# Low-cost techniques for soil erosion monitoring on mountain trails

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**ABSTRACT:**

This study presents low-cost techniques for monitoring soil erosion on mountain trails within the context of the HUMANITA project, which focuses on mitigating the environmental impacts from recreational activities in protected areas. Monitoring erosion in mountain environments poses several challenges that must be considered to select optimal techniques, such as limited accessibility, instrument portability, achievable level of detail, absence of data connectivity and Ground Control Point establishment. In addition, soil erosion is a widespread issue that requires surveys over large areas and must be repeated periodically to ensure accurate assessment and track changes over time. Consequently, the cost and ease of use of surveying equipment are critical.
Six protected areas in Italy and Central Europe were selected as pilot sites. Three scenarios were explored, each characterized by different spatial extents and level of details required for erosion assessment: detailed analysis of small areas (scenario 1), narrow forest trails (scenario 2), and broad open areas (scenario 3). Scenario 1 employed high-precision techniques such as Terrestrial Laser Scanning and close-range photogrammetry to capture micro-scale changes. Scenario 2 utilized spherical photogrammetry and UAVs to survey narrow, vegetated trails with high resolution and accuracy. Scenario 3 focused on UAV photogrammetry for monitoring large areas. Key challenges included multi-epoch data co-registration, establishing stable ground control points, and ensuring and assessing surveys repeatability. The results highlight the capabilities, limitations, and cost-effectiveness of these geomatics techniques, providing practical guidelines for sustainable trail management and erosion monitoring in protected mountain areas.

## 1. Introduction

In recent years, the demand for outdoor recreational activities such as hiking, mountain biking, and skiing has surged, posing both opportunities and challenges for the management of protected areas (PAs). This trend has led to increased pressure on natural landscapes, resulting in significant environmental impacts including soil erosion, vegetation degradation, and disruption of wildlife habitats.
The EU Biodiversity Strategy for 2030 ("Biodiversity Strategy for 2030. European Commission.," 2022) underscores the importance of effectively managing all protected areas, integrating different approaches, with clear conservation objectives and appropriate monitoring measures. The strategy also highlights the need for integrated approaches to counteract environmental degradation and ensure ecological connectivity. This context emphasizes the urgency of developing robust monitoring systems and mitigation strategies to preserve the ecological integrity of PAs.
The Interreg Central Europe project HUMANITA ("HUMANITA," 2024), started in 2023, aims to address these challenges by developing innovative, evidence-based tools and methodologies for assessing and mitigating the impacts of tourism on PAs. By fostering transnational collaboration and sharing best practices, the project seeks to enhance the capacity of PA managers to make informed decisions that minimize human-nature conflicts and promote sustainable tourism. The primary goal of the project is to identify and measure the impacts of recreational activities on natural assets within protected areas in Central Europe, explore and analyze the temporal and spatial variations of various tourist activities and correlating them with different environmental indicators, and develop a common integrated monitoring strategy. This innovative approach will illustrate the potential influence of human activities on different components of the environment, including physical, ecological, and hydrological impacts, as well as the impact on wildlife.
The work presented focuses on monitoring soil erosion on mountain trails. Soil erosion can significantly alter trail geometry, leading to increased maintenance costs and potential environmental degradation. High and unsustainable erosion rates have been documented, particularly in regions with significant recreational activities pressure, highlighting the need for more focused efforts on mitigation and restoration practices (Olive and Marion, 2009).
A comprehensive review of existing literature presented by (Salesa and Cerdà, 2020) reveals that, while soil erosion in agricultural contexts has been well-studied since the early 20th century, the impact of soil erosion on mountain trails, especially related to recreational activities (such as trekking, biking, and horse riding), has only recently garnered attention.
To monitor and quantify soil erosion, several remote sensing and geomatics techniques are available nowadays, such as Satellite Imagery (InSAR, reflectivity analysis) (Mihai et al., 2009), airborne/UAV photogrammetry (Ancin-Murguzur et al., 2020; Ćwiąkała et al., 2017), airborne/terrestrial laser scanning (Ballesteros-Cánovas et al., 2015; Bodoque et al., 2017; Tarolli et al., 2013), GNSS (Global Navigation Satellite System) and

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traditional topographic survey techniques (e.g. total station and leveling). These techniques provide valuable data for assessing erosion, offering a geometric description of the trails.

Nevertheless, monitoring soil erosion on mountain trails involves several challenges, which need to be taken into account in the planning phase, to choose the most suitable survey technique.

First of all, soil erosion varies depending on the trail's morphological characteristics and its usage. For example, activities like motorbiking, cycling, or horseback riding have a much greater impact compared to hiking. The type of ground cover also plays a significant role in determining how susceptible the trail is to erosion. Additionally, narrow paths force users to tread the same areas repeatedly, intensifying erosion in those specific sections. As a result, the extent and severity of soil erosion can vary significantly, even along the same trail, and should be studied at different scales, considering the various contributing factors. High detailed analysis may be necessary in small sample areas to accurately assess the extent of erosion, while less detailed assessments can be applied to longer trail sections to give a broader overview of the erosion process.

Additionally, monitoring soil erosion occurs in environments that are often particularly challenging. The areas may be remote and difficult to access, necessitating the use of lightweight, portable surveying equipment. Data connectivity (4G/5G/UMTS) is not always reliable and establishing stable ground control points can be problematic. Conversely, in less remote areas, the presence of people or animals on mountain trails may require techniques that minimize interaction and disturbance with the surroundings.

Finally, soil erosion is a widespread issue that requires surveys over large areas and must be repeated periodically to ensure accurate assessment and to evaluate track changes over time. As a result, the cost and ease of use of surveying equipment are crucial. The techniques employed should be affordable to facilitate broad application and frequent use, without placing a heavy financial burden on the organizations managing protected areas. Moreover, if easy to use techniques can be used, this would allow non-specialized personnel, such as existing staff or regular trail users (e.g., mountain guides), to conduct the data acquisition, eliminating the need for dedicated hires.

