.*, 2022a,b). The species is utilized to establish buffer zones in agroforestry systems, demonstrating an increase in crop yields, especially when combined with other land use techniques.

A notable property of *R. pseudoacacia* is its resistance in hostile environments, such as mining waste dumps, where it is commonly employed for ecological restoration. The species is notably proficient in soil stabilization in regions characterized by low fertility, inadequate water retention, and elevated levels of hazardous substances. Its extensive root system enables it to extract water from deep soil strata, facilitating its survival in regions with little water resources. *R. pseudoacacia* has been effectively utilized in reclamation initiatives in Romania's mining regions, where it has been introduced to mitigate erosion, stabilize terrain, and enhance soil quality. In many instances, black locust plantations have demonstrated biomass accumulation rates much above those of other species, rendering it an effective option for swift ecological restoration (Curovic *et al.*, 2020). Nevertheless, the species is recognized for its rapid proliferation and capacity for swift dissemination, which might provide challenges in regions where the conservation of local species is essential. Careful management is necessary to balance the species' advantageous applications in land reclamation while preventing ecological dominance that may result in diminished biodiversity (Sestras *et al.*, 2019). Despite this, *R. pseudoacacia* is among the most effective choices for restoring mining waste dumps and other damaged landscapes, exhibiting considerable capacity for growth and ecological restoration in harsh environments.

The main objectives of this research are to employ UAV photogrammetry to obtain a digital terrain model (DTM) of the investigated mine waste dump from Uricani, Romania, which will then be examined through Geographic Information Systems (GIS) spatial analysis. This data-centric methodology will generate maps that illustrate essential site attributes, including elevation, slope, aspect, solar radiation, flow direction, and fragmentation depth. These maps will be significant in assessing the site's physical and environmental parameters, facilitating the evaluation of the feasibility for growing black locust, a species recognized for its resistance and soil enhancement properties. Furthermore, pedological and climatic GIS maps will be developed, containing factors such as average annual temperature, average annual precipitation, land use, and soil types, to evaluate the appropriateness of *R. pseudoacacia* in the designated area. This comprehensive mapping will determine if the conditions correspond with the species' growth and ecological restoration requirements. Besides these data and GIS driven assessments, a ground approach assessment of a previous minor afforestation initiative is evaluated, in order to determine the feasibility of *R. pseudoacacia* on the investigated hazardous region.

A landscape architecture layout has been developed using data acquired from UAV photogrammetry, as part of a comprehensive ecological rehabilitation and restoration project. The landscape design proposes to convert the mine waste dump into a green space or park to serve both local residents and tourists. The DTM will function as the foundation for the new landscape design, enabling methodical consideration of vegetation placement and other restoration strategies that prioritize soil stabilization, erosion control, and the enhancement of ecosystem services. This approach reduces the environmental problems linked to the mine waste dump while creating a sustainable, aesthetically pleasing space that benefits the surrounding community. This method integrates current UAV technology with GIS spatial analysis and landscape design, establishing an integrated approach for the rehabilitation of mining waste dumps, thus guaranteeing enduring ecological and social benefits.

Materials and Methods

Study area and the mining history of the region

The mine waste dump in question is situated on the periphery of Uricani, a town in Hunedoara County, Transylvania, Romania. Located at coordinates 45°20′11″N and 23°9′9″E, Uricani is situated in the scenic Valea Jiului valley, at the base of the Retezat Mountains (Figure 1). The town, formerly a prosperous monoindustrial community owing to its abundant coal deposits, has experienced a substantial reduction in mining operations following the collapse of the communist system. Historically, Uricani was crucial in the coal industry, with the extraction of coking coal marking its evolution into a town that relied almost exclusively on coal mining from the 1950s onward.

Uricani's scenic location, however, is obscured by the mine waste dump, a continual environmental concern for the local community. The facility, located near the town, has remained mismanaged for an extended period, leading to many issues. It presents physical dangers due to its unstable and contaminated soils, while also inducing considerable visual and environmental distress. The pronounced disparity between the area's natural beauty and the deterioration caused by mine waste offers a concerning sight for inhabitants and visitors alike. The closeness of the dump to the town raises concerns about the pollution of the local water supply and soil, as well as the long-term ecological consequences of such negligence.

The history of coal mining in the Valea Jiului region commenced in the mid-19th century, when the area, surrounded by the Retezat, Parâng, and Vâlcan mountains, gained recognition for its abundant coal reserves. The initial mining activities commenced in the early 1860s in places like Petrila, Petroșani, Lupeni, Vulcan, and Uricani, drawing hundreds of laborers from surrounding areas and beyond. The little villages progressively evolved into thriving mining towns following the establishment of the Simeria-Petroșani coal line in the 1870s, which connected them to the broader Transylvania region.

By the early 20th century, the mining towns in Valea Jiului had expanded considerably, with Petroșani alone boasting a population exceeding 8,000 persons. The region evolved into a significant industrial centre, with coal mining peaking in the 1980s, when more than 100,000 individuals were employed in the mines, yielding about 11 million tons of coal each year. Nonetheless, the coal sector commenced its fall in the late 20th century, resulting in the shutdown of numerous mines. In 2015, the final operational mines in the region—Petrila, Paroșeni, and Uricani—terminated their activities, concluding more than a century of mining operations.

Today, the previous mining communities, such as Uricani, have transitioned into tourism, but with considerable challenges. The closure of mining operations created a substantial economic void, and the region continues to contend with the repercussions of this industrial downturn. The legacy of coal mining remains evident in the ruins of the once-thriving industry.