This article analyses several strategies for monitoring and managing soil erosion on mountain trails.

## 2. Materials and methods

The research explores soil erosion monitoring across various scenarios in terms of spatial extent and level of details required for erosion assessment (Figure 1). The first scenario focuses on a detailed analysis of small sample areas, typically just a few square meters, aiming to precisely measure the impact of small-scale erosion processes. Here, the objective is to survey small, localized trails sections with high levels of detail, enabling the detection of micro-scale erosion. Such detail is necessary for assessing even minimal changes in trail morphology, particularly in areas subject to intense foot traffic or specific environmental conditions. Beyond observing soil changes, this scenario includes a unique focus on exposed roots, which act as indicators of historical soil levels. As erosion gradually uncovers roots, their relative height above the current ground level provides insight into past soil loss, making this method particularly valuable for trail segments where roots are close to the surface and can serve as natural markers for prior soil heights.

The second scenario focuses on surveying trail segments of varying lengths, particularly narrow paths within wooded areas where erosion patterns can vary significantly. This setting introduces two primary challenges: first, ensuring high accuracy over an extensive spatial area requires balancing fine detail with the need to cover a long, continuous trail segment, thus necessitating a compromise between resolution and coverage. Second, these trails are situated within forested environments, where obstacles like vegetation and tree cover create frequent occlusions that complicate data acquisition and limit visibility along the path.

The final scenario examines broad, open areas to assess general trends in soil erosion and trampling effects. This approach focuses on capturing larger-scale changes, with a less granular level of detail than in the previous scenarios, aiming instead to track average erosion patterns and ground compaction over time.

Across all scenarios, the research prioritized identifying the most effective surveying technique/s, evaluating each method's ability to meet scenario-specific requirements, data acquisition speed, equipment portability, and associated costs.

A primary challenge was the reliable co-registration of surveys across multiple epochs, as each area was surveyed both before and after the tourist season to assess seasonal erosion impact. Establishing stable, long-term Ground Control Points (GCPs) presented significant logistical difficulties. First, the process of marking GCPs is time-intensive, adding substantial cost and effort that conflict with the study's goal of efficient, low-cost surveying. Additionally, environmental conditions often make it impractical, or even impossible, as remote or rugged terrain can limit accessibility. Finally, when GCPs are positioned near trails for convenience, they can be frequently displaced by foot traffic or affected by natural disturbances, compromising their stability and effectiveness for accurate, repeatable co-registration across different survey periods.

To address these issues, different methodologies were tested in each scenario to support consistent multi-temporal alignment. Since the primary objective of the study is to compare erosion changes across different epochs and to assess the relative impact over time, priority was given to repeatability comparisons across different epochs to assess the precision of the measurements.

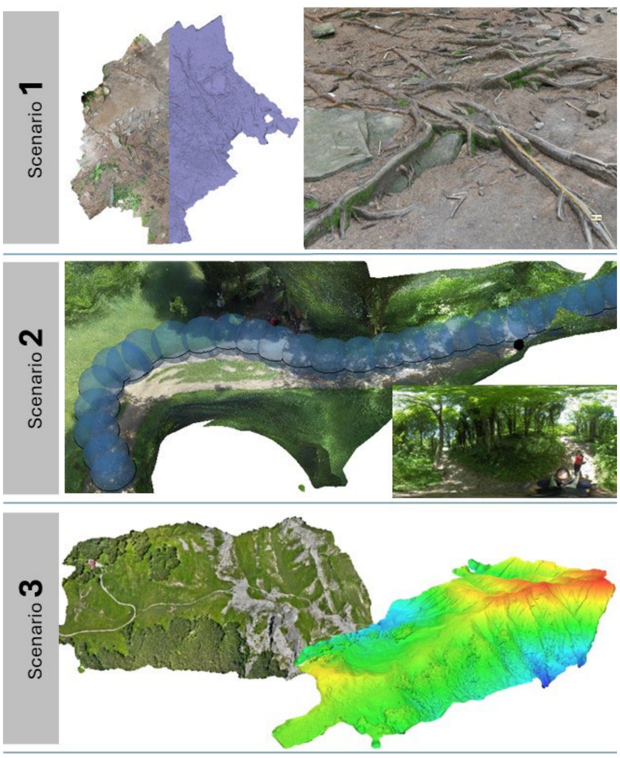


Figure 1. Summary of the three investigated scenario: 1. Small-scale sample areas; 2. Narrow paths; 3. Wide and open areas.

In this initial stage of the project, considerable emphasis was placed on validating the results obtained. This involved conducting numerous comparisons and checks (generally resource-intensive and challenging in such contexts) to evaluate the precision achievable with these methodologies.
The analysis of results is generally challenging to automate. A key issue in this context is distinguishing changes caused by erosion from those due to natural factors, as accumulation of leaves and debris, so that the differences measured in DTMs often reflect these phenomena rather than actual erosion. To this extent, several change-detection methodologies (manual or semi-automatic), ranging from more localized to more extensive approaches, were considered.

### 2.1 Test sites

The tests were conducted in six pilot sites within protected areas selected as part of the HUMANITA project, representing diverse geographical and environmental conditions. Three of the test sites are located in Italy's Tuscan-Emilian Apennine National Park, which has held UNESCO Man and Biosphere Reserve status since 2015.
The first pilot area is the Pietra di Bismantova site (TS A), a striking, isolated rock formation with a unique, ship-like silhouette. This massive rock plateau stretches approximately 1 kilometre in length, 240 meters in width, and rises 300 meters high, showcasing the effects of millennia of erosion. It is a popular destination for tourists, hikers, and rock climbers. Numerous trails of varying difficulty levels wind up to the plateau.
The second investigated area (TS B) is the Pass of Lamalite, a high-altitude pass connecting the Emilia-Romagna and Tuscany regions. Surrounded by dense forests and open meadows, it provides a habitat rich in diverse flora and fauna. The trails around the pass vary in difficulty, making it a popular route.
The third area (TS C) is Mount Marmagna, one of the highest peaks in the Tuscan-Emilian Apennines, standing at 1,852 meters. Trails leading to the peak wind through diverse landscapes of beech forests, alpine meadows, and rocky outcrops, appealing to both beginner and experienced hikers. At the foot of Marmagna Mount lies Lago Santo, the largest natural lake in the Emilian Apennines. The entire area is very popular for tourism, especially during the summer by being able to take advantage of both hiking and recreational activities on the lake.
One additional site (TS D) is situated in central Europe in the Karawanken-Karavanke UNESCO Global Geopark, a cross-border region spanning Slovenia and Austria. The park covers approximately 12,000 hectares and includes diverse ecosystems ranging from alpine meadows to dense forests, with elevations reaching up to 2,195 meters at the peak of Vršič. This region is home to rich biodiversity, including rare alpine plants and wildlife and is rich in geological features. The park offers visitors educational trails, guided tours and diverse outdoor activities, including hiking, rock climbing, and mountain biking, which pose challenges to conservation efforts.
Another test site (TS E) is located near Klagenfurt am Wörthersee, in the Austrian region of Carinthia. Specifically, TS E focuses on the Falkenberg hill, located north-west of the main city. This densely vegetated area features a variety of trails for outdoor activities, including a network of hiking paths on the southern slope, and a system of mountain bike trails descending along the northern slope of the hill. The area's already significant popularity has recently increased thanks to the organization of sport events (e.g., SloEnduro Day Klagenfurt-Falkenberg) taking place on newly inaugurated bike routes.
The last site (TS F) is the Kamenjak Park, a protected natural area situated at the southern tip of the Istrian Peninsula, near Premantura, Croatia. Spanning approximately 34 square kilometres, the park is characterized by a rugged coastline featuring numerous limestone cliffs, rocky beaches, and small coves, which have been shaped by erosional processes over time. The park is notable for its rich biodiversity, hosting a variety of habitats and is also an important geological site. The park is popular for swimming, snorkelling, and diving, while its network of walking and cycling paths are attractive for hiking and cycling. However, the park's accessibility by car poses challenges for its conservation. Increased vehicle traffic can lead to soil erosion, habitat disturbance, and pollution, impacting the delicate ecosystems within the park. Efforts to balance visitor access with environmental protection are ongoing.

### 2.2 Equipment

To acquire data, a selection of the most widely used data acquisition techniques was adopted, choosing the most appropriate ones based on the specific context of each survey (Figure 2).

**2.2.1 Scenario 1:** The use of a tripod-mounted Terrestrial Laser Scanner (TLS) and close-range photogrammetry (CRP) was investigated. Both instruments achieve high levels of precision (up to 1 mm for TLS and even higher for photogrammetry). Although laser scanning is not considered a low-cost technology, due to the substantial investment required for equipment and data management software, recent advancements have made modern TLS systems more portable and efficient. These systems enable rapid acquisition of millions of points without needing ground-based measurements to scale the data, making them advantageous even in complex environments like those investigated in this study.
Specifically, the Leica Geosystems RTC360 terrestrial laser scanner was used. This scanner uses high-dynamic time-of-flight

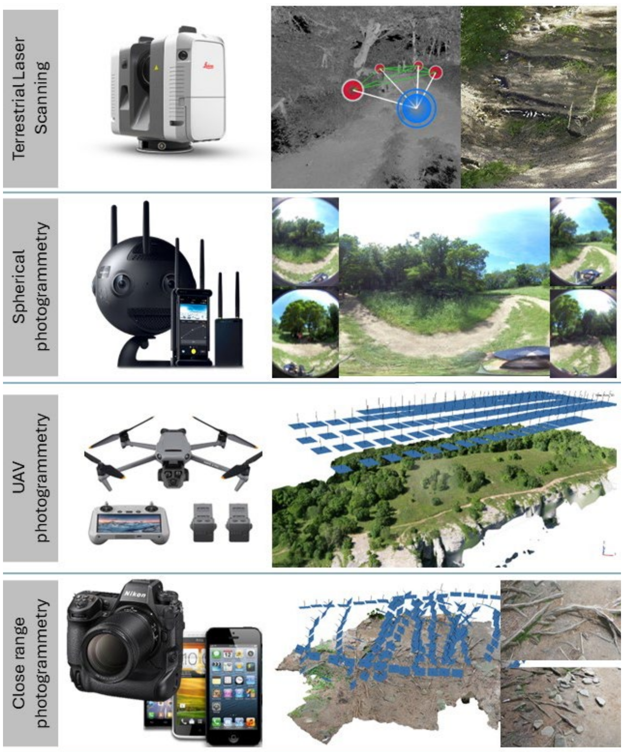


Figure 2. The most widely used geomatic technologies for soil erosion monitoring.

technology enhanced by Waveform Digitising (WFD), allowing it to capture up to 2,000,000 points per second within a range of 0.5 m to 130 m and achieving a maximum resolution of 3 mm at 10 m. Equipped with a Visual Inertial System (VIS) that includes a video-enhanced inertial measurement unit, it enables automated, target-free field scans registration by tracking the scanner's movement in real time between setups.
On the other hand, CRP offers significant advantages in terms of portability, a crucial factor in difficult and uneven terrains where bulky equipment may be impractical. CRP also combines high precision with the flexibility to produce both 3D models and orthophotos, allowing depth changes measurements and visual analysis of colour variations indicative of superficial erosion. However, achieving optimal accuracy and detail with photogrammetry requires a stable ground reference system.
For these CRP surveys, a digital single-lens reflex (DSLR) Nikon D3x camera was utilized. It is a full format camera with a resolution of 24 megapixels (6048x4032 pixel) and in these applications was equipped with a fixed 35 mm focal length optics (AF-S Nikkor 35 mm f/1.8G Lens).