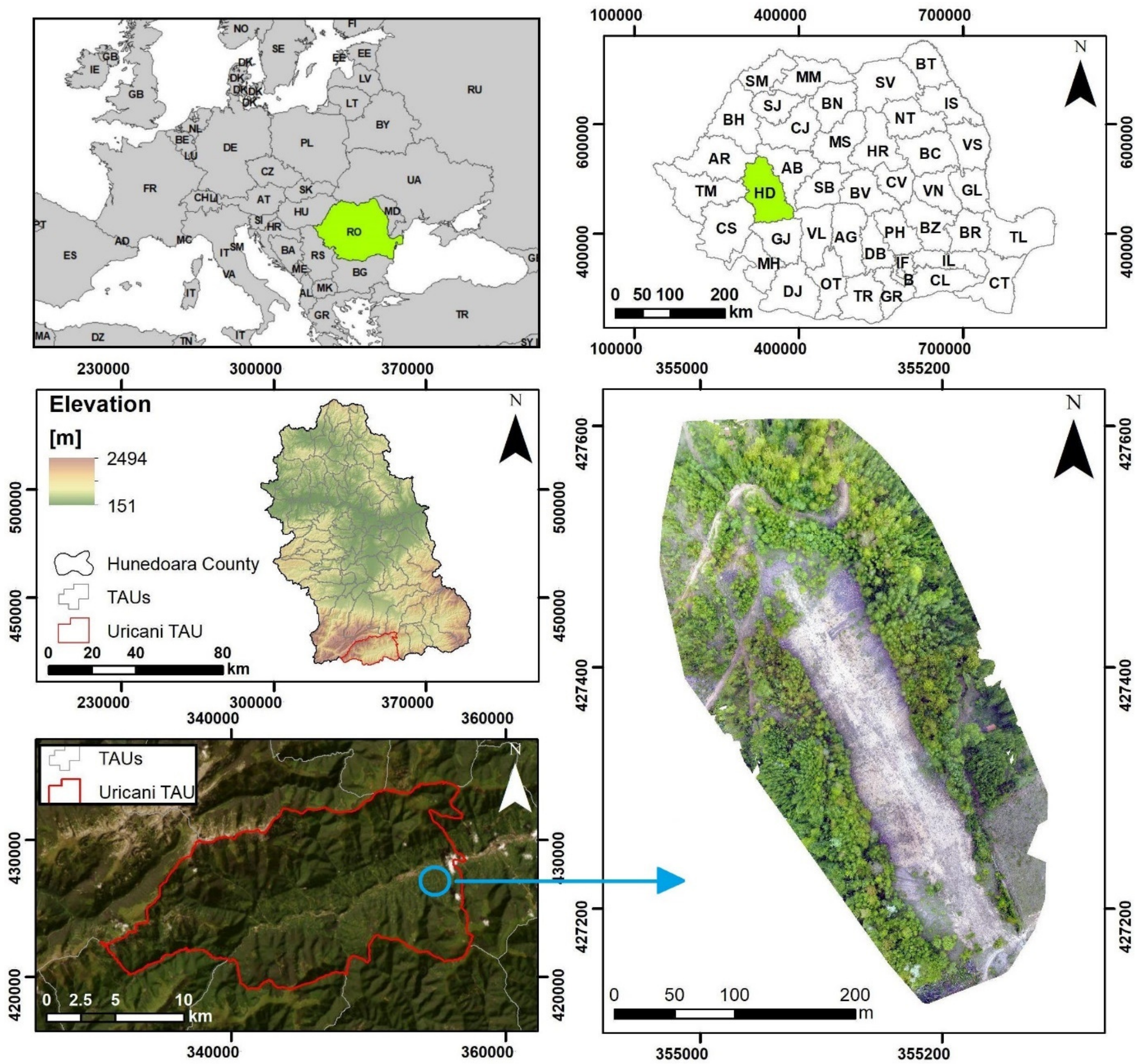


Figure 1. The geographical location of the study area with the UAV obtained orthophoto over the mine waste dump

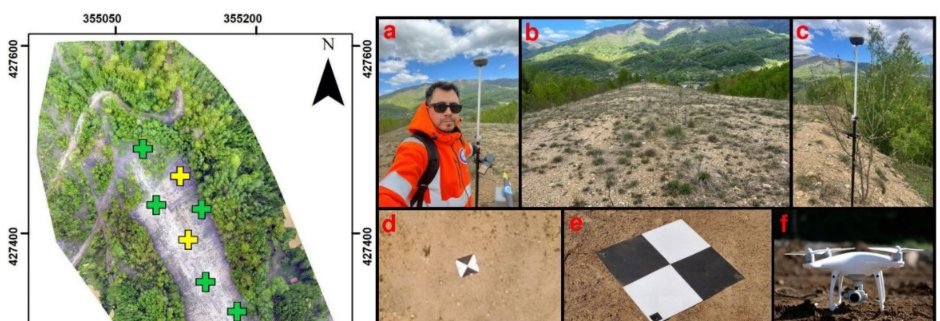
UAV survey with processed outputs

In this study, UAV-based photogrammetry was employed as the primary method for capturing topographical data from the mine waste dump site. The UAV photogrammetric process involves the use of digital cameras mounted on UAV platforms to capture overlapping images of the study area, which are then processed to generate high-resolution three-dimensional (3D) model and orthophoto. In this study, a DJI Phantom 4 UAV was used, providing high-quality imagery that, when processed through photogrammetric software and Structure from Motion principles, can produce a Digital Surface Model (DSM) and a Digital Terrain Model (DTM). These models are essential for detailed topographic mapping, allowing for accurate analysis of terrain features, including slope, elevation, and other critical site characteristics and metrics. The UAV characteristics and flight mission information is presented in Table 1.

Table 1. UAV characteristics and flight mission metrics

Flight properties	Data/Parameter
Aircraft	DJI Phantom 4
Flight Date	June 2024
Mapping Flight Speed	4 m/s
Sensor	RGB 4K digital camera; FC330_3.6_4000x3000; 20MP
Fly height (m)	80 m
Mission duration	18 minutes
Image Forward Overlap (%)	80%
Image Side Overlap (%)	75%
Mission type	Single grid
Image Overlap	>9
Number of Images Captured	153
Surveyed area	≈ 9.64 hectares
Number of GCPs/ICPs	8/4 placed inside the area of interest
Ground Resolution	3.20 cm/px
RMSE $_{X, Y, Z}$	0.061 m X, 0.047 m Y and 0.092 m Z
RMSE $_{3D}$	0.067 m XYZ

To ensure precise georeferencing of the imagery, ground control points (GCPs) were strategically placed across the area of interest. These points are essential for aligning the UAV-derived models with real-world coordinates, making the models suitable for use in Geographic Information Systems (GIS) spatial analysis and subsequent landscape design (Sestras *et al.*, 2023). In this case, GNSS instrumentation, specifically the Leica G08 GNSS receiver, was used to measure the positions of these GCPs with high accuracy. The GNSS system's Real-Time Kinematic (RTK) mode enabled precise positioning, with a planimetric accuracy of approximately 1.5-2 cm and a vertical accuracy of approximately 2-3 cm. In addition to GCPs, the use of independent check points (ICPs), which are measured at specific locations across the survey area, further allows for the evaluation of the accuracy of the DTM and orthophoto outputs (Figure 2). By comparing the height values from the UAV-derived models to those from the GNSS-surveyed check points, the root mean square error (RMSE) can be calculated, providing a quantitative measure of the model's accuracy.



$$RMSE_X = \sqrt{\frac{\sum_{i=1}^{n} (X_i^{DSM} - X_i^{GNSS})^2}{n}},$$

$$RMSE_Y = \sqrt{\frac{\sum_{i=1}^{n} (Y_i^{DSM} - Y_i^{GNSS})^2}{n}},$$

$$RMSE_Z = \sqrt{\frac{\sum_{i=1}^{n} (Z_i^{DSM} - Z_i^{GNSS})^2}{n}},$$

$$RMSE_{3D} = \sqrt{\frac{\sum_{i=1}^{n} [(X_i^{DSM} - X_i^{GNSS})^2 + (Y_i^{DSM} - Y_i^{GNSS})^2 + (Z_i^{DSM} - Z_i^{GNSS})^2]}{n}}$$

Figure 2. The obtained orthophoto with the GCPs and ICPs placement (left); Photo collage from the survey depicting (a, b, c) the ground GNSS measurements on the mine waste dump, (d, e, f) the GCPs as observed from the georeferencing process, on the ground, the DJI Phantom 4 UAV; the RMSE equations used to evaluate the accuracy of the obtained orthophoto and elevation model

Specialized software, such as Agisoft Metashape, utilizes Structure from Motion (SfM) techniques to process the imagery and GCPs into 3D models and orthophoto. SfM works by analyzing the overlapping images to extract features and triangulate the geometry of the terrain, enabling the generation of dense point clouds. These point clouds are used to create DSMs, which represent the highest surfaces (including vegetation and anthropic elements), and DTMs, which depict the bare ground after filtering out non-ground elements like vegetation and man-made structures.