**2.2.2 Scenario 2:** The most effective techniques in this context are mobile (e.g., SLAM) laser scanning, spherical photogrammetry, and low-altitude UAV photogrammetry. While SLAM-based mobile laser scanning offers rapid data collection, it can be less accurate and requires expensive equipment. In contrast, photogrammetry provides high-quality 3D reconstructions at a significantly lower cost. Spherical or panoramic cameras, which are lightweight and can be mounted on backpacks, are particularly useful for surveying long, narrow trails with obstacles. UAVs equipped with omnidirectional sensors for obstacle detection and avoidance are also highly effective in these settings, offering high resolutions on the terrain reconstruction. However, both spherical cameras and UAVs require ground control points (GCP) (at least) at the beginning and end of the trail due to the (probable) lack of GNSS support for precise positioning if the trail passes through forested areas.
For this scenario, photogrammetric methods were exclusively selected, using the INSTA 360 Pro2 spherical camera, and the DJI Mavic 3 Enterprise drone.
The INSTA 360 Pro2 is a professional 360° camera equipped with six cameras, each with a resolution of 4000x3000 pixels and fixed focal length of 1.88 mm, offering a 200° field of view. The sensors are arranged equidistantly around the equator with a 60° relative rotation. The camera captures raw fisheye images and can produce equirectangular images (7680 x 3840 pixels) through real-time or post-processing stitching of the acquired fisheye images. The camera supports various shooting modes for 360° still images, videos, and timelapses, and stabilizes equirectangular images using a 9-axis gyroscope.
The DJI Mavic 3E is a professional-grade drone designed for photogrammetry and mapping applications. It features an RGB camera with a 4/3 CMOS sensor and a 20-megapixel resolution, equipped with a mechanical shutter. The Mavic 3E also includes an integrated Real-Time Kinematic (RTK) positioning module, enabling centimetre-level accuracy in georeferenced coordinates, making it especially suitable for broader surveys in Scenario 3.

**2.2.3 Scenario 3:** In this scenario, UAVs equipped with imaging and LiDAR sensors are advantageous due to their ability to cover large areas efficiently and with high accuracy. The (usually equipped) RTK module allows for GNSS assisted orientation of the image block, often reducing or eliminating the need for GCPs (Forlani et al., 2018), which significantly enhances operational efficiency, particularly in remote or inaccessible environments.
In this study, all UAV datasets were acquired using the DJI Mavic 3E. However, as many of these survey sites lacked internet connectivity, the DJI D-RTK 2 GNSS mobile station was used as a fixed reference station sending real-time GNSS corrections to the drone, to maintain high-precision positioning. The point where the antenna was positioned was first marked and surveyed using a GNSS receiver, establishing known coordinates. This fixed point then served as a stable base for differential corrections, allowing for consistent data quality across epochs and reducing the number of required GCPs to a single Control Point.

## 3. Results

### 3.1 Scenario 1

For Scenario 1, two areas were selected within the Bismantova site (TS A1 and TS A2) and one at Mount Marmagna (TS C). The surveyed areas are located along trails adjacent to protruding roots, which were sampled to estimate past erosion. At the current stage, two different epochs have been surveyed for each site.
The surveyed areas, particularly in the Bismantova sites, are quite small in size and were surveyed using redundant close-range photogrammetric blocks, combining nadir and oblique images. This approach aimed to minimize occlusions and obtain a complete reconstruction of the ground. Table 1 provides details on the surveys.

| Test site | Area [m$^2$] | N. Img. | Survey Type | GSD [mm/pix] | Epochs | Avg. repeat. [mm] |
|---|---|---|---|---|---|---|
| A1 | 9 | 112 | CRP | 0.2 | 2 | 7 |
| A2 | 12 | 108 | CRP | 0.2 | 2 | 5 |
| C | 37 | 199 | CRP | 0.3 | 2 | 9 |

Table 1. Summary of the surveys executed in scenario 1.

To set the reference system and provide a stable reference model for co-registering subsequent photogrammetric surveys, a preliminary TLS survey was conducted during the first acquisition campaign (Figure 3). The number of scans varied across the test sites and was designed to ensure high overlap, in order to optimize cloud-to-cloud registration (an aspect often more challenging in environmental applications due to the presence of vegetation), minimize occlusions and holes and obtain point clouds with a resolution comparable to CRP surveys. Being the sampled areas on the trail, the physical placement of coded targets was avoided to prevent potential disturbance. Natural stable and recognisable features, such as distinct rock formations and tree roots, were therefore utilized as reference points between TLS scans and photogrammetric blocks. However, this approach posed challenges due to the dynamic nature of the environment, with rocks, leaves, and small branches moving over time, and vegetation undergoing continuous changes. These natural variations complicated the identification of consistent features (Figure 4).


Figure 3. Planar and immersive view of the TLS point cloud at TS A2.

Figure 4. Visual comparison between the same trail section in two different epochs (Left, Epoch1; Right, Epoch 2) – TS A2.