The DJI Phantom 4 UAV was employed for the acquisition phase of the photographic dataset for the photogrammetric 3D reconstruction of the terrain. Photogrammetry is used to create three-dimensional models from two-dimensional photos by triangulating images taken using high-quality cameras. The creation of 3D models, contour maps, volumetric surveys, and other goods is possible using images taken by UAVs or the LiDAR technology (Forlani *et al.*, 2018). The image acquisition plan was divided into three steps: specification of image acquisition plan type, determination of Ground Sampling Distance (GSD), and definition of picture overlap in order to obtain a model with centimetre accuracy and reconstruct a high-quality model. In order for the UAV to fly automatically, the image acquisition type was set to automatic waypoint flight mission. The following parameters were defined by the program to automatically determine the picture acquisition plan and mission settings: flight height (and subsequently GSD), overlap (%), and region to be covered. UAV imagery can be processed with various traditional photogrammetry software tools. However, recent advancements have led to the development of specialized software designed specifically for analysing UAV image data. These new programs integrate expertise from computer vision and traditional photogrammetry, offering enhanced capabilities for processing and interpreting aerial imagery captured by drones. These programs employ a strategy known as Structure from Motion (SfM) (Agüera-Vega *et al.*, 2017). The photogrammetry program Agisoft Metashape was used to carry out the 3D reconstruction, with the conventional workflow depicted in Figure 3. Four distinct phases make up the elaboration process:

1. Picture alignment: utilizing binding points in order to merge the site. In order for the points selected in the different photographs to be properly overlaid, they must share certain traits. High image quality, limited areas of shade, and appropriate lighting are necessary for a satisfactory outcome.

2. Build dense cloud. During this stage, dense image matching algorithms are used to build a dense cloud. They are separated into stereo matching, which finds matches using a stereo pair, and stereo multi-view, which finds matches across numerous images.

3. Build a mesh, which entails building a polygonal model from the freshly formed dense cloud. A solid is divided into smaller solids called "meshes" that have polyhedral shapes.

4. Build texture rather than allowing for the 3D depiction of the job under review. Figure 3 depict the general photogrammetric workflow with the finalized orthophoto and 3D model.

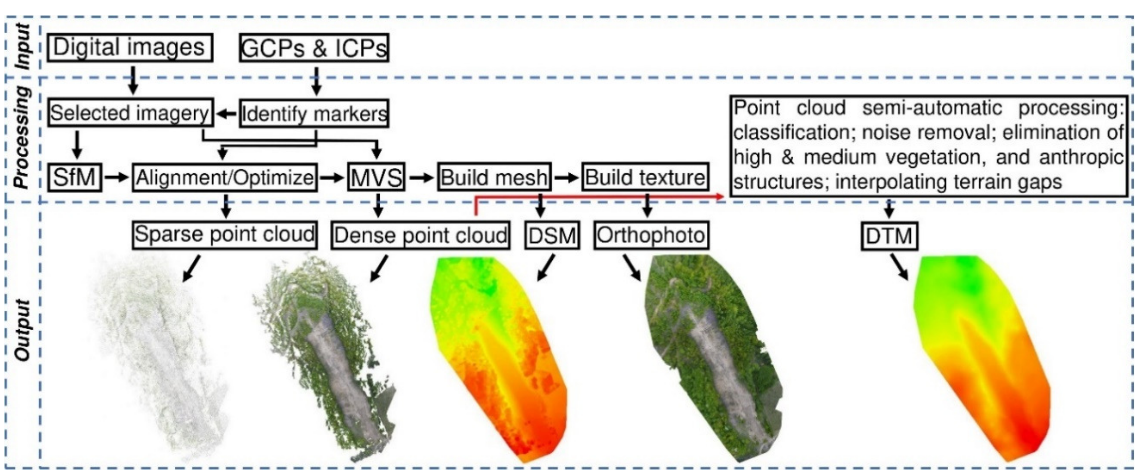


Figure 3. Conventional photogrammetric workflow with the processed outputs

The utilization of UAV-based photogrammetry has significantly improved the efficiency and safety of data collecting, addressing the difficulties presented by hazardous terrain and inaccessible locations, such as mine waste dumps. This technique facilitates the rapid collection of high-quality data, guaranteeing the accuracy of the generated digital models. When integrated with GIS technologies, these models are indispensable for thorough environmental and spatial analysis, offering critical data for landscape design and ecological restoration. UAV photogrammetry, in conjunction with GNSS technology and SfM processing, provides an economical and effective approach for generating accurate digital terrain models. These models are important for evaluating the viability of planting *R. pseudoacacia* and analysing the site's capacity for sustainable ecological restoration.

Methodologic approach and database

Based on the UAV survey, a high-resolution Digital Terrain Model (DTM) was created. This DTM was used for two main objectives. First, it helped generate six GIS maps, which depict key site features such as elevation, slope, aspect, solar radiation, flow direction, and fragmentation depth. These maps are essential for understanding the physical and environmental characteristics of the mine waste dump and for evaluating the site's suitability for rehabilitation. Second, the DTM was used to create CAD (Computer-Aided Design) outputs, including contour lines, 3D models, and terrain profiles. These CAD outputs are important for the landscape design process, as they provide the necessary data to plan and develop a restoration strategy for the site. These models and profiles will guide the design of interventions aimed at rehabilitating and restoring the mine waste dump. The desired steps are presented in Figure 4.

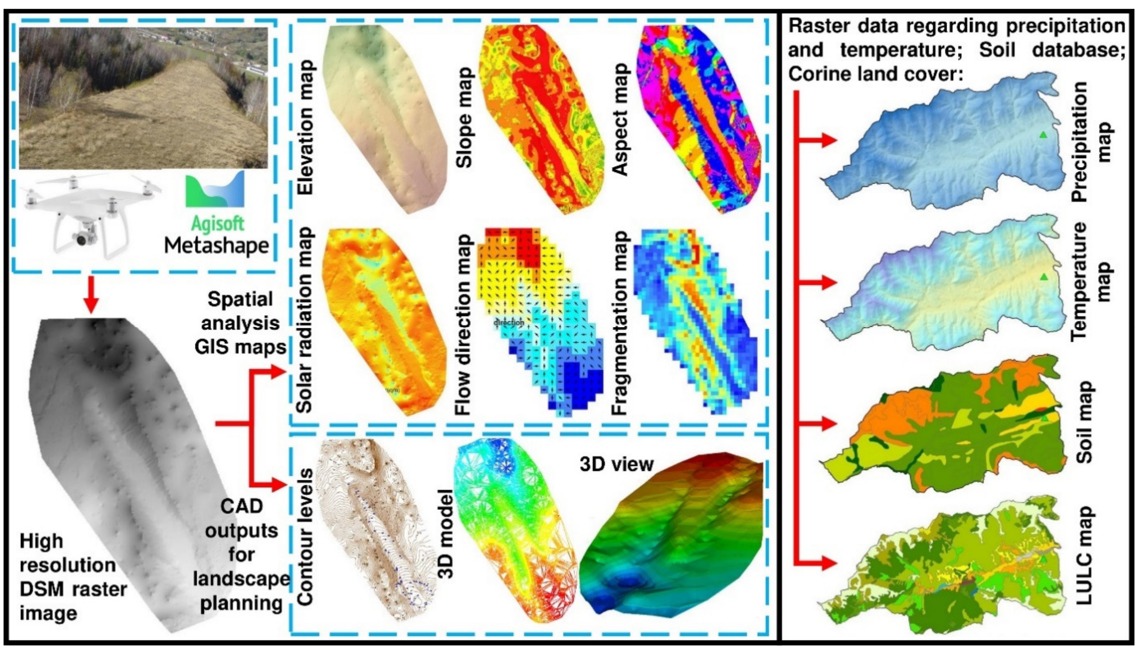


Figure 4. Workflow of UAV Survey, GIS Analysis, and Design Outputs for mine waste dump rehabilitation and feasibility assessment

The integration of meteorological and soil data within GIS-based systems plays a crucial role in evaluating the environmental feasibility of planting species such as *R. pseudoacacia* on mining waste dumps. The data obtained from various open access sources is used to generate maps that help assess the suitability of the site for rehabilitation and determine the species' potential for growth in specific locations. Meteorological data, especially average annual temperature and precipitation, provides essential information regarding the climatic conditions of the study area. These factors directly influence vegetation growth and soil stability. To assess the feasibility of *R. pseudoacacia* on a mine waste dump, average annual temperature and precipitation data from nearby meteorological stations are used to create GIS climate maps. For example, regions with higher annual rainfall and temperatures typically provide better conditions for plant growth, while extreme drought conditions or temperature fluctuations can limit the viability of certain species.

Soil properties are important for determining the ability of vegetation to establish and thrive on a mine waste dump. Soil maps, which classify soil types based on their chemical and physical properties, play a significant role in the rehabilitation process. The soil maps used in this study, derived from digitized sources and updated classification systems, help identify areas with different types of soil textures and fertility. These maps are essential for understanding which areas might have nutrient-poor soils that require soil amendments or additional support for plant growth. The soil database was created by digitizing 1:200,000 scale maps using the SRCS ICPA-1980 (Romanian Soil Classification System) nomenclature and subsequently updating them to the FAO UNESCO SRTS 2003 (Romanian Soil Taxonomy System) classifications.

Land use and land cover data, such as the Corine Land Cover (CLC) dataset, further support the feasibility analysis by providing information about the existing land cover types within the study area. The CLC dataset helps to understand the current state of the landscape and the types of human interventions in the area, such as agricultural activity, industrial developments, and natural vegetation.

Evaluation of Robinia pseudoacacia planting success and feasibility for full-Scale rehabilitation

In 2020, an experimental afforestation initiative was implemented on the Uricani mine waste dump, aimed for a future site stabilization and ecological restoration. The primary objective of this endeavour was to assess the adaptability and growth capacity of *R. pseudoacacia* in the mine's barren, deteriorated soils. This species was selected for its recognized robustness, rapid growth, and nitrogen-fixing characteristics, which are especially advantageous for enhancing soil quality and reducing erosion on disturbed areas such as mining waste dumps.

The plantation procedure commenced with minor terrain preparation, which entailed levelling and fertilizing the slopes to establish an appropriate foundation for afforestation. A 10-15 cm layer of fertile soil was placed, and the slopes were initially planted with 300 seedlings of *R. pseudoacacia* obtained from standard nurseries. Planting was place in the spring to guarantee that the soil retained sufficient moisture, essential for seedling establishment. The seedlings, roughly 1 meter in height and bare-rooted, were planted in holes measuring 40 × 40 × 40 cm, with a spacing of 2.0 meters between rows and 1.0 meter between individual plants (Figure 5). To optimize the plantation's success, the seedlings were properly handled post-planting. Their stems were pruned to 1 cm above ground level prior to the growing season to promote enhanced root formation and increase survival rates.

Figure 5. Plantation scheme and four-year-old *R. pseudoacacia* trees on the investigated mine waste dump, Uricani, Romania

The efficacy of the afforestation pilot on the mine waste dump was assessed through continuous monitoring, which involved evaluating the survival rate of the plants and examining the general health of the vegetation. Over the course of four years since the initial pilot afforestation, approximately 75% of the *R. pseudoacacia* seedlings have survived, demonstrating significant resilience despite the challenging conditions of the mine waste dump. This survival rate, which is considered favourable in the context of afforestation efforts on disturbed and nutrient-poor sites, highlights the feasibility of scaling up the project for full-scale afforestation and ecological rehabilitation. The average height of the surviving trees has reached around 2 meters, with an average stem diameter ranging from 3 to 4 cm, indicating robust growth under the site's harsh environmental conditions. Furthermore, the overall health of the plantation appears promising, with the trees showing a relatively healthy aspect, suggesting that the species is adapting well to the site. This success not only supports the potential for broader afforestation efforts but also underscores the suitability of *R. pseudoacacia* for rehabilitation projects in similar degraded landscapes, where its fast growth and soil-improving properties can contribute to long-term ecological restoration.

Results and Discussions

Accuracy analysis of the UAV survey and subsequent outputs

UAV-based photogrammetry has become a widely adopted method for surveying and mapping terrain, particularly in complex environments such as mine waste dumps. This technology allows for the collection of high-resolution imagery that can be processed into detailed digital models, providing accurate spatial data for various applications, including landscape design, ecological restoration, and environmental monitoring. By capturing overlapping images from multiple angles, UAVs can generate three-dimensional surface models that represent the terrain's topography with remarkable detail and precision. These models are essential for assessing the physical characteristics of a site, such as elevation, slope, and surface features, which are critical when planning rehabilitation efforts and designing restorative landscapes.

In this study, the UAV-derived DSM was compared with an additional 40 control points that were measured using GNSS equipment, besides the ones used as GCPs and ICPs in the georeferencing stage. The aim was to assess the vertical accuracy of the DSM, ensuring that it meets the required standards for use in further GIS analysis and landscape design processes. The control points were distributed across the surveyed area, with the vertical differences between the DSM and GNSS measurements indicating the model's accuracy (Figure 6).

The differences between the DSM and GNSS data were visualized using a color-coded system. Green and yellow circles indicate small discrepancies, while orange and red circles highlight larger deviations. The vertical differences ranged from -0.146 meters to +0.204 meters, with the majority of points showing minimal errors. The box plot in the top right corner of the figure summarizes the data, illustrating an interquartile range of 0.060 meters and a median of 0.013 meters. This indicates that, in general, the DSM aligns very closely with the GNSS measurements, with most discrepancies falling within a few centimetres.

The Root Mean Square Error (RMSE) for the DSM was calculated at 0.086 meters, which is well below the 10 cm accuracy threshold typically recommended for earthworks and landscape design, as per professional criteria. This level of accuracy is considered excellent for most geospatial applications, ensuring that the model is sufficiently reliable for detailed terrain analysis, including slope, flow direction, and elevation mapping. Such precision is essential for developing landscape designs that will be used for rehabilitation projects, where accurate topographic data is crucial for planning interventions that stabilize the terrain and restore ecological functions.

With an RMSE well under the acceptable threshold, the UAV-derived elevation model is deemed highly reliable for further analysis and landscape planning. This accuracy supports the feasibility of using UAV photogrammetry in complex and hazardous environments like mine waste dumps, where traditional surveying methods may be difficult or unsafe. The precision of the elevation model provides a strong foundation for future restoration efforts, ensuring that the designed interventions are based on accurate, time and price efficient, real-world terrain data.