Considering these challenges, these reference points were used as GCPs to set the photogrammetric reference system and for an initial co-registration, which was then refined through an Iterative Closest Point (ICP) procedure applied to invariant parts of the model, such as rock boulders.
This procedure was evaluated through repeatability tests performed across different epochs, in order to assess the measurement precision and the minimum detectable erosion value. Specifically, starting from the Digital Surface Models DSMs, stable and invariant areas were first isolated, and the 3D differences between the DSMs were calculated for these regions. The Root Mean Square Error (RMSE) of these differences was used as the metric to assess precision. The resulting data are presented in Table 1 (average repeatability – avg. repeat.).
The results show an average repeatability RMSE lower than 1 cm. While this value may initially appear high, especially when compared to the GSD value, which ranges between 0.2-0.3 mm, it is important to consider the context of a natural environment, where achieving sub-millimetre precision in data co-registration is unrealistic. The co-registration and comparison are always performed on natural elements whose surfaces are highly subject to variations such as leaf accumulation, mud, moss growth, or other vegetation changes, inevitably introducing a certain variability. Additionally, the collimation of points used as GCPs by the operator was carried out on natural elements that cannot be identified with sub-millimetre precision. Consequently, while the very small GSD allows for capturing a significant level of detail in each model, it does not enable multitemporal co-registration with the same precision.
The results obtained in this scenario encompass co-registered DSMs, orthophotos and raster Digital Elevation Models (DEMs). Figure 5 shows an example of comparison between DSMs at TS C taken near a sampled root. Here, the root cut is clearly visible and marked in blue, while a pinecone that accidentally fell to the side is highlighted as an addition. The rest of the area remained almost unchanged.


Figure 5. Example of comparison between Epoch 1 and Epoch 2 at TS C.

### 3.2 Scenario 2

This scenario involved the survey of three trail sections within forested areas, with lengths ranging from 70 meters to 500 meters. In all three cases, two epochs were acquired. The goal was to investigate the optimal approach for different trail lengths. Table 2 summarizes details of the surveys.

| Test site | Length [m] | N. Img. | Type | Flight alt.[m] | GSD [mm/pix] | Epochs |
|---|---|---|---|---|---|---|
| D | 510 | 598* | 360° | 2.2 | 2.2 | 2 |
| Dbis | 510 | 1325 | UAV | 3 | 0.8 | 2 |
| E-1 | 70 | 269 | UAV | 4 | 1.1 | 2 |
| E-2 | 185 | 530 | UAV | 5.5 | 1.5 | 2 |

* Number of shooing points. The total number of images is 1180

Table 2. Summary of the survey executed in scenario 2.

In Test Site D, the trail was heavily wooded presenting obstacles and occlusions. Data acquisition was performed using both the UAV and the INSTA spherical camera.
The UAV survey was flown at a very low altitude (3 m) to avoid obstacles passing under the trees' branches. The drone was manually piloted to precisely track the trail path. Images were captured in timelapse mode with a 2-second interval between shots. This approach simplified the data acquisition process, making it more efficient and manageable.
The INSTA was mounted on a backpack at a height of approximately 220 cm above the ground, to simplify data acquisition on the move along the trail. The time-lapse acquisition mode was employed to acquire images every 2 seconds, saving the operator from shooting images by himself. Being the acquisition on the move, shutter priority was activated to prevent motion blur. This setting can be tricky as, in low light conditions due to dense vegetation, balance between exposure time and ISO must be found to avoid getting too noisy images.
Image processing was performed on the raw fisheye images acquired by the six sensors of the camera (rather than on the stitched equirectangular images), applying a multicamera constraint between the sensors. Specifically, the exterior orientation parameters were computed only for the master sensor, with those of the slave sensors based on the known relative orientation among the sensors themselves. More details on this processing procedure are provided in (Perfetti et al., 2024).
Also in this case, for the reasons described in section 2, coded GCPs, surveyed using topographic techniques, were not employed to establish the reference system. Additionally, given the long linear extent of the survey site and the primary objective of allowing multitemporal comparisons, the focus was not on maximizing accuracy but on establishing a reference for scale and the Z direction that remains sufficiently stable and consistent across the different epochs. This approach was intended to enable comparisons with an acceptable level of uncertainty, consistent across the epochs. Since the trail is located in a forested area, direct georeferencing using GNSS solutions was impractical and would have introduced errors up to several metres. However, this site has a unique configuration that partially allows for the use of RTK positioning. Specifically, the trail under study is adjacent to a forest road devoid of tree cover and connected to it at three points via short transverse paths. This setup enabled the drone survey to cover both the studied trail and the forest road along with its connecting paths, creating a stable closed double-loop configuration (see Figure 6) and utilizing RTK positioning solely over the forest road (average altitude 60 m).
Although partial, the RTK positioning was sufficient to establish the scale and georeferencing of the entire photogrammetric

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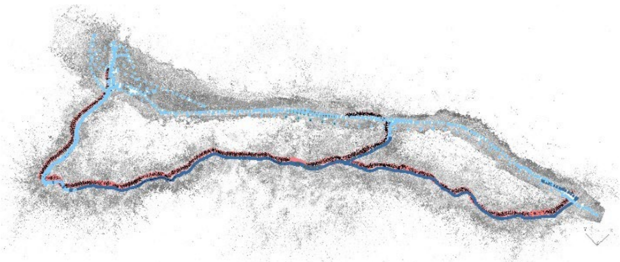


Figure 6. Photogrammetric blocks in TS D. The blue dots represent UAV images captured along the trail, the light blue dots indicate UAV images taken along the forest road, while red dots correspond INSTA spherical camera images.

block. The UAV flight conducted during the first acquisition epoch, performed in this manner, served as the reference ground truth for co-registering all subsequent surveys, including those conducted with the UAV and spherical camera, by employing GCPs identified on stable natural elements extracted from this reference survey.

UAV and spherical camera surveys were also carried out at the TS E1 and TS E2 sites, using the same acquisition settings as in TS D. However, at present, the data obtained from the spherical camera are still being processed and, therefore, have not been included in the results presented in this article.

At this site, however, it was not possible to benefit from even partial RTK positioning. GNSS positions of the centres of projection were recorded, though significant errors were expected due to poor signal reception, with the aim of providing an approximate scaling of the model. In this case as well, co-registration between multi-temporal acquisitions was optimized using manually extracted GCPs, whose coordinates were obtained from the first epoch (used as the reference).

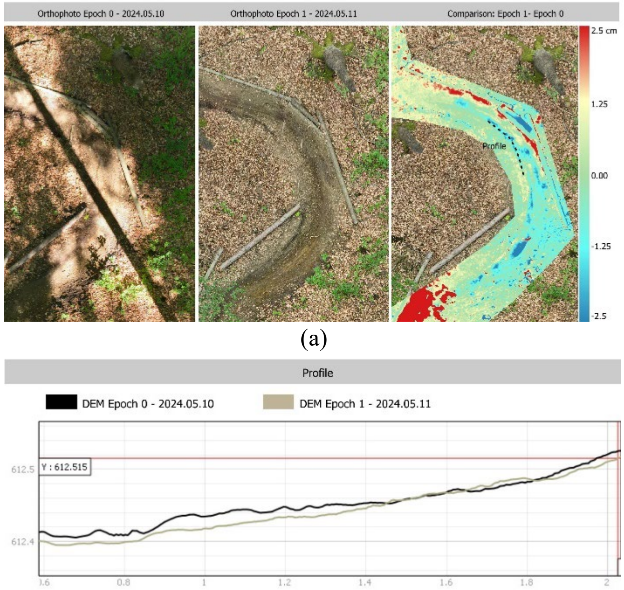
To assess the precision of the surveys, using the same methodology applied in Scenario 1 proved to be highly computationally intensive and not cost-effective, given the larger area under investigation. As an alternative, common, unchanged check points were identified and matched across models. The average RMSE of the differences between their coordinates across the epochs was used to assess precision (Table 3).

Although focused on a reduced number of sampled points, this procedure provides a thorough assessment of co-registration in both the planimetric and vertical directions. Furthermore, it allows for the exclusion of areas from metric quantification that have inevitably changed due to surface deposits, as highlighted earlier in Scenario 1, thus enabling a more accurate assessment of the repeatability of observations.

Apparently, the results indicate that the precision achievable with UAV surveys usually surpasses that of the spherical camera. However, it should be noted that trail sections E1 and E2 are considerably shorter (70-185 meters) than the one tested in site D, where the spherical camera survey outperformed the corresponding UAV. This difference can partially be attributed to the acquisition geometry and the relative positioning of the camera with respect to the terrain. It is evident that, for the same trail length, the number of shooting points is considerably higher

| Test site | Average repeatability - RMSE [mm] | | | |
|---|---|---|---|---|
| | X | Y | Z | XYZ |
| D | 42 | 45 | 30 | 71 |
| Dbis | 66 | 123 | 120 | 184 |
| E-1 | 5 | 7 | 7 | 11 |
| E-2 | 11 | 13 | 17 | 24 |

Table 3. Results of repeatability tests performed in Scenario 2.




(a)

(b)

Figure 7. Examples of erosion assessment at TS E2. (a) From left to right, orthophotos corresponding to Epoch 0 and Epoch 1, and a false-colour difference map comparing the DEMs of the two epochs. (b) Cross section extracted along a bike track showing the terrain profile for both epochs.

with the UAV compared to the spherical camera (598 positions for the INSTA camera versus 1325 for UAV images), resulting in an average base length of 85 cm for the INSTA and 38 cm for the drone. On the other hand, the scene captured with the UAV (that points approximately nadiral toward the ground) is limited w.r.t. the 360° capture of the INSTA and, to avoid obstacles while trying following the terrain, the trajectory of the UAV is considerably less regular than the one obtained with the spherical camera. This is probably the principal cause of higher check points residuals (double or more) found in the UAV survey, being the imaging geometry of the former, even if with a lower number of shooting positions, more regular and rigid. In terms of level of details achievable, on the other hand, the smaller GSD and being framed only the terrain, makes the UAV survey better than the corresponding spherical camera acquisition.

Regarding the analysis of displacement components, the behaviour varies by site without a clear predominance of errors along a particular direction. Particularly at Site D, due to its greater length, planimetric errors (for the INSTA) are more noticeable. When examining paths with a considerable linear length, some planimetric drift is to be expected, especially when ground constraints are limited. However, planimetric shifts are less critical since they can be easily corrected using a co-registration optimization procedure (e.g., ICP) applied specifically to the sections of the path being analysed. In contrast, the altimetric shifts are more critical, as they can impact the evaluation of the actual erosion that has occurred.

Figure 7 illustrates examples of soil erosion assessment at TS E2 in a curved section of the trail. The two epochs correspond to two consecutive days before and after a mountain bike race conducted along the trail. The data were derived from two DEMs with a resolution of 5 mm. The false colour map displays in blue areas of soil erosion greater than 2.5 cm and in red accumulations greater than 2.5 cm. The bike tracks are clearly visible in blue, along with material accumulation on the sides (red). Figure 7b shows a comparison between profiles extracted along a longitudinal section in the curve, corresponding to the bike tracks, revealing the terrain's variation in the two DEMs.

In such contexts, it is important to analyse the data carefully and critically to exclude changes not caused by erosion, such as material accumulation (e.g., leaves, as shown in the red spot at the bottom of the image) or the displacement of rocks or branches. The combined use of DEMs and orthophotos is essential for visualizing and accurately interpreting these changes.