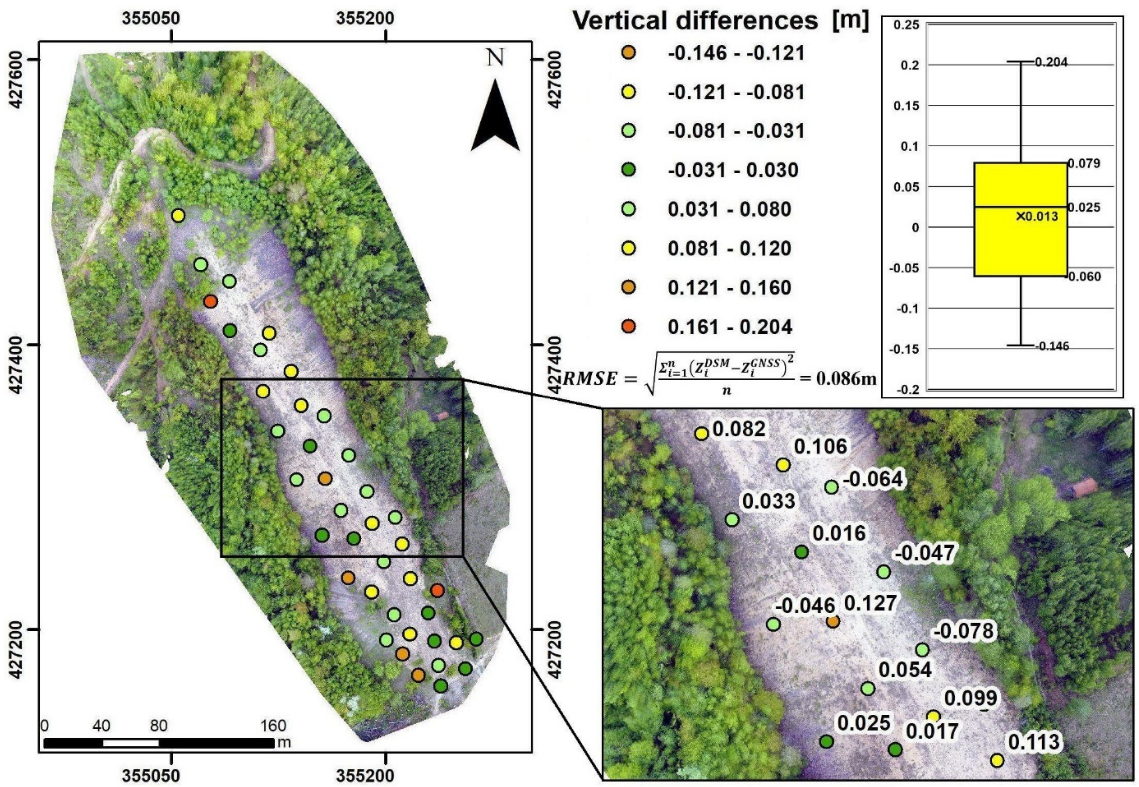


Figure 6. Vertical differences, error propagation and RMSE between the UAV-Derived DSM and GNSS measurements for the investigated mine waste dump

GIS analysis of terrain characteristics and pedo-climatic factors for mine waste dump rehabilitation

The GIS spatial analysis presented here was conducted using a high-resolution Digital Surface Model derived from UAV photogrammetry, which, as demonstrated previously, offers a high degree of accuracy (with an RMSE of 0.086 m). This spatial analysis allows for a detailed examination of the site's topographical and environmental characteristics, providing important insights into the feasibility of afforestation and ecological restoration, particularly with species such as black locust. The GIS derived maps depicted in Figure 7 highlight how the characteristics of the site align with certain benefits of afforestation using *R. pseudoacacia*.

The elevation map (top left) reveals the variation in height across the mine waste dump, with the range between 737.981 meters and 822.497 meters. The terrain is relatively undulating, with some areas showing more pronounced topographic features. These variations in elevation are important for understanding how water will behave across the site and which areas may be more prone to erosion or flooding. *R. pseudoacacia* thrives in disturbed soils and is known for its deep root system, which can help stabilize soils on slopes with moderate to steep inclines, such as those identified in the mine waste dump. The tree's ability to grow rapidly and anchor soil with its extensive root network can help reduce soil movement and prevent erosion in these areas, effectively reducing the risk of further degradation and improving the overall stability of the landscape.

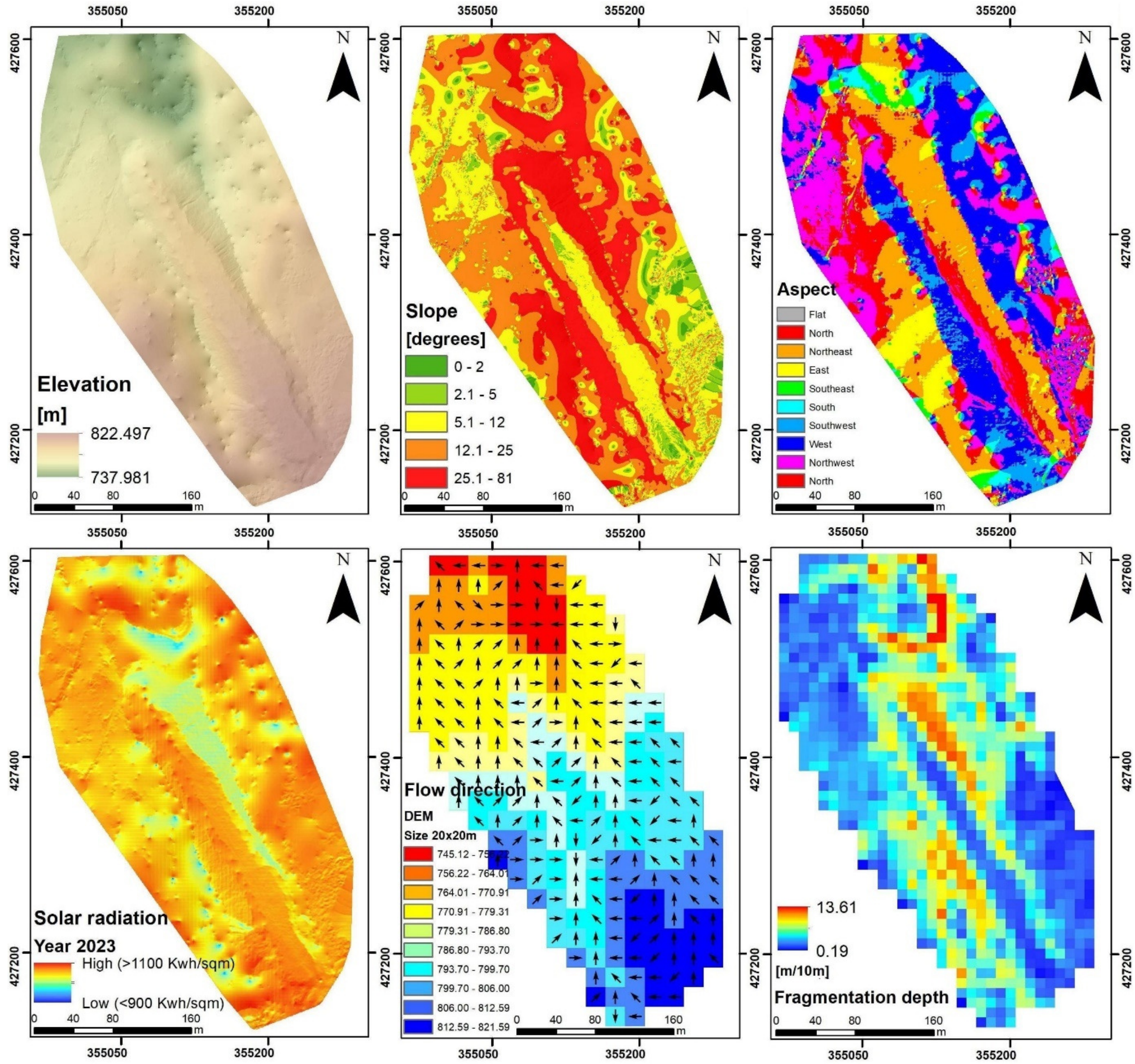


Figure 7. GIS Spatial Analysis of mine waste dump characteristics: Elevation, slope, aspect, solar radiation, flow direction, and fragmentation depth for *R. pseudoacacia* afforestation feasibility