### 3.3 Scenario 3

Scenario 3 examines five different areas located at Pietra di Bismantova, Pass of Lamalite, the slopes of Marmagna Mount, and within Kamenjak Park. Each site consists of broad, open areas, making UAV photogrammetry the primary surveying technique across all test sites. This choice was driven by the need for extensive spatial coverage and high-resolution terrain mapping.
Table 4 provides details of the surveys, with flights conducted at altitudes ranging from 50 to 90 meters, depending on the maximum permissible flight heights for each area. The surveys were conducted with nadir strips and 80% longitudinal and side overlap.

| Test site | Area [km$^2$] | N. Img. | Flight alt.[m] | GSD [mm/pix] | Epochs |
|---|---|---|---|---|---|
| A | 0.734 | 386 | 90 | 25 | 2 |
| B-1 | 0.395 | 320 | 70 | 20 | 3 |
| B-2 | 0.137 | 125 | 75 | 20 | 3 |
| C | 0.184 | 277 | 80 | 21 | 2 |
| F | 0.101 | 182 | 53 | 14 | 2 |

Table 4. Summary of the survey executed in scenario 3.

| Test site | Average repeatability - RMSE [mm] | | | |
|---|---|---|---|---|
| | X | Y | Z | XYZ |
| A | 45 | 25 | 23 | 56 |
| B-1 | 34 | 36 | 49 | 65 |
| B-2 | 21 | 26 | 46 | 57 |
| C | 21 | 54 | 44 | 72 |
| F | 8 | 45 | 23 | 51 |

Table 5. Repeatability analysis performed in Scenario 3.

As in previous scenarios, a significant challenge was ensuring the consistent co-registration of photogrammetric models across multiple epochs. All flights were conducted in RTK mode, with positions corrected using the DJI D-RTK 2 GNSS reference base station.
Initial data processing relied solely on the RTK-corrected positions of centres of projections, considering a precision of these observations in the bundle adjustment of 5 cm. However, this approach led to vertical deviations of up to 40 cm, particularly pronounced at Site A, where the flat terrain complicated accurate camera focal length estimation due to its correlation with flight altitude. The absence of reliable Z constraints in such flat areas negatively impacted model accuracy.
To address this issue, the point used for positioning the DJI D-RTK 2 GNSS mobile station was used as a GCP. By incorporating this single GCP as a ground constraint, the strong correlations between flight height and principal distance in the bundle adjustment reduced considerably, improving significantly the vertical repeatability, especially at sites with flat terrain. For consistency, this approach was applied across all sites.
As in Scenario 2, the repeatability analysis was performed comparing the estimated coordinates of invariant points, analysing all possible cross-combinations between acquisition

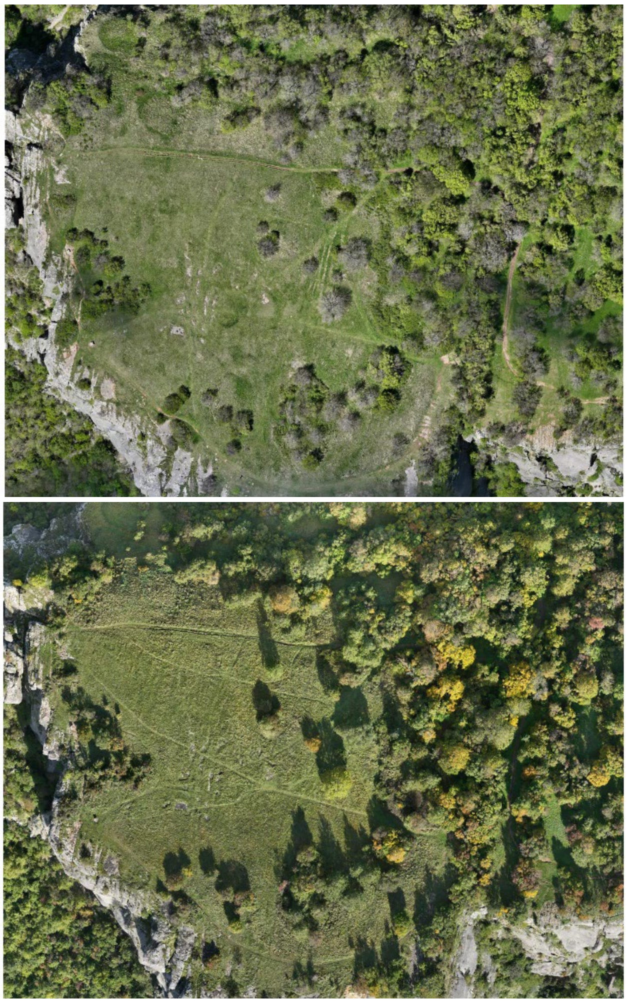


Figure 8. Orthophotos corresponding to the two different epochs of acquisition at TS A.

epochs. Table 5 summarizes the results, showing the average RMSE obtained from these cross-comparisons. The results indicate a good overall consistency, with values ranging between 5 and 7 cm, aligning with the expected precision based on the RTK constraints applied for orientation.
The results obtained from the surveys in this Scenario were high-resolution orthophotos, DSMs, and DEMs for each test site. The orthophotos provided a detailed, georeferenced view of surface conditions, while the DSMs and DEMs captured elevation changes. In wide areas covered with grass vegetation, visual comparisons between orthophotos prove to be a key method for evaluating the impact of trampling or the formation of new "paths" alongside existing trails due to frequent use. In contrast, elevation comparisons between DSM or DEM are less effective in such contexts, as changes in grass height caused by seasonal phenomena or human interventions could be misinterpreted as erosion. Elevation comparisons can be highly useful, instead, on non-vegetated trail sections.
Figure 8 illustrates a comparison between the two data sets acquired at Site A during spring and autumn of 2024. It is evident that, after the summer season, the ground surface exhibits significantly more incisions caused by tourist activity.