The slope map (top middle) is a critical factor in evaluating the site for rehabilitation, as it indicates steep inclines ranging from 2° to 81°. Steep slopes, especially those above 25°, are particularly prone to erosion and landslides, which are common issues in mine waste dumps. The *R. pseudoacacia* species is well-suited for stabilizing such areas due to its strong root system that can hold soil in place and mitigate the effects of erosion. Its fast growth also allows it to quickly establish a protective vegetative cover, which reduces the direct impact of rainfall and wind, preventing further soil loss. Robinia's deep root system can help bind the soil, making it particularly useful in steep areas where other vegetation may struggle to establish. In these regions, Robinia will not only contribute to soil stabilization but will also promote soil improvement through nitrogen fixation, enhancing soil fertility over time.

The aspect map (top right) provides valuable information about the direction of the slopes, showing areas facing different cardinal directions. These directional aspects influence the amount of sunlight received by different areas of the mine waste dump, which in turn affects the microclimates and growing conditions for plants. *R. pseudoacacia* thrives in areas with ample sunlight, and the orientation of the slopes in the study area, particularly those facing south and southeast, provides favourable conditions for this species. These areas are exposed to higher solar radiation, which is beneficial for the growth of Robinia as it prefers warm climates with full sun exposure. By focusing on planting Robinia on these slopes, we can take advantage of the species' tolerance to heat and dry conditions, allowing it to establish and grow rapidly, contributing to the overall ecological rehabilitation of the site.

The solar radiation map (bottom left) for the year 2023 shows a significant amount of solar energy reaching the surface of the mine waste dump, with areas receiving high solar radiation (>1100 KWh/sqm). This level of solar exposure is advantageous for many plant species, particularly *R. pseudoacacia*, which is known for its tolerance to high temperatures and sunlight. The species thrives in environments with abundant light and heat, making the mine waste dump an ideal location for its afforestation. High solar radiation promotes photosynthesis, which is essential for healthy growth, particularly in the early stages of plantation establishment (Takebayashi *et al.*, 2017). In addition, Robinia's ability to fix nitrogen in the soil can further enhance the soil's fertility, contributing to the creation of a more hospitable environment for both the species itself and other vegetation in the long term.

The flow direction map (bottom center) is another important tool for understanding how water moves across the site. It reveals how water will travel downhill, often exacerbating erosion in areas with steep slopes. However, *R. pseudoacacia* plays an essential role in controlling water flow and reducing surface runoff. Its dense root system increases soil infiltration and retention, preventing water from rapidly flowing over the surface and causing erosion (Trif and Bilașco, 2024). In areas with high water flow, such as those indicated by the arrows on the flow direction map, planting Robinia can help manage runoff by slowing down water movement, thus reducing erosion risks and improving soil stability (Sestras *et al.*, 2023). The species also contributes to improving the soil's water retention capacity, which is crucial in areas prone to erosion or heavy rainfall.

The fragmentation depth map (bottom right) highlights the degree of soil disturbance across the site, with a colour scale representing rapid elevation changes. Regions with increased fragmentation depth are more susceptible to erosion, landslides, and various types of soil instability (Costea *et al.*, 2022). These regions frequently necessitate immediate assistance in rehabilitation initiatives. *R. pseudoacacia* has demonstrated efficacy in stabilizing severely affected regions due to its rapid growth, resilient root system, and nitrogen-fixing capacity. Planting *R. pseudoacacia* in regions with significant fragmentation depth helps stabilize the soil, mitigate erosion, and improve soil structure. As the trees age, their canopy and root systems will enhance the environment, facilitating the emergence of supplementary plants and encouraging enduring soil health. The extensive roots of *R. pseudoacacia* contribute to alleviating soil compaction, facilitating improved water infiltration and diminishing the probability of more fragmentation and deterioration.

Figure 8 provides important details regarding the climatic, soil, and land use conditions of the Uricani territorial administrative unit (TAU), specifically highlighting the location of the mine waste dump. Analysing spatial data, such as maps of average annual precipitation and temperature, soil types, and land use, enhances the understanding of the context in which the mining waste dump was constructed and the possibilities for afforestation and ecological restoration in the area. The data indicates that the mining waste dump's location, as seen in the figure, is located in an area characterized by clay soils and designated for pasture usage (Figure 8).

The average annual precipitation map (top left) reveals that the region receives an average of approximately 876.29 mm of precipitation annually, which is a moderate level for this type of terrain. This consistent rainfall supports the growth of vegetation, and while the mine waste dump itself may have altered the natural water retention capacity of the soil, the overall climate of the area remains conducive to vegetation establishment. The average annual temperature map (top right) shows that the area experiences a relatively cool climate, with an average temperature of about 6.62 °C. This is favourable for *R. pseudoacacia*, which can adapt to cooler climates and endure the winter conditions typical of the region. The ability of Robinia to thrive in moderate temperatures, coupled with its drought-tolerant nature, gives it a distinct advantage in terms of long-term survival and growth in this environment.

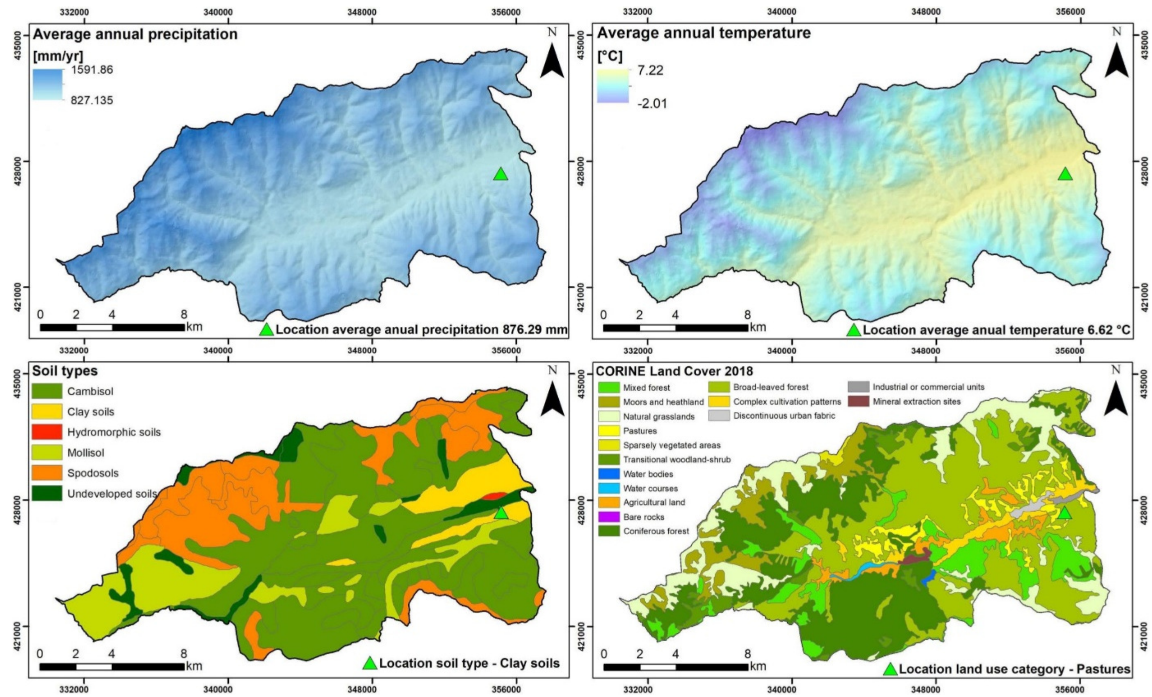


Figure 8. GIS analysis of climatic, soil, and land use conditions in the Uricani TAU: precipitation, temperature, soil types, and land use in the context of mine waste dump rehabilitation

The soil map (bottom left) shows that the mine waste dump area is situated in a region dominated by clay soils, as indicated by the yellowish colour. While clay soils are often less permeable and can retain more water than sandy or loamy soils, they can also present challenges for plant establishment due to their compactness and tendency to become waterlogged under certain conditions. However, the presence of clay soil can actually be beneficial for the afforestation of *R. pseudoacacia*. This species is known for its ability to adapt to a wide range of soil types, including clay soils, and its deep root system allows it to anchor firmly in these types of soils. Additionally, Robinia can help improve soil structure over time by increasing organic matter and promoting soil aeration, which can, in turn, reduce the soil compaction that often limits plant growth in clay soils. The natural nitrogen fixation process of Robinia will further benefit the soil, making it more fertile and supportive of both the species itself and other potential plants in the future.

The land use map (bottom right) indicates that the area was predominantly used as pasture prior to the establishment of the mine waste dump. This historical land use suggests that the soil was likely managed for grazing or agricultural purposes before it became disturbed by the mining activities. Pastures, by nature, support relatively low-density vegetation compared to forests, and the soil may have been periodically disturbed by grazing, trampling, or even tilling. However, this pre-existing land use could offer certain advantages for ecological restoration. Since *R. pseudoacacia* is a pioneer species, it is well-suited for establishing itself on disturbed lands. The fact that the land was previously used as pasture, rather than being covered by dense forest or other more sensitive ecosystems, may make it easier for Robinia to establish itself and begin the process of soil stabilization. The species' ability to grow rapidly and improve soil conditions can accelerate the rehabilitation process and foster the regeneration of a more diverse ecosystem.

While the mine waste dump itself has drastically altered the site's physical conditions, including the soil structure and nutrient content, the pre-existing pasture land use and clay soils offer opportunities for ecological restoration. The relatively mild climatic conditions of the region, with moderate precipitation and temperatures, create a favourable environment for the survival of *R. pseudoacacia* and other vegetation in the future. The clay soils, while problematic, can gain from the soil-improving attributes of Robinia, and the prior utilization of the land as pasture suggests that the site has experienced disturbances that Robinia can assist in correcting. With effective management and meticulous planting, Robinia can significantly contribute to soil stabilization, enhancement of soil quality, and restoration of the ecological equilibrium in the mining waste dump region.

Therefore, the combination of a temperate climate, clay soils, and a past history of pastureland promotes an ecosystem that is favourable for the afforestation of *R. pseudoacacia*. Despite the obstacles presented by the mining waste dump, the advantageous climatic conditions and soil types, along with the plant's adaptability, indicate that afforestation might be integral to a comprehensive landscape design. This design would assist ecological restoration and long-term land rehabilitation while transforming the region into a dynamic, multipurpose green space. The area in question can yield significant advantages for the residents by providing recreational facilities and environmental improvements, while also stimulating tourism in this historically disadvantaged area. The land reclamation process, emphasizing ecological and social regeneration, has the ability to convert the area into a valuable asset, advancing sustainable development and enhancing the local economy and quality of life.

Landscape design proposal for ecological rehabilitation and community engagement at the Uricani mine waste dump

The rehabilitation of the Uricani mine waste dump offers a unique opportunity to transform a degraded industrial landscape into an accessible, ecological space for the local community. This proposal envisions a balanced integration of ecological regeneration and recreational use, ensuring that the space serves both environmental and social needs. The landscape design concept focuses on a thematic trail that would guide visitors through the area, blending natural rehabilitation efforts with an engaging educational experience. Starting from the highest point of the site, the trail leads to a viewpoint that offers a comprehensive view of the landscape, allowing visitors to witness the full extent of the ecological restoration process (Figure 9).

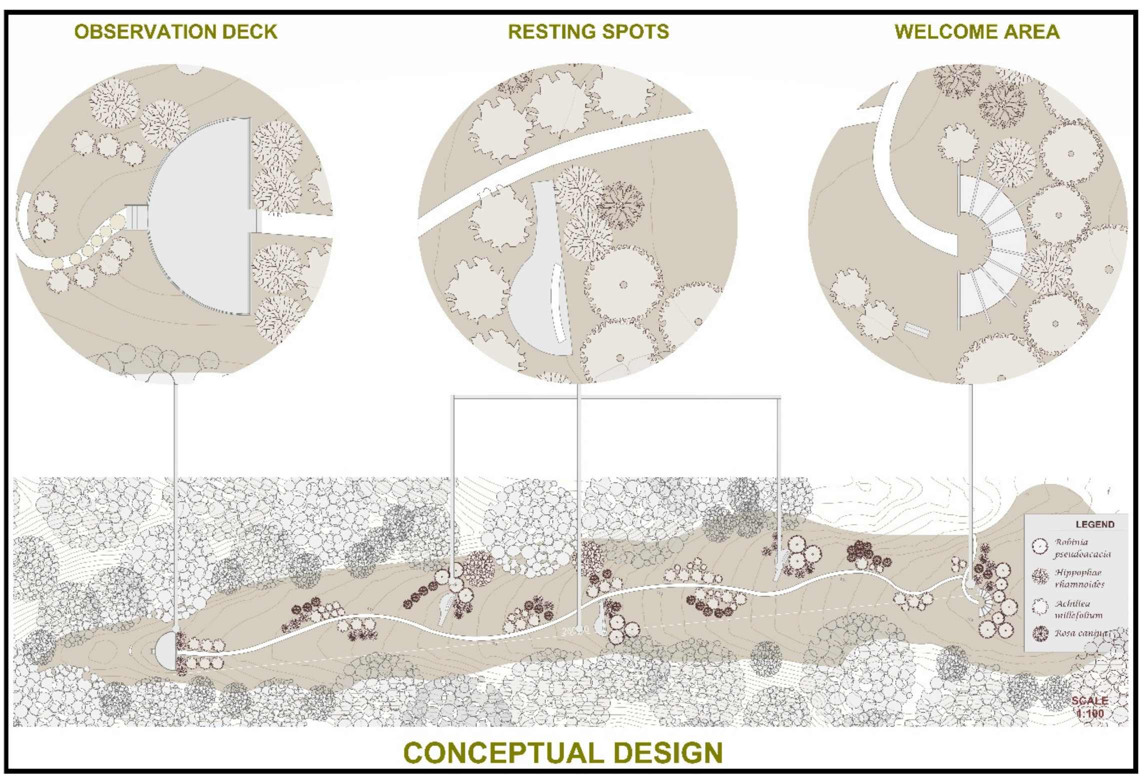


Figure 9. Conceptual landscape design for the Uricani mine waste dump rehabilitation

The design incorporates both functional and symbolic elements, starting with a pavilion located at the highest point of the site. This pavilion serves as the trail's starting point and is designed to introduce visitors to the area's industrial history and the ongoing rehabilitation efforts. It also provides a space for visitors to gather and relax before beginning their journey (Figure 10). The structure of the pavilion is minimalist, using a wooden frame with minimal environmental impact. It is surrounded by clusters of native vegetation, such as *Achillea millefolium*, *Rosa canina*, *Hippophae rhamnoides*, and *R. pseudoacacia*. These species are strategically selected not only for their aesthetic value but also for their ecological functions, such as stabilizing the soil, improving biodiversity, and attracting pollinators.