## 4. Conclusions

This paper presented the results from applying established geomatics techniques to monitor soil erosion on mountain trails,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focusing on their capabilities, limitations, and cost-effectiveness, while providing operational guidelines based on the spatial extent of the area to be investigated and the required level of detail.
CRP has proven to be very effective in surveying small trail sections, reaching millimetric detail. It relies on portable equipment but requires initial support from TLS or Total Station surveys to establish the reference system.
For longer, narrower paths, both UAV and spherical photogrammetry provided satisfactory results, allowing the joint usage of DEMs and orthophotos. UAV surveys needed more shooting positions to cover the same area as spherical camera, which allows for longer base lengths between consecutive shots while ensuring higher overlap. This makes spherical camera surveys faster in data acquisition but more computationally demanding due to the multiple images captured per shooting position. Focusing on ground reconstruction, the UAV, capturing terrain from a nadir perspective, provides higher level of detail compared to spherical photogrammetry, which takes images from an oblique angle relative to the ground. On the other hand, the spherical camera captures the surrounding environment, useful for optimizing co-registration of blocks across different epochs (providing references for correcting planimetric shifts) or offering insights into changes along the trail The spherical camera also provides better flexibility, handling obstacles and staying closer to the ground, while operating a drone at similarly low altitudes would require many more images.
In open areas, drone surveys proved to be the most suitable technique, providing quick data acquisition, portability, accessibility to remote regions, and GNSS assisted image block orientation through RTK solutions. It is of the utmost importance, in these cases, to provide at least one single GCP (in all the cases presented here was the fixed reference point where the GNSS base station was placed), to reduce/remove unwanted correlation between orientation parameters and dangerous systematic bias.
Georeferencing and co-registration of multi-temporal surveys posed the greatest challenge for all techniques. Establishing stable, marked GCPs is challenging due to environmental conditions, accessibility issues, and uncertainty about the long-term stability of these points. Moreover, direct GNSS or topographic surveying of GCPs is not always feasible and could be costly. Conversely, using natural features introduces uncertainties, as their identification and stability can be problematic. Even points considered stable, like those on rock formations, were found to shift due to natural environmental changes. To address these challenges, fast and simple solutions were developed to consistently set scale and vertical direction across all survey epochs. The aim was not to maximize accuracy but to allow relative comparisons across periods for realistic erosion assessments.
This initial phase of the study revealed that while data acquisition in the field is quick, processing, co-registration, and validation remain resource-intensive and are hardly automatable.
The HUMANITA project is reaching its mid-term development at the time of writing, and additional comparisons and analysis in the next epochs will provide additional (hopefully useful) insights on the best practices to implement in soil erosion monitoring by geomatics techniques.

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## References

Ancin-Murguzur, F.J., Munoz, L., Monz, C., Hausner, V.H., 2020. Drones as a tool to monitor human impacts and vegetation changes in parks and protected areas. Remote Sens Ecol Conserv 6, 105–113. https://doi.org/10.1002/RSE2.127

Ballesteros-Cánovas, J.A., Corona, C., Stoffel, M., Lucia-Vela, A., Bodoque, J.M., 2015. Combining terrestrial laser scanning and root exposure to estimate erosion rates. Plant Soil 394, 127–137. https://doi.org/10.1007/s11104-015-2516-3

Biodiversity Strategy for 2030. European Commission. [WWW Document], 2022. URL https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en (accessed 7.31.24).

Bodoque, J.M., Ballesteros-Cánovas, J.A., Rubiales, J.M., Perucha, M.Á., Nadal-Romero, E., Stoffel, M., 2017. Quantifying Soil Erosion from Hiking Trail in a Protected Natural Area in the Spanish Pyrenees. Land Degrad Dev 28, 2255–2267. https://doi.org/10.1002/ldr.2755

Ćwiąkała, P., Kocierz, R., Puniach, E., Nędzka, M., Mamczarz, K., Niewiem, W., Wiącek, P., 2017. Assessment of the Possibility of Using Unmanned Aerial Vehicles (UAVs) for the Documentation of Hiking Trails in Alpine Areas. Sensors 2018, Vol. 18, Page 81 18, 81. https://doi.org/10.3390/S18010081

Forlani, G., Dall'Asta, E., Diotri, F., di Cella, U.M., Roncella, R., Santise, M., 2018. Quality Assessment of DSMs Produced from UAV Flights Georeferenced with On-Board RTK Positioning. Remote Sensing 2018, Vol. 10, Page 311 10, 311. https://doi.org/10.3390/RS10020311

HUMANITA [WWW Document], 2024. URL https://www.interreg-central.eu/projects/humanita/ (accessed 7.31.24).

Mihai, B., Reynard, E., Werren, G., Savulescu, I., Sandric, I., Chitu, Z., 2009. Impacts of tourism on geomorphological processes in the Bucegi Mountains in Romania. Geogr Helv 64, 134–147. https://doi.org/10.5194/gh-64-134-2009

Olive, N.D., Marion, J.L., 2009. The influence of use-related, environmental, and managerial factors on soil loss from recreational trails. J Environ Manage 90, 1483–1493. https://doi.org/10.1016/j.jenvman.2008.10.004

Perfetti, L., Bruno, N., Roncella, R., 2024. Multi-Camera Rig and Spherical Camera Assessment for Indoor Surveys in Complex Spaces. https://doi.org/10.20944/PREPRINTS202410.0939.V1

Salesa, D., Cerdà, A., 2020. Soil erosion on mountain trails as a consequence of recreational activities. A comprehensive review of the scientific literature. J Environ Manage 271. https://doi.org/10.1016/j.jenvman.2020.110990

Tarolli, P., Calligaro, S., Cazorzi, F., Dalla Fontana, G., 2013. Recognition of surface flow processes influenced by roads and trails in mountain areas using high-resolution topography. Eur J Remote Sens 46, 176–197. https://doi.org/10.5721/EuJRS20134610