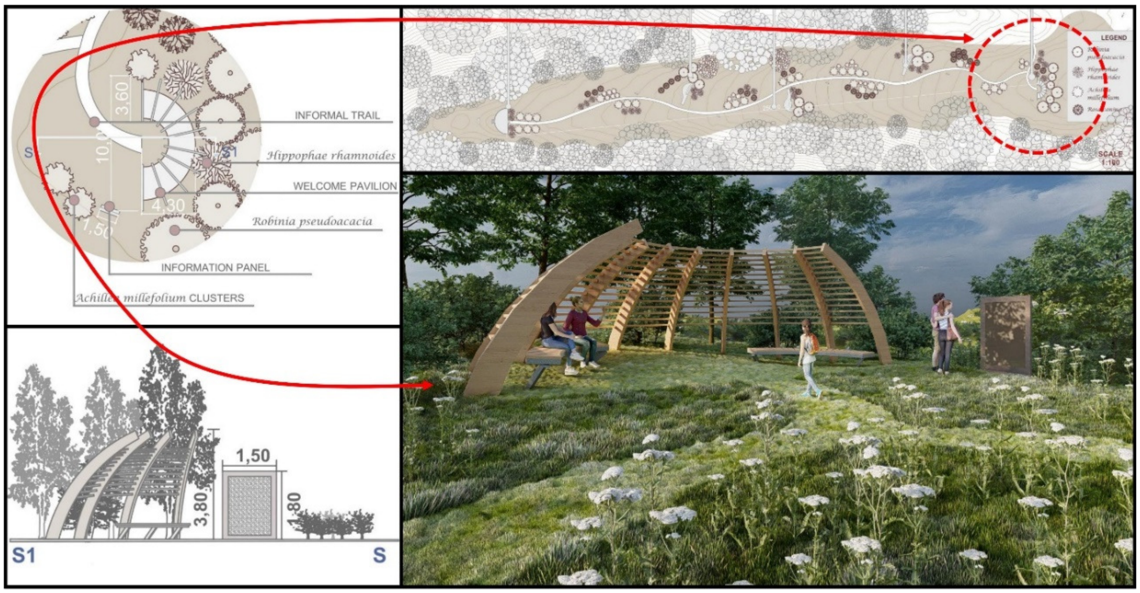


Figure 10. Conceptual design for 'Welcome Area': informal trail, information panel, and pavilion with *R. pseudoacacia* and other species planted

Along the thematic trail, resting spots are strategically placed, offering visitors places to pause, reflect, and enjoy the surroundings. These resting areas consist of wooden benches placed on deck platforms surrounded by vegetation, providing a seamless integration with the landscape. The design of the footpath, maintained by foot traffic or occasional trimming, allows for an unconventional, yet ecological approach to trail management, where the visitors are naturally guided through the landscape by the vegetation itself. This design approach is in harmony with the ecological goals of the project, reinforcing the connection between human activity and the natural environment (Figure 11).

The observation deck is another key feature of the landscape proposal. Positioned at a high point on the site, the deck offers visitors an opportunity to observe the entire area, allowing them to appreciate the extent of the ecological restoration and the improvements made to the site. This space provides a panoramic view and serves as the highlight of the trail (Figure 12).

Figure 11. Conceptual design for 'Resting Spot': informal trail, deck platform, and *R. pseudoacacia* and other species planted

The platform, made of wood, features seating areas and railings for safety, while also maintaining a simple, functional design that blends naturally with the landscape. The design also includes log stairs that lead to a secluded bench, encouraging individual contemplation and offering a peaceful retreat from the main trail. This element further enhances the connection to nature, creating an immersive experience for visitors (Figure 13).

Figure 12. Visualization of the 'Observation Deck' for the ecological rehabilitation landscape proposal

Figure 13. Conceptual design for 'Observation Deck': Deck platform, wooden log stairs, and *R. pseudoacacia* and other species planted

The landscape design proposal is not just a rehabilitation project, it is a multipurpose space that integrates ecological restoration with community engagement (Dinu Roman-Szabo *et al.*, 2023). By utilizing minimal design interventions, the project aims to support both ecological regeneration and human-nature connectivity. The selected plant species, primarily including *R. pseudoacacia*, are resilient and adaptable to the challenging conditions of the mine waste dump, providing long-term soil stabilization and enhancing the site's biodiversity (Băbău *et al.*, 2021; Ciuvăț *et al.*, 2022; Chirilă Băbău *et al.*, 2024). The landscape design not only restores the environment but also creates a valuable space for the local community, offering opportunities for recreation, education, and reflection. This project demonstrates how the rehabilitation of industrial sites can be harmonized with social, environmental, and educational goals, turning a previously degraded space into a valuable asset for the future.

Conclusions

The present research demonstrates how the integration of UAV-based photogrammetry and GIS spatial analysis can significantly enhance the efficiency and accuracy of environmental assessments, particularly in the context of mine waste dumps. The UAV survey, with its high-resolution DTM, has proven to be an effective tool for extracting key field metrics, providing a detailed understanding of the site's physical characteristics such as elevation, slope, and soil conditions. The derived data was instrumental in creating a comprehensive landscape proposal that considers both the technical and ecological challenges of the area. The GIS spatial analysis further contributed to this process, producing six important maps depicting elevation, slope, aspect, solar radiation, flow direction, and fragmentation depth, each providing insights into the site's terrain and behaviour. Additionally, the four pedoclimatic maps, which included factors like average temperature, precipitation, soil types, and land use, allowed for a holistic understanding of the area's environmental context. These maps are pivotal in assessing the feasibility of planting *R. pseudoacacia*, a species well-suited to the site's conditions, offering both soil stabilization and ecological restoration benefits. The successful application of UAV and GIS technologies in this landscape design stage illustrates the immense potential of such tools in land reclamation and ecological restoration projects. The accurate, data-driven approach adopted in this study emphasizes the importance of modern surveying techniques in achieving sustainable land improvement goals. The interdisciplinary nature of this article, which bridges the fields of geodesy, forestry, and landscape architecture, demonstrates how collaboration between these domains can lead to innovative solutions for environmental challenges. By combining technological precision with ecological knowledge, this project not only proposes a path toward the rehabilitation of a degraded landscape but also sets a precedent for future ecological restoration efforts, contributing to the environmental, social, and economic revitalization of previously disadvantaged regions.

Authors' Contributions

Conceptualization: GP and PS; Data curation: PS, TS, SB, AC, VC, MDRS; Formal analysis: LOD, MVH, AH, TS; Funding acquisition: GP, LOD, MVH; Investigation: GP, PS, SK; Methodology: PS, TS, SB; Project administration: GP, AH, AMTC, AC, VC; Resources: CAP, LOD, MVH; Software; Supervision: CAP, AC, VC; Validation: AC, VC; Visualization: SB, MDRS, SK; Writing - original draft: GP, PS, SK; Writing - review and editing: CAP, LOD, MVH, TS. All authors read and approved the final manuscript.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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